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Effects of gravel mulching on yield and multilevel water use efficiency of wheat-maize cropping system in semi-arid region of Northwest China

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ABSTRACT

Gravel mulching technology has been applied in the arid and semi-arid regions of Northwest China for many years. However, systematic field studies concerning its effects on ecological effects and water productivity are insufficient. A field study was conducted during two consecutive cycles of Wheat-Maize cropping system in the Yangling District of Northwest China to evaluate water productivity and crop productivity with the four treatment combinations: CK (control, no mulching), WCK (CK plus 50 mm irrigation), GM (CK plus 8 kg/m^2 gravel mulching, covering 100% of soil surface) and WGM (WCK plus GM). Soil temperature, soil moisture, total biomass and yield were significantly increased, whereas CO_2 emissions were decreased by gravel mulching treatment over the control. System yield improved by 19.87% and 15.59% by applying 50 mm irrigation, 53.58% and 43.18% by applying gravel mulching and 60.64% and 48.28% by applying gravel mulching and 50 mm irrigation over the control during both the cycle of Wheat-Maize rotation, respectively. Gravel mulching results in a positive contribution to annual net primary productivity (NPP) and net ecosystem exchange (NEP), and high-water use efficiency (WUE) were achieved under gravel mulching treatment for the two rotation cycles. Annual WUE_{eco} and WUE_{yield} significantly increased by 40.6% and 49.2% and 57.6% and 51.4% under the gravel mulching treatment over the control during the two cycles, respectively. However, during cycle 1 WUE_{veg} and WUE_{bio} did not significantly affected whereas during cycle 2 it affected, with a maximum value of 14.4 kg ha^{-1} mm^{-1} in WGM and 47.1 ± 5.1 kg ha^{-1} mm^{-1} in GM, respectively. Taking into account crop yield, ecological effects and water use, covering the soil with gravel is an effective approach to enhance multilevel water use efficiency while increasing the productivity of wheat-maize cropping system in semi-arid regions of China.

1. Introduction

Water and food scarcity, as a global problem, severely affects the development of arid and semiarid regions (Misra, 2014). An increasing number of studies have demonstrated that climate change could aggravate the risk of drought and decrease agricultural production in semi-arid areas. Thus, improvement of crop yield with less water resources available is a key issue that needs to be addressed (Lioubimtseva and Henebry, 2009; Wu et al., 2017). Concerns over food security have existed throughout the agricultural history of the Loess Plateau of Northwest China, where intensive agriculture (e.g., wheat-maize double cropping) with limited water has been practiced to meet the large demand for grains (Green et al., 2010). One of the objectives in innovating agricultural practices is to improve crop production and water use efficiency to ensure food security within the context of climate change and water crises in arid and semi-arid region (WUE, or water productivity) (Bu et al., 2013; Kang et al., 2017). Field management tools for multi-scale agricultural water management (e.g., irrigation, nutrient management) have been investigated to identify a better water supply system to meet the water demand and actual crop water requirement determined by local soil and climate conditions (Fang et al., 2010; Li et al., 2010; Guo et al., 2016). Field techniques, such as conservation tillage and mulching using different materials (e.g., straw amendment, plastic film, sand, and gravel), have been applied to adjust soil moisture and improve crop production in water-limited agricultural regions (Kar and Kumar, 2007; Chen et al., 2015; Shao et al., 2016; Kumar and Dey, 2011; Li, 2003). Both gravel and plastic film mulching greatly improve crop yields due to increased soil

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moisture (Li et al., 2000; Wang et al., 2009), reduced soil evaporation (Wang et al., 2009, Wang et al., 2011), and increased topsoil temperatures. Plastics are lightweight and economical, however, plastics pollute environment and pose difficulties during recycling. Straw amendments has also been widely recommended for sustaining soil organic matter and avoiding the environmental pollution in China. But straw amendments to soil can alter microbial access to carbon substrates, leading to an increase in soil CO_2 emissions (Zhang et al., 2017). For environmental protection, gravel mulching has an absolute advantage. Surface gravel also protect the soil from rain washed and soil erosion and act as a mulch. It is regrettable that surface gravel are easy to mix with soil and hard to removed, however, the value of this traditional technique did not lie in its direct application or suitability for the rest of the world (Gale et al., 1993).

Gravel mulching is such an indigenous field technology and has been used for crop production for over 300 years in the loess area of northwest China (Wang and Sun, 1986). In China, gravel-mulched fields are concentrated in the Gansu province, as well as in adjoining counties in the neighbouring Ningxia Hui Autonomous Region and the Qinghai Province. At present, 118,000 ha of such fields are distributed in Gansu Province. Soils with gravel on the surface are also widespread in the world and may be found in areas near the Mediterranean Sea (Poesen and Lavee 1994), in the USA (Miller and Guthrie 1984), and in China (Gale et al., 1993). A number of studies performed both at home and abroad have shown that gravel cover has a significant effect on water conservation and crop production in arid and semi-arid regions. Early studies by Lamb and Chapman (1943) and Epstein et al. (1966) declared that surface gravel mulching could apparently reduce evaporation, as well as runoff, and dramatically increase soil infiltration. A study conducted by Faibourn (1973) indicated that gravel mulching can improve soil temperature, soil moisture and crop yield. Gale et al. (1993) introduced the creation and maintenance of a gravel-sand mulched field and briefly discussed some of the underlying principles that enable the agricultural practice to be successful. Over the last two decades, gravel mulching technology has been widely verified by numerous researchers as a promising and effective solution to reduce evaporation and improve soil physical status and crop production in semiarid and arid regions of China (Zhang et al., 2009; Wang et al., 2011; Ma and Li, 2011; Qiu et al., 2015). Yuan et al. (2009) reported that a gravel-mulched field can reduce evaporation by 49.1–83.6% compared to bare soil. Changes in soil hydro-thermal processes under surface gravel mulches could provide a more favourable environment for plant growth than non-mulched fields in arid and semiarid areas (Li, 2003). From the literature review, we found that the majority of existing research was focused on the influence of surface gravel mulching on soil hydro-thermal processes, and less work has been devoted to the ecological effects, crop yield and water use efficiency in these areas. Therefore, this study was carried out to relevant research on the application of gravel mulching.

Gravel mulching can alter soil hydro-thermal processes and carbon processes, enhance the system's ability to conserve water as well as carbon, and promote ecological activities. Crop yield and water use efficiency eventually will be affected to a great extent. Published studies have paid more attention to water use efficiency under the yield level. Recently, multi-level water use efficiency (i.e., the ratio of productivity to water use at net primary productivity, net ecosystem exchange, biomass production, and economic yield levels) has become one of the frontiers of agricultural water management (Hsiao et al., 2007; Morison et al., 2008; Monson et al., 2010; Gong et al., 2017). Biomass accumulation is also a key indicator of sustainability and soil physical status in any cropping system (Adak et al., 2013; Liu et al., 2016). Numerous studies have demonstrated that agriculture is one of the major contributors to greenhouse gas emissions. Smith et al. (2008) reported that roughly 10–12% of the total greenhouse gas (GHG) emission is released by agriculture. According to IPCC (2014), global agriculture released 5.1–6.1 Pg CO_2-equivalents yr^{-1} of the total global anthropogenic greenhouse gas emissions in 2005. Therefore, the relationship between farmland ecological effects and crop production should also be of concern (Shurpali et al., 2013; Zhou et al., 2014). In some studies, the total amount of carbon accumulation (or loss) from ecosystems is applied to evaluate net ecosystem production (Chapin et al., 2006; Ceschia et al., 2010; Luo et al., 2015). Quantifying the effects of gravel mulching on multi-level water use efficiency is essential for evaluating its eco-hydrological effects and developing efficient water use strategies for agriculture in arid areas of China (Shen et al., 2013). However, there is currently an insufficient understanding of how gravel mulching actually influences crop evaporation (or water loss), ecosystem CO_2 emissions, biomass accumulation and final economic yield. Elucidating these links via calculation of water use efficiency at different levels will clarify the mechanism by which gravel mulching produces more biomass and grain with less water and thus aid in optimizing gravel mulching technical parameters.

Therefore, the objective of this study is to elucidate the effect of gravel mulching on the dynamics of soil moisture, soil temperature and CO_2 emissions from ecosystems, crop growing indexes (i.e., height, leaf area index, biomass, number of grains per ear), and crop yields by investigating two consecutive wheat-maize rotations. In particular, water use efficiency, such as WUE_{veg} (NPP/ET_0), WUE_{eco} (NEP/ET), WUE_{bio} (Biomass/ET), and WUE_{yield} (Economic Yield/ET), were calculated at different levels. ET_0 (reference crop evapotranspiration) was calculated using the FAO Penman-Monteith equation, and ET (evapotranspiration) was calculated as a given amount of water lost through evapotranspiration (Allen et al., 1998; Gong et al., 2017). Numerous studies have reported that reducing E is an effective method of conserving soil moisture and improving crop WUE (Mellouli et al., 2000; Kang et al., 2002; Chen et al., 2010). In this study, we investigate the mechanism of how gravel mulching affects the soil physical environment, as well as ecosystem CO_2 fluxes, thereby affecting the biomass production, economic yield and water-use efficiency (WUE) of crops. Water productivity and crop productivity may largely depend on application methods of gravel mulching. Furthermore, this study can be regarded as a basic case to assess the influence of gravel mulching on ecological effects and agricultural water management.

2. Materials and methods

2.1. Experimental site and climate

The field experiment was conducted from 2013 to 2015 at the Experimental Station of Water Saving Irrigation of Northwest A&F University, Yangling, China (34°20′N, 108°24′ E, 521 m a.s.l.). The site is in a semi-arid to sub-humid climatic zone, with a mean temperature of 13.0 °C and a mean annual precipitation of 620 mm concentrated from June to October (Zhang et al., 2017). The mean annual pan evaporation exceeds 990 mm, and the mean annual sunshine duration is 2100–2200 h (Feng et al., 2016). The soil texture (0–10 cm) is silty clay loam, consisting of 8% sand, 74% silt, and 18% clay. The soil properties in the top 20 cm (sampled on October 19, 2013) are as follows: the bulk density was 1.45 g cm^{-3}, the field water capacity was 23.5% (v/v), and the soil organic matter (SOM) was 9.6 g kg^{-1}. The data of air temperature and daily precipitation from October 1, 2013 to October 30, 2015 were collected from an automatic weather station, which is close to the experimental field (Fig. 1). Mean annual maximum and minimum temperatures were 19.6 °C and 9.2 °C during 2013-14 (cycle 1), and 19.7 °C and 9.2 °C during 2014-15 (cycle 2). Annual precipitation was 685.8 mm during cycle 1 (291.2 mm and 394.6 mm for the wheat and maize seasons, respectively) and 589.2 mm during cycle 2 (253.4 mm and 335.8 mm for the wheat and maize seasons, respectively).

2.2. Experiment treatments and field management

This experiment was conducted in a randomized complete block

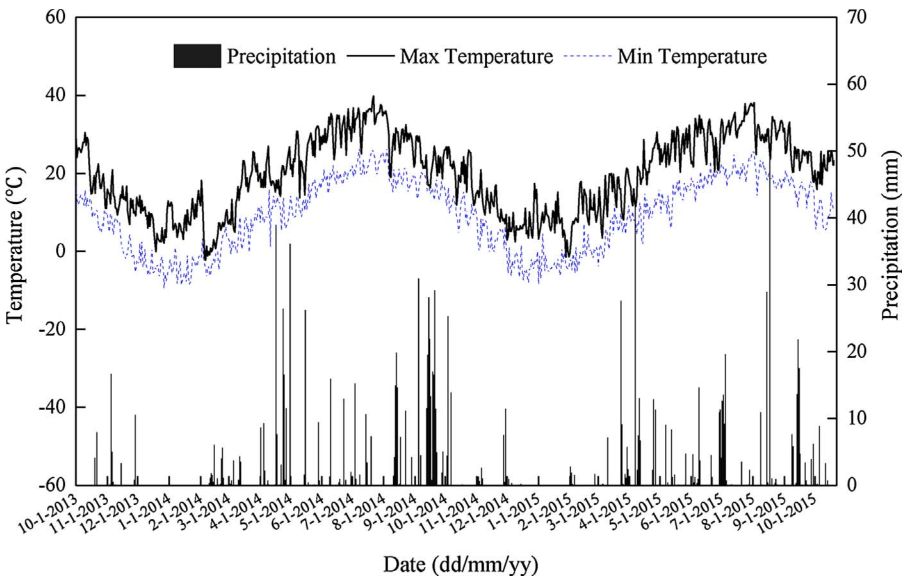


Fig. 1. Daily precipitation (vertical bars) and maximum air temperature (black solid curve) and minimum air temperature (blue dotted curve) during the two wheat-maize rotation cycles studied. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

design with three replicates for the four treatments: CK (control, no mulching), WCK (CK plus 50 mm irrigation at the key growth periods), GM (CK plus 8 kg m^{-2} of 2–4 cm diameter gravel mulching, covering 100% of the soil surface) and WGM (WCK plus GM) with three replications. Each plot was 3 m in width and 5 m in length, wrapped in 8-μm-thick polyethylene plastic film (1 m deep) along a vertical profile of a ridge edge for preventing lateral infiltration of soil moisture. Individual plots were separated by 0.3 m spacing. For the gravel mulched field, gravel was evenly laid artificially after the planting of wheat or maize and removed once the crop harvest was done, thus avoiding experimental used gravel mixed with soil. Winter wheat (cv Xiaoyan 22), at a seed rate of 187.5 kg ha^{-1} with 30 cm row spacing was planted on October 19, 2013 and on October 17, 2014 and harvested on June 7, 2014 and June 8, 2015, respectively. Whereas summer-maize (cv Qinlong 11), at 45000 plants ha^{-1} with alternating wide and narrow row spacing of 60 cm and 40 cm was planted on June 8, 2014 and June 12, 2015 and harvested on October 8, 2014 and October 9, 2015 for cycles 1 and 2, respectively. When harvested, any visible roots or organic residues were removed manually.

A uniform dose of fertilizers was applied at the rate of 150 kg N and 100 kg P_2O_5 ha^{-1} $yr^{-1}$for wheat, and 225 kg N and 90 kg P_2O_5 ha^{-1} yr^{-1} was applied, with the source of urea as an N fertilizer and calcium superphosphate for P to all treatments. In this experiment, the water supply for the CK and GM treatments was solely from natural rainfall. The W and WGM treatments received 50 mm of irrigation (flood) water on December 29, 2013; March 15 and August 3, 2014; and January 5 and March 13, 2015 (Table 1). In addition, periodic artificial weeding was applied to control weeds.

2.3. Measurements and calculations

2.3.1. Evapotranspiration and CO_2 fluxes

Meteorological parameters, including net radiation (R_n, MJ $m^2 day^{-1}$), sunshine hours (n, *h*), average daytime wind speed at 2 m height (u_2, m/s), the slope of the vapor pressure curve (Δ, KPa $°C^{-1}$), and other correlated parameters were collected from a nearby weather station. Reference crop evapotranspiration (ET_0) was calculated using the following procedure described by Allen et al. (1998) and Pereira et al. (2015):

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma\frac{900}{T+273}u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \quad (1)$$

A soil profile water detection tube (3 m deep) from Trime-TDR was centrally installed to measure the soil water content at 10 cm intervals within the 0–40 cm profile and 20 cm intervals within the 40–200 cm profile. The soil moisture in the 0–100 cm soil profile in each plot was calculated as the total soil water storage (W) during the wheat and maize growing seasons. Then *ET* could be determined using the field water balance equation as follows (Allen et al., 1998; Sun et al., 2010; Parihar et al., 2017):

$$ET = P + I - R - D - \Delta W \quad (2)$$

There was no runoff (R) from the experimental plots, as they were bunded up to a sufficient height (40 cm height), and no case of bound overflow was observed during the study period. As the groundwater level was relatively low (8–10 m in depth), soil moisture studies were made down to a soil depth of 200 cm and the profile was loam layers. Deep percolation below 200 cm profile (D) was assumed to be negligible (Chen et al., 2010; Muniandy et al., 2016; Parihar et al., 2017).

Table 1
Crop management details for all four treatments over the two wheat-maize rotations from October 2013 to October 2015.

Crop season	Planting	Harvest	Gravel mulching *for GM, WGM*	Irrigation *for W, WGM*	Fertilization
2013–2014 wheat	October 19, 2013	June 7, 2014	October 21, 2013	December 29, 2013 March 15, 2014	October 17, 2013 (150 kg N ha^{-1}, 100 kg P_2O_5 ha^{-1})
2014 maize	June 8, 2014	October 8, 2014	June 10, 2014	August 3, 2014	June 7, 2014 (225 kg N ha^{-1}, 90 kg P_2O_5 ha^{-1})
2014–2015 wheat	October 17, 2014	June 5, 2015	October 19, 2014	January 5, 2015 March 13, 2015	October 16, 2014 (150 kg N ha^{-1}, 100 kg P_2O_5 ha^{-1})
2015 maize	June 12, 2015	October 5, 2015	June 9, 2015	July 22, 2015	June 20, 2015 (225 kg N ha^{-1}, 90 kg P_2O_5 ha^{-1})

In this study, the static chamber and gas chromatography method was used to measure the carbon dioxide fluxes during the period from October 2013 to October 2015 and is highly similar to the one described in Zhang et al. (2013) and Zou et al. (2005). A stain-steel frame with a groove ($50 \times 50 \times 20\ cm^3$) was inserted 20 cm into the soil between the wheat rows and maize plants in each plot. During sampling, a chamber ($50 \times 50 \times 50\ cm^3$) was inserted into the water-filled groove to seal the top chamber airtight for a period of 30 min. In the later stages of plant growth, we increase the chamber height by stacking the bottomless and coverless gas boxes. The chamber was equipped with a small circulation fan and a polyvinyl chloride (PVC) gas channel with a three-way stopcock. Gas samples were collected using a 60-ml plastic syringe with a three-way stopcock at 0 min, 10 min, 20 min, and 30 min after chamber closure. Over the two annual cycles, CO_2 fluxes measurements were carried out once ten days in triplicate plots for all the treatments.The CO_2 concentration in a gas sample was simultaneously analysed using a gas chromatograph (Agilent 7890A, Agilent Technologies, Inc., Santa Clara, USA). Total emissions of CO_2 over the two cycles were sequentially accumulated from emissions and averaged from every two adjacent intervals of the measurements (Zhang et al., 2017; Zou et al., 2005).

2.3.2. Biomass and yield and auxiliary measurements

The sampled plants (total leaves and stover) were heated at 105 °C for 30 min and then dried at a constant temperature (75 °C) before weighing. The total above-ground biomass in each plot was expressed as kg dry-matter ha^{-1}. At harvest, the wheat biomass and grain yield were measured for all plants selected from a 1 m^2 area marked by a red woolen in the middle of each plot. Ten maize sample plants, randomly collected from each plot, were used to measure maize biomass and grain yield. The biomass and grain yield were determined by the average of the three plot replicates, and all grain samples were dried to a constant weight in a fan oven at 75 °C. All mass values are expressed in relation to the dry weight.

Soil temperature was monitored together with soil water content using a geothermometer (WQG-16, Ruiming Ltd., Changzhou, China), which was inserted into the soil at the central plot for the exploration of thermal effects along a vertical profile. Data were recorded at 8:00 am, 10:00 am, 12:00 pm, 2:00 pm and 6:00 pm Growing degree days (GDD) were calculated as the sum of the daily average soil temperature in 0–25 cm layers. The oven drying method can also used to measure the soil bulk density (BD) before planting and after harvest, respectively. Soil organic matter (SOM) content was analysed by wet digestion with H_2SO_4–$K_2Cr_2O_7$ solution (Zhang et al., 2017). Soil samples were collected from two or three soil cores by randomly. We monitored plant height (H) using scale ruler and leaf area index (LAI) using Canopy Analysis Instrument (Sunscan 2000, Delta T, co, UK) during each growth period. Number of grains per year (NGP) were counted manually when harvested, and we calculated the harvest index (HI) by the crop yield per unit area divided by total dry biomass above ground. These auxiliary measurements were conducted to perform principal component analysis (PCA) for different treatments.

2.3.3. Calculation of NPP, NEP and multilevel water use efficiency

We allocated net ecosystem productivity of CO_2 (NEP) using an equation (Zhang et al., 2013) as follows:

$$NEP = R_H - NPP \tag{3}$$

where NPP was the net primary productivity, kg ha^{-1}, and RH was the microbial respiration of soil, kg ha^{-1}, which was approximately equal to total soil CO_2 flux (Raich and Tufekcioglu, 2000). The NPP was simply derived from biomass harvested and determined by the maximum biomass (W_{max}) at maturity from the plots where CO_2 emissions were measured. Then NPP was calculated using an equation proposed by Osaki et al. (1992) as follows:

$$NPP = 0.446W_{max} - 0.00067 \tag{4}$$

Vegetation water use efficiency is defined as the ability of vegetation to fix carbon (minus crop respiration) via net primary productivity (NPP) for a given amount of water loss through crop evapotranspiration (ET_0) (Kotani et al., 2014; Zhou et al., 2014). It can be expressed as follows:

$$WUE_{veg} = NPP/ET_0 \tag{5}$$

Ecosystem water use efficiency is the ratio of the net ecosystem productivity (NEP = −NEE, net ecosystem exchange) over water loss through evapotranspiration (ET) at an ecosystem level (Wagle and Kakani, 2014; Tong et al., 2014; Gong et al., 2017). Its mathematical expression is described as follows:

$$WUE_{eco} = NEP/ET \tag{6}$$

Biomass water use efficiency (WUE_{bio}) and economic output water use efficiency (WUE_{yield}) are calculated as the ratio of total biomass production or economic yield over total ET (Oikawa et al., 2015; Gong et al., 2017). The mathematical models are defined as follows:

$$WUE_{bio} = biomass\ \ production/ET \tag{7}$$

$$WUE_{yield} = economic\ \ yield/ET \tag{8}$$

2.4. Statistical analyses

SPSS 20.0 (IBM SPSS Statistics, USA) was used to conduct statistical analyses in this study. Mean values and standard deviations for three replicates have been calculated for all parameters. The distribution of the dependent and independent variables under different treatments have been tested using principal component analysis (PCA) using the vegan package in R (version 3.2.1). Crop WUE at different levels is subjected to an analysis of variance. The results were compared to the least significant difference (LSD) at the 5% level to identify significant differences. Two-way analysis of the variance method (ANOVA) is used to evaluate the significant levels of the effects of irrigation and gravel mulching as well as their combination on grain yield and multi-level WUE. The figures in this paper were drawn using the software Origin 9.0.

3. Results

3.1. Soil temperature and moisture

The dynamics of the soil temperature in the top soil (0–30 cm) between the seasonal and annual treatments are similar. Soil temperature was greatly influenced by daily air temperature and also varied among different gravel mulching practices (Figs. 1 and 2a). In our study, soil temperature was 0.46 °C, 0.49 °C and 0.63 °C higher under the WCK, GM, WGM treatments than the CK treatment on average, respectively, over two rotation cycles. Although soil temperature was reduced under irrigation, the average soil temperature increased for the whole growing period. Annual GDD (≥0 °C) was 258.50 °C d, 266.29 °C d and 368.27 °C d higher under WCK, GM and WGM as compared to CK (4607.64 °C d), respectively, over the two rotation cycles. The results show that the seasonal and annual dynamics of topsoil water content (0–30 cm) are largely dependent on daily precipitation and irrigation practices and also vary among different field treatments (Figs. 1 and 2b). GM and WGM tended to have higher soil water content than CK and WCK if rain events occurred. The soil water content of CK and GM is lower than that of the irrigation treatments of WCK and WGM.

However, average soil moisture was 2.63%, 1.98% and 4.19% higher under WCK, GM and WGM than under CK, respectively, over the two Wheat-Maize cycles. In particular, the change in soil water storage (ΔW) at the profile of 0–1 m increased by 33.25 mm, 26.54 mm, and 68.60 mm under WCK, GM and WGM compared to CK on average,

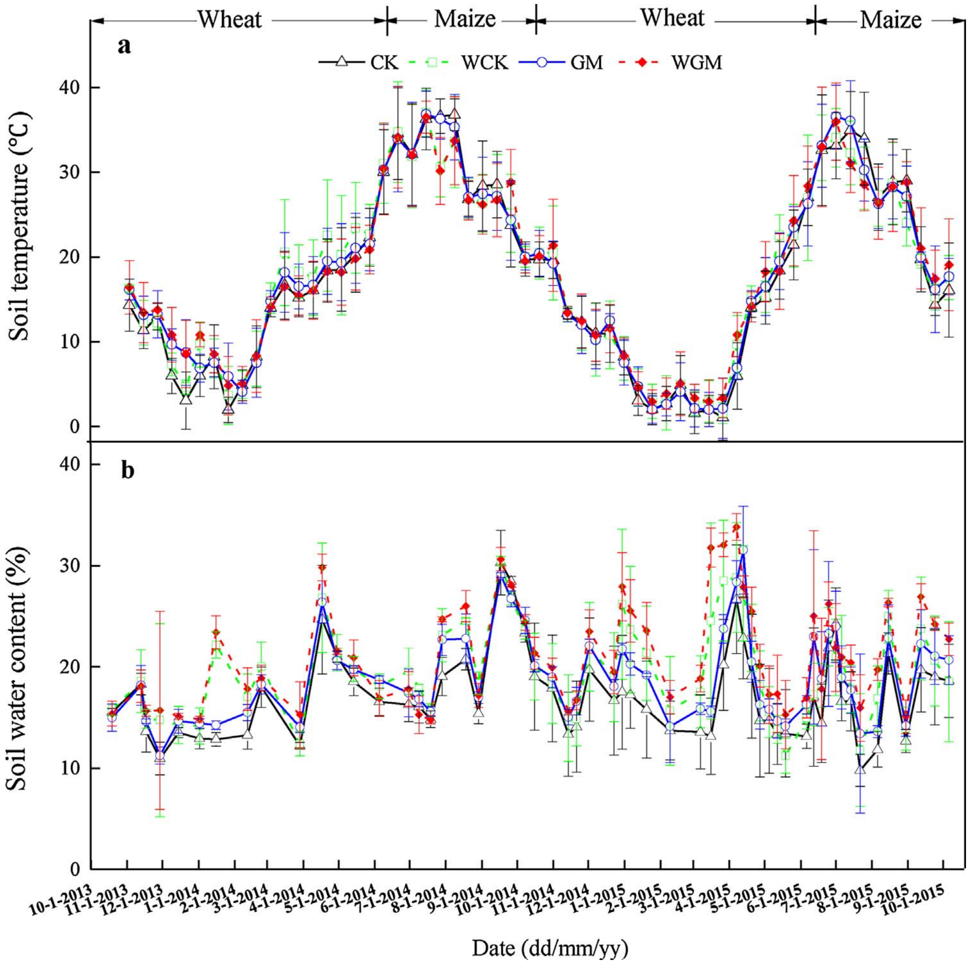


Fig. 2. Dynamics of soil temperature (a) and soil water content (b) (mean ± SD, n = 3) in the top layer (0–30 cm depth), measured when GHGs emissions were monitored in the field, during two annual wheat-maize growing seasons under different treatments.

respectively, for the two cycles.

3.2. CO_2 fluxes

Seasonal and annual dynamics in CO_2 flux generally followed the changes in air and soil temperature with high peaks of CO_2 flux from April to August during both years during the late wheat and early maize growing periods (Figs. 1, 2a, 3), whereas CO_2 flux was the converse of the soil water content change during the two cycles (Figs. 2b, 3). Improved soil temperature and moisture under gravel mulching change the farmland greenhouse gas emissions. Many studies have modeled greenhouse gas emission response to soil temperature using an empirical index formula, i.e. the Van't Hoff equation, and to soil moisture using a linear or polynomial equation (Van't Hoff, 1923; Bowden et al.,

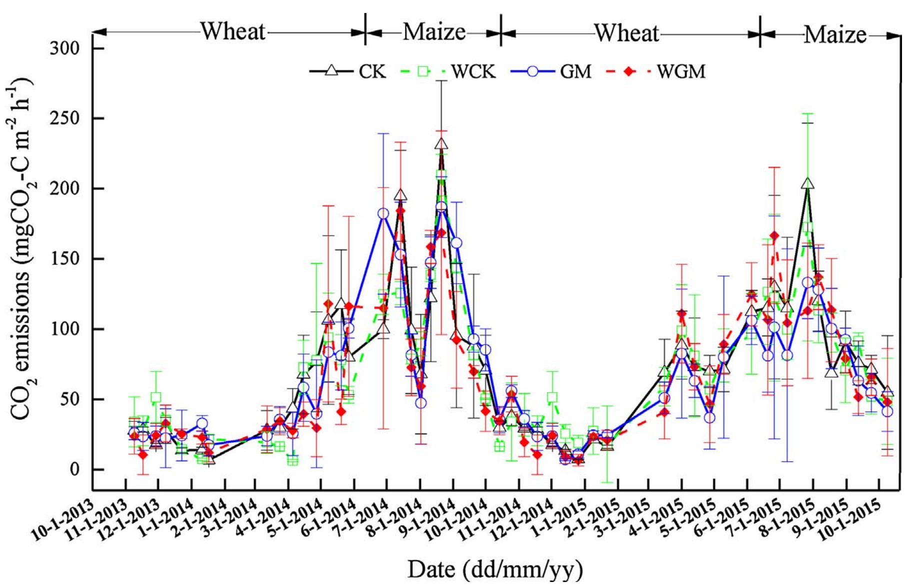
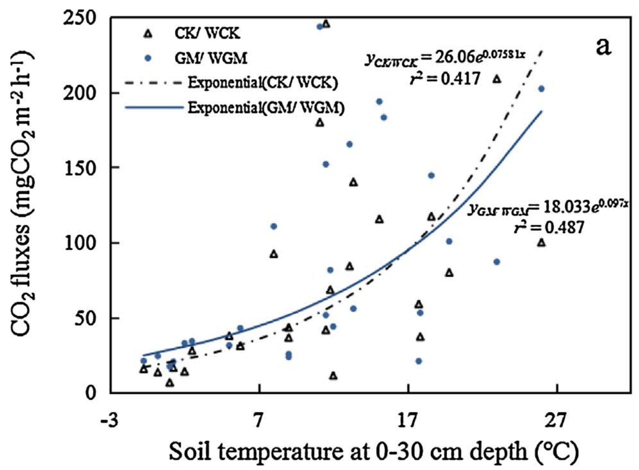
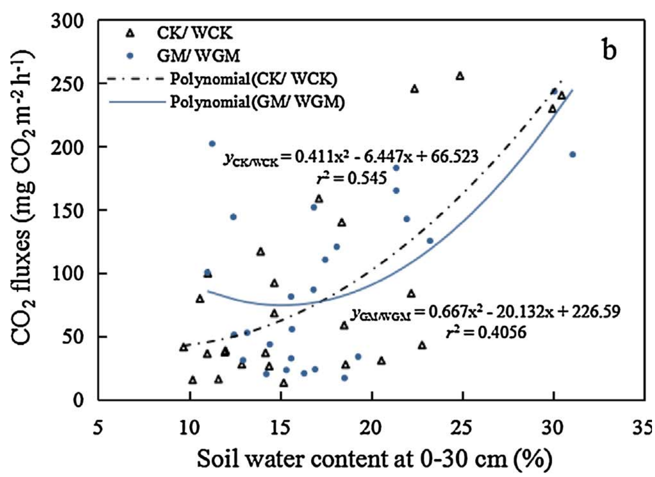


Fig. 3. Fluxes of CO_2 (mean ± SD, n = 3) during the two annual wheat –maize growing seasons under different treatments.



a. Relationship of ecosystem CO_2 fluxes with soil temperature.



b. Relationship of ecosystem CO_2 fluxes with soil water content.

Fig. 4. Ecosystem CO_2 fluxes response to a change in soil temperature (a) and soil water content (b) at 0–30 cm depth during two annual wheat-maize growing seasons under the four treatments.

1998; Xu and Baldocchl, 2004). In our study, the linear fitting results were not very good, while index fitting and polynomial fitting fit well. Fig. 4 shows the relationship between ecosystem CO_2 fluxes and the average soil temperature (a) and soil water content (b) during the experiment. CO_2 fluxes significantly increased over the treatments at a higher soil temperature (> 18 °C) and moisture (> 17.5%); however, a higher value of CO_2 fluxes was recorded under the control treatments than under the gravel mulching treatments. As we found in Fig. 4, the relationship of ecosystem CO_2 fluxes and soil water content can be well modeled by polynomial function, whilst the exponential function could give acceptable goodness of fit to depict the interrelation between ecosystem CO_2 fluxes and soil temperature.

Annual total CO_2 emissions were significantly affected by soil mulching practices over the two-year period, ranging from 5333.1 ± 573.0 to 6347.2 ± 173.4 kg CO_2-C ha^{-1} over cycle 1 and from 4679.7 ± 750.5 to 5686.9 ± 535.7 kg CO_2-C ha^{-1} over cycle 2 (Table 2). Significantly decreased CO_2 emissions occurred under WCK, GM and WGM compared to CK over both cycles, with values of 7.39%, 14.07%, and 15.97% and 7.98%, 12.98%, and 17.71%, respectively.

3.3. Dry biomass and crop yield

Total biomass and crop yield at the harvest stage are shown in Table 2. For the four treatments, the values of biomass are close during both the wheat and maize growing seasons in cycle 1. Whereas in cycle 2, both GM and WGM significantly increased seasonal biomass accumulation and annual system biomass accumulation. The increase of total biomass therefore increased the crop yield. As shown in the Graphical Abstract, the applying of gravel mulching generally exerted greater effects on total biomass and yield than the control treatments during both cycles.

Annual total dry biomass significantly increased by 1.62%, 5.79% and 7.55% and by 4.06%, 17.40% and 19.15% in WCK, GM and WGM compared to CK during cycle 1 and cycle 2, respectively. Along with time, annual total biomass significantly increased in the second year than in the first year by applying gravel mulching over than the control. Annual crop yield increased by 19.87%, 53.58% and 60.64% and by 15.59%, 43.18% and 48.28% in WCK, GM and WGM compared to CK during the both cycles, respectively. We also found that gravel mulching during the first year has a greater effect on crop yield than during the subsequent year. This is mainly due to decreased annual precipitation, which was 96.6 mm lower in cycle 1 than in cycle 2, making the soil status unconducive to crop yield during cycle 2. Meanwhile, there is a decrease in the yield-improving effects of gravel mulching.

3.4. NPP and NEP

The annual NPP ranged from 11363 ± 2469 to 12221 ± 548 kg CO_2 ha^{-1} and from 10253 ± 147 to 12217 ± 324 kg CO_2 ha^{-1} during cycle 1 and during cycle 2, respectively (Table 2). The annual NPP has no significant differences during cycle 1, due to the close values of total biomass for all treatments.Whereas in cycle 2, WCK, GM and WGM had higher annual NPP by an amount of 0.78%, 17.4% and 19.1%, respectively, as compared to CK.

The NEP relating the NPP to the total amount of CO_2 fluxes was significantly affected by different mulching practices during both cycles. For the four treatments, the annual NEP ranged from 4.16 ± 1.36 to 6.30 ± 0.88 kg CO_2 ha^{-1} during cycle 1, and from 3.94 ± 0.99 to 6.43 ± 0.33 kg CO_2 ha^{-1} during cycle 2 (Table 2). The annual NEP significantly increased by 17.06%, 28.84% and 51.48% during cycle 1 and by 7.46%, 40.61% and 63.09% during cycle 2, under WCK, GM and WGM as compared to CK, respectively.

3.5. Water use efficiency at different levels

Multilevel water use efficiency (WUE) for different experimental treatments during the two cycles is presented in Table 3. A comparison of multilevel water use efficiency from 2013 to 2015 is shown in the Graphical

Abstract

It is noticeable that WUE_{veg} is very close and changes within a range of from 12.2 ± 2.7 to 14.4 ± 0.6 kg CO_2 ha^{-1} mm^{-1} during cycle 1. As for cycle 2, WUE_{veg} response to the total biomass and annual NPP experienced a great increase compared to the gravel mulching; in particular, WUE_{veg} increased by 5.40%, 24.32% and 29.73% in WCK, GM and WGM compared to CK, respectively. There is a small discrepancy between the two wheat-maize cycles in terms of WUE_{eco}. The value of WUE_{eco}, for all the treatments varies from 6.4 ± 2.8 to 8.9 ± 1.8 kg CO_2 ha^{-1} mm^{-1} during cycle 1 and between 6.5 ± 1.4 and 10.0 ± 2.4 kg CO_2 ha^{-1} mm^{-1} during cycle 2. WUE_{bio} is slightly different from WUE_{veg} and WUE_{eco}. It increases with gravel mulching but decreases under the combined irrigation treatment. WUE_{bio} significantly increased in GM compared to CK, as it increased by 11.36% during cycle 1 and by 24.27% during cycle 2. However, relative to irrigation treatment, WUE_{bio} decreased by 14.63% during cycle 1 and 9.98% during cycle 2, in WGM compared to GM, respectively. For the four treatments, WUE_{yield} significantly changed within a range from 11.8 ± 2.5 to 18.6 ± 0.9 kg Seed ha^{-1} mm^{-1} during cycle 1 and within a range from 13.8 ± 1.1 and 20.9 ± 2.7 kg Seed ha^{-1} mm^{-1}

Table 2
Total amount of evapotranspiration (ET_0) and water consumption (ET), CO_2 emissions and net primary productivity (NPP) and net ecosystem productivity (NEP), aboveground biomass and yield in wheat-maize rotation fields under different treatments during the experimental period from 2013 to 2015.

Cycle	Crop	Treatment	ET_0 (mm)	ET (mm)	CO_2-C (kg CO2 ha − 1)	NPP (kg CO2 ha − 1)	NEP (kg CO_2 hm^{-2})	Biomass (kg ha^{-1})	Yield (kg ha^{-1})
2013–2014	Wheat	CK	519.06	318.1 ± 72.4b	3458.8 ± 295.4a	5983 ± 1851a	2241 ± 1533b	13415 ± 4152a	3332.8 ± 927.3b
		WCK	509.53	405.1 ± 29a	3285.3 ± 675.3a	6025 ± 476a	2634 ± 482b	13509 ± 1068a	3974.2 ± 728.7ab
		GM	494.87	303.6 ± 32.7b	3034.3 ± 507.3a	6460 ± 416a	2847 ± 504b	14484 ± 933a	5155.3 ± 842.4a
		WGM	491.76	388.7 ± 23ab	2959 ± 750.2a	6556 ± 1070a	3597 ± 1812a	14699 ± 2400a	5379.6 ± 460.5a
	Maize	CK	409.64	306.8 ± 7.3bc	2888.4 ± 132a	5379 ± 1475a	1920 ± 1768b	12061 ± 3307a	3926.2 ± 634c
		WCK	406.30	336.5 ± 6.1a	2592.9 ± 362.6a	5522 ± 511a	2237 ± 705b	12381 ± 1146a	4727.5 ± 170.2bc
		GM	372.58	295.1 ± 11.2c	2419.5 ± 806.7a	5549 ± 593a	2514 ± 1079a	12441 ± 1329a	5993.1 ± 1085.7ab
		WGM	359.83	317.6 ± 13.3b	2374.2 ± 218.1a	5665 ± 1473a	2706 ± 1344a	12701 ± 3302a	6278.4 ± 544.8a
	Annual	CK	928.70	624.9 ± 79.2bc	6347.2 ± 173.4a	11363 ± 2469a	4161 ± 1357b	25476 ± 5535a	7259 ± 939.5b
		WCK	915.83	741.7 ± 34a	5878.1 ± 990.2a	11547 ± 972a	4871 ± 1167b	25890 ± 2179a	8701.7 ± 783.2b
		GM	867.45	598.7 ± 40.9c	5453.8 ± 1259a	12009 ± 706a	5361 ± 684ab	26925 ± 1583a	11148.4 ± 566.7a
		WGM	851.59	706.3 ± 21.3ab	5333.1 ± 573a	12221 ± 548a	6303 ± 884a	27400 ± 1230a	11658 ± 968.4a
2014–2015	Wheat	CK	537.77	308.5 ± 15.4B	3369.6 ± 500.7A	5778 ± 1321B	1841 ± 667B	12955 ± 720B	3738 ± 372.7B
		WCK	534.88	378 ± 54A	3170.8 ± 523.8A	5823 ± 1079B	1984 ± 816B	13058 ± 200B	4647.6 ± 1377.2AB
		GM	523.41	283.2 ± 38B	2897.1 ± 299.5B	6610 ± 434A	3001 ± 924A	14821 ± 973A	5887.7 ± 518.9A
		WGM	515.28	350.9 ± 72.9A	2813.9 ± 365.8A	6678 ± 178A	3310 ± 608A	14973 ± 211A	5982.8 ± 552.1A
	Maize	CK	388.13	298.4 ± 29.8B	2317.3 ± 84.7C	4475 ± 410A	2100 ± 368B	10033 ± 920A	4596.1 ± 58.6C
		WCK	373.71	330.1 ± 35.8A	2080 ± 497.4B	4845 ± 602A	2252 ± 267B	10863 ± 1351A	4986.1 ± 822.9BC
		GM	347.38	289.4 ± 36B	2051.6 ± 211.6B	5431 ± 1252A	2542 ± 1122B	12176 ± 2807A	6045.4 ± 767.5AB
		WGM	335.57	307.7 ± 42.8B	1865.7 ± 452A	5539 ± 305A	3119 ± 745A	12418 ± 683A	6375.5 ± 587.6A
	Annual	CK	925.90	606.9 ± 15.9A	5686.9 ± 535.7A	10253 ± 147B	3942 ± 998B	22989 ± 330B	8334.1 ± 344.1B
		WCK	908.59	708.1 ± 87.8A	5250.8 ± 636.6AB	10669 ± 664B	4236 ± 1064B	23921 ± 1488AB	9633.7 ± 1667.5B
		GM	870.78	572.6 ± 15.2A	4948.8 ± 296B	12041 ± 1485A	5543 ± 1722AB	26998 ± 3329A	11933.2 ± 1273.9A
		WGM	850.85	658.7 ± 115.6A	4679.7 ± 750.5B	12217 ± 324A	6429 ± 333A	27391 ± 727A	12358.3 ± 1106.7A

Significant differences among the treatments are indicated by lower case letters (cycle 2013–2014) and capital letters (cycle 2014–2015) at $P < 0.05$ (LSD), the same as below.

Table 3
Multilevel annual water use efficiency (WUE) affected by different treatments during the experimental period from 2013 to 2015..

Cycle	Treatment	ET_0 (mm)	ET (mm)	Multilevel WUE			
				WUE_{veg} Kg CO_2 ha^{-1} mm^{-1}	WUE_{eco} Kg CO_2 ha^{-1} mm^{-1}	WUE_{bio} Kg DM ha^{-1} mm	WUE_{yield} kg Seed ha^{-1} mm^{-1}
2013–2014	CK	928.7	624.9 ± 79.2bc	12.2 ± 2.7a	6.4 ± 2.8b	40.5 ± 3.7a	11.8 ± 2.5b
	WCK	915.8	741.7 ± 34a	12.6 ± 1.1a	6.6 ± 1.8b	35 ± 4a	11.7 ± 0.6b
	GM	867.4	598.7 ± 40.9c	13.8 ± 0.8a	9 ± 1.7a	45.1 ± 4.5a	18.6 ± 0.9a
	WGM	851.6	706.3 ± 21.3ab	14.4 ± 0.6a	8.9 ± 1.8a	38.8 ± 1a	16.5 ± 1a
2014–2015	CK	925.9	606.9 ± 15.9A	11.1 ± 0.2B	6.5 ± 1.4B	37.9 ± 0.9B	13.8 ± 1.1B
	WCK	908.6	708.1 ± 87.8A	11.7 ± 0.7B	5.9 ± 1B	34 ± 3.3B	13.9 ± 3.7B
	GM	870.8	572.6 ± 15.2A	13.8 ± 1.7A	9.7 ± 2.9A	47.1 ± 5.1A	20.9 ± 2.7A
	WGM	850.8	658.7 ± 115.6A	14.4 ± 0.4A	10 ± 2.4A	42.4 ± 7AB	19 ± 2.7A

during cycle 2. Overall. Gravel mulching significantly increased the values of WUE_{yield}.

3.6. Impact factors for yield and WUE

The principal component analysis (PCA) method, a statistical technique used to examine the interrelations among a set of variables in order to identify the underlying structure of those variables, has been applied to study the effects of some key factors, as shown in Fig. 5, including soil water and heat factors, i.e. thermal conductivity (K) and accumulated temperature (GDD); other physical indicators (i.e. soil bulk density (BD) and soil organic matter (SOM)); wheat-maize growth parameters (i.e. Tiller numbers, leaf area index (LAI) plant height (H), number of grains per ear (NGP)); and harvest index (HI) on biomass production, wheat-maize yields and multi-level WUE under different gravel mulching practices. The data used for analysis are the mean annual values of these factors during the two wheat-maize rotation cycles. Fig. 5 shows that the distributions of water storage change (ΔW), reference crop evapotranspiration (ET_0) and total amount of CO_2 emissions (GHG_s) are very close in CK and WCK but are very different in GM and WGM. We found the unfavorable factors for water use, crop productivity and environment protection often closely related to both control treatments. However, the distributions of the favourable factors of K, GDD, LAI, Biomass, NGP, Y, HI and WUE_{yield}, are extremely close to WGM and far from CK. Due to irrigation, the SOM, Tiller, H, NPP, NEP, WUE_{veg}, WUE_{eco}, WUE_{bio} distributions are in a zone between GM and WCK.

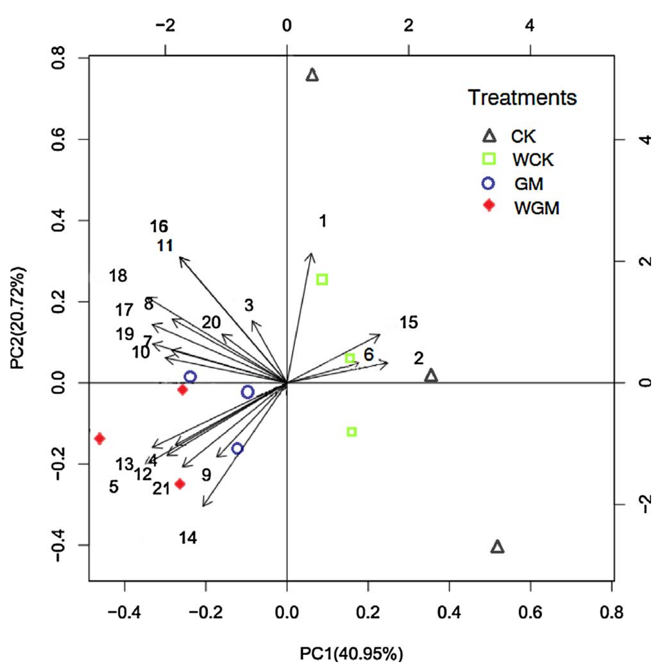


Fig. 5. Principal component analysis (PCA): soil environment factors, crop growth parameters, ecological effects and four water use efficiencies in annual under different gravel mulching practices during the two wheat-maize rotation cycles.

The two factors analysis of variance method (ANOVA) has also been applied in this study. Further studies will focus on the significance level of analyses of irrigation, gravel mulching and gravel mulching combined with irrigation on yield and multilevel WUE (Table 4). Gravel mulching combined with irrigation provides a great contribution to annual yield and WUE_{veg} at the $P < 0.01$ level and increases WUE_{eco} and WUE_{yield} at the $P < 0.05$ level. However, no significant effect on WUE_{bio} ($P > 0.05$) has been found. These results suggested the applying of gravel mulching combined with irrigation could be an effective approach to increase crop and ecosystem productivity and lower water use at multilevel. We adopted a single design of gravel mulching and irrigation level, to better reveal the interactions between different treatments, further research is required to elucidate the possibly influence mechanism of variety application of different gravel mulching and irrigation applications.

4. Discussion

4.1. Effects of gravel mulching on soil temperature and water

Seasonal climate and regional conditions play an important role in gravel mulching affecting the soil water-heat balance (Jury and Bellantuoni, 1976; Li et al., 2000; Wang et al., 2004). It has been reported that gravel mulching reduces evaporation and conserves soil moisture. Consequently, crop water status will be improved particularly in arid and semi-arid regions, where water limitation is the main constraint affecting crop growth (Nachtergaele et al., 1998; Doolittle, 1998; Li, 2003; Xie et al., 2006; Yuan et al., 2009; Wang et al., 2011; Lü et al., 2013). The aforementioned results are consistent with the observed increase in soil water content over the two rotation cycles in our study (Fig. 2b). Moreover, gravel mulching protects the soil surface from receiving direct sunlight and reduces soil radiation absorption, as well as soil crusting (Wang et al., 2011; Lü et al., 2013; Poesen and Lavee, 1994). Therefore, soil evaporation can be reduced while retaining soil moisture. However, high soil water content in a gravel-mulched field slows the response of soil temperature to air temperature, particularly at temperatures higher than 20 °C in the later wheat growing seasons and in most maize growing seasons due to increased soil heat capacity. Pérez (1998) reported that the average maximum soil temperature was 4.4 °C lower than the air on alpine talus slopes under gravel covers. Our study has found that soil temperature in a gravel mulched field is higher than that in a non-mulched field during the cold seasons (Fig. 2a). Lü et al. (2013) noted that the average temperature for the 0–20 cm soil layers in the gravel-sand mulch field is from 1.0–5.3 °C higher than that observed in the non-mulched field. This is consistent with the observed results of soil temperature in our study, given the fact that average soil temperature in the 0–30 cm profile in GM and WGM is 0.49 °C and 0.63 °C higher than that in CK during both cycles, respectively. We

Table 4
Significance level (*P* Value) of the effect of irrigation and gravel mulching on annual yield and multilevel annual water use efficiency (WUE) during the two rotation cycles compared to the control (CK) using the two factors analysis of variance method (ANOVA)..

Cycle	Factors	Yield Kg ha^{-1}		Multilevel WUE							
				WUE_{veg} kg CO_2 ha^{-1} mm^{-1}		WUE_{eco} kg CO_2 ha^{-1} mm^{-1}		WUE_{bio} Kg DM ha^{-1} mm		WUE_{yield} kg Seed ha^{-1} mm^{-1}	
		P Value	Significance	*P* Value	Significance	*P* Value	Significance	*P* Value	Significance	*P* Value	Significance
2013–2014	Irrigation	0.066	n.s.	0.772	n.s.	0.916	n.s.	0.098	n.s.	0.961	n.s.
	Gravel Mulching	0.000	***	0.232	n.s.	0.166	*	0.150	n.s.	0.000	***
	Irr. × GM	0.000	***	0.127	n.s.	0.018	n.s.	0.579	n.s.	0.004	**
2014–2015	Irrigation	0.221	n.s.	0.414	n.s.	0.765	n.s.	0.335	n.s.	0.958	n.s.
	Gravel Mulching	0.006	**	0.008	**	0.092	n.s.	0.041	*	0.013	*
	Irr. × GM	0.003	**	0.003	**	0.035	*	0.268	n.s.	0.048	*

* significant at $P < 0.05$; ** significant at $P < 0.01$; *** significant at $P < 0.001$; n.s. not significant.

believe that gravel mulching can moderate soil temperature more favourably for wheat and maize growth.

4.2. Effects of gravel mulching on biomass production and crop yield

The use of gravel as a surface-mulching material has been a traditional farming technique to increase soil temperature and moisture, as well as crop production, for many years (Li et al., 2005; Lü et al., 2013; Qiu et al., 2015). Previous studies attempted to delineate the contribution of different gravel mulching techniques (i.e., different particle sizes, different thicknesses, gravel mixed with sand, embedded modes) to improve agricultural success (Xie et al., 2010; Wang et al., 2014; Sun et al., 2013). As early as 1943, Lamb reported that surface gravel covers acting as mulch could decrease/slow down evaporation and that high temperatures under gravel might be one factor in economic crop production. Faibourn (1973) indicated that gravel mulching can not only increase crop yield but also has the potential for mechanized application and maintenance. Various studies have confirmed that gravel mulching could significantly increase total biomass and crop yield (Bu et al., 2013; Schmithals and Kühn, 2017; Parihar et al., 2017). Our observation of an increase in the yield of wheat and maize are in agreement with these findings (Table 2, Graphical Abstract).

Biomass productivity and crop yield appeared to be the most strongly related to soil temperature and soil water status during the different growth stages (Nachtergaele et al., 1998; Zhang et al., 2009; Zhou et al., 2009; Bu et al., 2013; Lü et al., 2013; Schmithals and Kühn, 2017). These stages are correlated with sunlight capture and conversion, evaporation interception and moisture infiltration (Yuan et al., 2009; Cerdà, 2001; Kemper et al., 1994; Mukherjee et al., 2010). Additionally, field mulch measures introduce extra C into the soil, reduce the soil bulk density and improve soil structure. This, normally, is a long-term process (Johnston, 1986; Poesen and Lavee, 1994; Christensen, 2001; Li et al., 2009; Qiu et al., 2015). The gravel mulching treatments WGM and GM resulted in greater SOM than CK by an average of 21.74% and 18.79%, respectively. However, BD decreased by an average of 5.68% and 2.27% under WGM and GM, respectively, compared to CK over the two cycles. A significant increase in LAI and plant height leads to better growth and greater biomass accumulation and crop yield during the wheat and maize growing seasons. Compared to the controls, the gravel mulching treatments could effectively increase soil moisture and maintain soil temperature. This is beneficial in promoting crop growth and achieving better growth targets and impacts biomass and crop production.

4.3. Effects of gravel mulching on CO_2 fluxes, NPP and NEP

The changed soil temperature and moisture status as a result of gravel mulching, can affect soil biological activity and greenhouse gas emissions (Bu et al., 2013; Liu et al., 2016). Chen et al. (2017) and Zhang et al. (2017) indicated that CO_2 fluxes are significantly affected by soil temperature and soil moisture in the same region. Lavigne et al. (2004) exhibited that soil respiration is related to soil temperature and water potential. This has been further demonstrated in our study because we found that soil water content and soil temperature are curvilinearly correlated with CO_2 emissions under different gravel mulching treatments (Fig. 4). Gravel mulching could effectively decrease CO_2 fluxes (Table 2). This is likely due to the fact that the favourable soil temperature and moisture status below the gravel mulch can affect biological activity and the mineralization process, which is helpful for the accumulation of photosynthetic organisms. Additionally, Okuda et al. (2007) and Li et al. (2011) reported that gravel mulching, as a physical barrier, can also reduce CO_2 fluxes to a certain extent. However, Lahav and Steinberger (2001) have found that soil samples from underneath stones on the valley slopes produce high levels of CO_2. This is in contrast to our findings. Mulching percentage, gravel size and land types might contribute to these polar results. Principal component analysis (Fig. 5) indicates that the distributions of ET_0 and CO_2 fluxes are very close. Various results have confirmed that gravel mulching can reduce evaporation and evapotranspiration (Yamanaka et al., 2004; Xie et al., 2006; Li, 2000); therefore, the decreased CO_2 fluxes under gravel mulching could be explained indirectly. There might be more factors that could influence biological activities and CO_2 evolution (Parker et al., 1984). Currently, studies regarding the effects of gravel mulching on ecosystem activities and greenhouse gas emissions are insufficient. More work is required to understand the underlying relationship, as it is helpful to assess farmland ecological effects and carbon emission reduction effects of gravel mulching.

The total amount of CO_2 emissions from ecosystems has been studied to evaluate net ecosystem production (Abdalla et al., 2013; Chapin et al., 2006; Ceschia et al., 2010). In our study, we compared the differences of the measured NPP and NEP among the four treatments. Although there is a small change in NPP during cycle 1, gravel mulching significantly promoted net ecosystem exchange during both cycles (Table 2). As a key strategy for mitigating global climate change, different field management measures have been carried out to promote ecosystem exchange and reduce CO_2 emissions from farmland ecosystems (Liu et al., 2016). Greenhouse gas reduction plays an important role in ensuring sustainable development. The aforementioned results suggest that gravel mulching would contribute to carbon sequestration and greenhouse gas emission reduction within the context of rapid climate change.

4.4. Effects of gravel mulching on multilevel WUE

Previous research has shown that gravel mulching treatments are effective methods for improving WUE (Wang et al., 2009; Xie et al., 2010; Bu et al., 2013). Crop yield does not solely rely on soil properties (i.e. water and heat), as it also depends on water use efficiency (Yang et al., 2004). Although actual evapotranspiration (ET) under gravel mulching treatments is higher than that under the control treatments during the two cycles, our results indicate that the gravel mulching treatments significantly improve WUE_{yield} to a greater extent than the controls (Table 3). This is due to the higher crop yield and lower water use. In arid regions, both GM and WGM treatments could improve WUE_{yield} mainly because the gravel mulching treatments could fully utilize the moisture delivered by rainfall or irrigation water (Peng et al., 2016; Li et al., 2005). Recently, multilevel WUE has become one of the frontiers of agricultural water management (Hsiao et al., 2007; Morison et al., 2008; Gong et al., 2017). Gravel mulching, as a type of agriculture practice, could not only alter soil water and temperature, microbial populations and activity, and carbon sequestration but could also release CO_2 at the interface between soil and the atmosphere. This results in the incremental ability to promote crop development, and significantly affects ecosystem carbon exchange and crop production (Abdalla et al., 2013; Liu et al., 2016; Gong et al., 2017). WUE_{veg} has a small variation within a range from 12.2 ± 2.7 to 14.4 ± 0.6 kg CO_2 hm^{-2} for the four treatments during cycle 1. These values are similar to the findings reported by Tallec et al. (2013) but lower than those of Gong et al. (2017). This is because of the different mulch materials, crop varieties and weather conditions that were considered. However, a significant increase in WUE_{veg} was observed during cycle 2. Gravel mulching can shorten the growth period and reduce ET_0 (Liu, 2016). Thus, WUE_{veg}, which is determined by vegetation growth, increased. The values of WUE_{eco} for the GM and WGM treatments during the two cycles are higher than those of the CK and WCK treatments. This might have been caused by gravel mulching that can reduce CO_2 emissions from the ecosystem, thus leading to a higher NPP and NEP during the two cycles. Gong et al. (2017) have drawn similar conclusions in their paper. Compared to the control treatments, gravel mulching can increase WUE_{bio} and WUE_{yield}, particularly under the GM treatment. This is a result of greater biomass accumulation and crop yield with lower water use. In general, the average values of WUE in GM and WGM during the two rotation growing seasons are higher than in CK and WCK at the ecosystem, biomass and yield levels.

For the four treatments, the value of WUE_{yield} in the WGM was the maximum, followed by that of GM. Both gravel mulching and gravel mulching combined irrigation practices significantly affected WUE_{yield}. Whereas, the interaction between the two factors of gravel mulching and irrigation applications for other three WUE are not consistent, as shown in Table 4. Therefore, further research is still required to investigate the long-term influence of different treatment factors. In Fig. 5, the distribution of gravel mulching treatment is always closed to the favourable factors of soil properties and crop growth parameters, whereas, the control treatment is exactly in contrast. We also found in Fig. 5, the gravel mulching treatment is also helpful to reduce ecosystem CO_2 emissions. Overall, the application of gravel mulching can alter soil properties and stimulate crop growth, thus contributing to increase system yield while lowering water use and mitigating climate change. All these results suggest that gravel mulching is an effective approach to counteract the shortage of available water and to balance food production and mitigate ecological impact for the studied region, as well as other arid and semi-arid areas.

5. Conclusions

This study provided insight into crop yield and multilevel water use by evaluating crop productivity, ecological effects and water productivity as affected by gravel mulching in a typical wheat-maize rotation in a semi-arid region of Northwest China. The two gravel-mulching treatments significantly increased soil temperature and soil moisture and decreased ecosystem CO_2 emissions during the two cycles. Gravel mulching alone and combined with irrigation increased biomass accumulation and crop yield during both cycles. Annual NPP and NEP as affected by gravel mulching increased, although there was a small change in NPP during cycle 1, but NPP during cycle 2 and NEP during both cycles significantly increased. Based on these results, multilevel water use efficiency, i.e. the ratio of productivity to water use at the vegetation, ecosystem, biomass and yield levels, was calculated in our study. No evidence of an effect on the annual WUE_{veg} and WUE_{bio} was observed under the two gravel mulching treatments, whereas in cycle 2, there was a significant effect. Compared to the control, the annual WUE_{eco} increased by 40.6% and 49.2% under gravel mulching and by 39.1% and 53.8% under gravel mulching combined with irrigation, and the annual WUE_{yield} increased by 57.6% and 51.4% under gravel mulching and by 39.8% and 37.7% under gravel mulching combined with irrigation during the two cycles, respectively. Our study also indicated that applying the gravel mulching during the first year has a great effect on crop yield, WUE_{eco} and WUE_{yield}, but elicits a slow increase during the subsequent year. Overall, the application of gravel mulching is an effective approach to improve crop yield and enhance multilevel water use efficiency in arid and semi-arid regions. However, further research is required to elucidate the perennial influence mechanism of gravel mulching applications.

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