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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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A R T I C L E I N F O

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A B S T R A C T

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