Agricultural Water Management 208 (2018) 414–421

Contents lists available at ScienceDirect

Agricultural Water Management

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

Effects of different fertilizer strategies on soil water utilization and maize yield in the ridge and furrow rainfall harvesting system in semiarid regions of China

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ARTICLE INFO

Keywords:
Fertilizer rate
Maize yield
Ridge and furrow rainfall harvesting system
Semi-arid area
Soil water consumption properties

ABSTRACT

Shortages of water resources and low soil fertility are two key factors that limit crop production in semiarid areas. The ridge and furrow rainfall harvesting (RFRH) system is an effective method for enhancing the efficiency of rainfall water use and fertility. In this study, we conducted a field experiment over five years (2012–2016) to determine the effects of different fertilizer application rates on the soil water consumption properties, water use efficiency, and maize yield under RFRH. We found that the evapotranspiration (ET), maize dry matter (DM), water consumption strength (CD), and soil water use rate (SP) increased with the fertilizer application rate. Compared with the no fertilizer treatment (RCK), ET, DM, CD, and SP increased significantly by 7.2%, 38.3%, 16.4%, and 37.6% under high fertilizer (RH) treatment, respectively, by 6.7%, 35.8%, 18.0%, and 39.1% with medium fertilizer (RM) treatment, and by 5.5%, 31.1%, 16.1%, and 32.6% with low fertilizer (RL) treatment. RM achieved the highest average yield of 11.3 t ha^{-1} and the lowest coefficient of variation at 12.9%. The yield, DM, and water use efficiency did not differ significantly between RH and RM. Regression analysis showed that the highest yield could be obtained by applying nitrogen at 265.0 kg ha^{-1} combined with P_2O_5 at 132.5 kg ha^{-1}. The yield and water use efficiency were significantly higher under RL compared with RH and RM in wet year. However, in both normal and drought years, the grain yield and water use efficiency was significantly higher under RM. These results indicate that the RFRH system can promote crop use of fertilizers by regulating soil moisture. The best fertilization strategy for planting maize with RFRH system was 265.0 kg ha^{-1} of pure nitrogen combined with 132.5 kg ha^{-1} of P_2O_5 in the semiarid area of the Loess Plateau, in China.

1. Introduction

The semiarid region of northwestern China is a typical rain-fed farming area with annual rainfall of 300–550 mm (Xiao and Wang, 2003). The uneven spatial and temporal distribution of rainfall can lead to a mismatch between the water supply and crop water demands, thereby causing water deficits during the crop growth period, which severely hinders the capacity to improve crop production in this area (Hu et al., 2014; Zhao et al., 2014). In addition, poor soil quality and low fertility are other key factors that limit crop production in semiarid areas (Liu and Zhang, 2007; Dai et al., 2015).

Film mulching is an effective agricultural treatment that is applied worldwide to improve the soil temperature and water conditions, which can increase the crop yield and economic efficiency (Steinmetz et al., 2016). The ridge and furrow rainfall harvesting (RFRH) system is widely used in the rain-fed areas of northwestern China which it is an effective tillage measure for improving the rainfall use efficiency (RUE) and crop yield in dry farming areas (Li et al., 2000; Zhang et al., 2007a, b; Hu et al., 2014; Zhang et al., 2017). The RFRH system significantly improves the rhizosphere soil water conditions by guiding precipitation into furrows and suppressing the evaporation of water from the ridged soil (Li et al., 2001; Zhou et al., 2009; Li et al., 2012; Lian et al., 2016). The RFRH system can enhance the growth of crop roots and improve the water use efficiency (WUE) and fertilizer use efficiency, thereby significantly increasing the plant height, dry matter, and economic yield (Ren et al., 2008; Wang et al., 2009), especially in areas with

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https://doi.org/10.1016/j.agwat.2018.06.032
Received 31 March 2018; Received in revised form 24 June 2018; Accepted 25 June 2018
Available online 20 July 2018
0378-3774/

rainfall of 230–440 mm where the effect on increasing the yield is most significant (Ren et al., 2010, 2016).

Since the 1980s, the nutrients used in traditional agriculture in the northwestern region of China have gradually changed from a single application of manure to the use of various chemical fertilizers (Roelcke et al., 2004; Hao et al., 2005; Liu and Zhang, 2007). Studies have shown that the application of appropriate fertilizers can increase the water retention capacity, inhibit soil evaporation, enhance the WUE, and improve crop yields (Hao et al., 2005; Dang et al., 2006). However, the application of excessive amounts of fertilizers can adversely affect the soil physics, chemistry, and biodiversity, as well as leading to nitrate leaching and excessive soil water consumption (Perego et al., 2012; Yang et al., 2017; Lian et al., 2016). Thus, it is very important to develop a scientific and reasonable fertilizer use strategy for the RFRH system in order to fully exploit its potential for increasing production in arid areas and reducing agricultural pollution, where this is a key focus of dry-land farming research.

The effects of soil water content and nutrients on crop growth and development are not irrelevant, but interact with each other (Liu and Zhang, 2007). Therefore, using the special water regulation method of the RFRH system to formulate a fertilization scheme suitable for the system, tapping the potential water uses efficiency is an important issue for crop cultivation and management in the arid area. The previous research about the RFRH system were mainly focused on the effects of soil water content, temperature, covering materials, ridges and furrows ratio and crop yields (Liu et al., 2009; Li et al., 2013; Wang et al., 2015; Wu et al., 2017; Ren et al., 2017). However, little is known about the appropriate fertilization strategy for the RFRH system. We conducted a 5-year field experiment in order to (1) determine the effects of different nitrogen and phosphorus fertilizer application rates on the soil water consumption properties, WUE, and maize yield under the RFRH system, (2) investigate the relationship between nitrogen and phosphorus application rate and water consumption and maize yield under the RFRH system, (3) provide a scientific basis for the sustainable development of the RFRH and provide an effective solution to alleviate the agro-ecological problems caused by excessive application of chemical fertilizers in semiarid areas of the Loess Plateau, in China.

2. Materials and methods

2.1. Site description

The study was performed between 2012 and 2016 at the Dry-land Agricultural Experiment Station, Pengyang city, Ningxia Province, China (35°51′E, 106°48′N; 1658 m above sea level). The average annual evaporation was 1753.2 mm, the average annual temperature was 6.1 °C, the frost-free season lasted 150 days, and the average annual rainfall was 430 mm, where over 60.0% of the rainfall occurred during July–September. The rainfall distribution characteristics for 2012–2016 and the rainfall during the growth period are shown in Table 1. Based on the annual rainfall in 2012–2016 (Table 1), we divided the separate years into normal years (2012, 2014, and 2015), a wet year (2013) and a drought year (2016) by calculating the standardized precipitation index (Tigkas et al., 2013; Mpelasoka et al., 2018). The rainfall during the growing seasons from 2012 to 2016 ranged from 251.6 to 594.1 mm, where the frequency of rainfall < 5 mm was as high as 66.0%, except in the wet year (2013). The maximum one-off rainfall in 2013 was 71.8 mm. In the drought year (2016), the total amount of invalid rainfall comprised 27.7% of the annual rainfall, and there were two consecutive > 50 mm high-intensity precipitation events in July. The soil at the experimental site was loess soil with a mean bulk density at a depth of 2 m of 1.3 g cm^{-3}. The main physical and chemical properties for each soil layer before sowing in 2012 are shown in Table 2.

Table 1
Precipitation (mm) distribution and typical drought levels during 2012–2016 at Pengyang Experimental Station, Ningxia Province, China.

Precipitation distribution character	Year 2012	2013	2014	2015	2016
Jan.	8.4	0.2	0.5	2.2	2.4
Feb.	3.4	10.2	13.6	1.2	5.6
Mar.	16.0	5.7	7.0	26.7	18.0
Apr.	30.2	29.5	58.5	62.8	49.7
May	48.0	91.9	7.5	61.0	30.7
Jun.	86.0	54.4	24.7	72.7	35.2
Jul.	59.8	267.3	41.3	29.0	123.3
Aug.	136.7	42.1	63.6	86.1	31.7
Sep.	73.0	108.9	146.3	93.0	20.5
Oct.	12.3	32.7	33.8	27.9	21.2
Nov.	1.4	15.2	11.6	9.6	0.2
Dec.	1.1	0.0	0.1	1.8	0.2
GP	411.4	594.1	375.7	333.2	251.6
Typical years	Normal	Wet	Normal	Normal	Drought
Rainfall times (T)	96	81	40	103	110
< 5 mm times (RT)	62	51	14	75	71
RT/T (%)	64.6	63.0	35.0	72.8	64.5
Total rainfall (TA, mm)	476.3	643.1	408.5	474.0	338.7
RA (mm)	81.0	92.9	14.6	92.0	94.3
Ra (mm)	38.2	110.1	48.7	0.0	111.3
RA/TA (%)	17.0	14.4	3.6	19.4	27.8
Ra/TA (%)	8.0	17.1	11.9	0.0	32.9

Note: GP is the amount of rainfall (mm) during the whole maize growth period. RA is precipitation < 5 mm (mm); Ra is the amount of rainfall > 35 mm (mm).

2.2. Experimental design and field management

Four fertilizer rates (control, RCK = no fertilizer; low fertilizer, RL = N:P_2O_5 at 150:75 kg ha^{-1}; medium fertilizer, RM = N:P_2O_5 at 300:150 kg ha^{-1}; high fertilizer, RH = N:P_2O_5 at 450:225 kg ha^{-1}) were evaluated in the experiment. The field experiment employed a completely randomized block design with three replicates where each plot area measured 91.8 m^2 (17.0 × 5.4 m). In order to reduce the impacts of different treatments, each plot was separated by a 90 cm-wide border. The RFRH system used ridge and furrow widths of 60 cm, where the height of each ridge was 15 cm and the ridges were covered by plastic film (0.8 m wide × 0.008 mm, clear and impermeable film; TianshuiTianbao Plastic Industry Ltd, Gansu, China). The fertilizer comprised urea (N 46%; China Petroleum Ningxia Petrochemical Production Company) with diammonium phosphate (P_2O_5 46.0%, N 18.0%; Yunnan Three Circles Sinochem Fertilizer Co. Ltd, US-sheng). All of the phosphorus and 60% of the nitrogen were applied at the time of sowing by spreading the materials evenly over the planting zone and plowing into the soil layer (about 25 cm), while the other 40% of the nitrogen was applied at 69–75 days after sowing.

Spring maize (Dafeng 30) was planted at a rate of 75,000 plants ha^{-1}. The seeds were sown on April 29 in 2012, April 16 in 2013, April 28 in 2014, April 22 in 2015, and April 22 in 2016 with a row distance of 60 cm. The maize was harvested on October 14 in 2012, September 27 in 2013, October 4 in 2014, October 2 in 2015, and September 20 in 2016. Weeds were controlled manually in each growing season. No obvious diseases and pest damages were observed during the years of the experiment. Irrigation was not applied throughout each year. The growth and developmental progress of maize in 2012–2016 were shown in Table S1.

2.3. Sampling and measurements

2.3.1. Plant sampling

Crop growth stages including emergence, V4 (fourth leaf), V6 (sixth leaf), V8 (eighth leaf), VT (tasseling), R3 (milk), and R6 (physiological maturity) were recorded when 75% plants were with the appearance