Agricultural Water Management 150 (2015) 9–17

Contents lists available at ScienceDirect

Agricultural Water Management

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

Soil water use, grain yield and water use efficiency of winter wheat in a long-term study of tillage practices and supplemental irrigation on the North China Plain

Shangyu Ma[a,b], Zhenwen Yu[a], Yu Shi[a,*], Zhiqiang Gao[a], Lanping Luo[a], Pengfei Chu[a], Zengjiang Guo[a]

[a] Key Laboratory of Crop Ecophysiology and Farming System, Ministry of Agriculture, Shandong Agricultural University, Tai'an 271018, China
[b] Department of Agronomy, Anhui Agricultural University, Hefei 230036, China

ARTICLE INFO

Article history:
Received 12 March 2014
Accepted 19 November 2014
Available online 10 December 2014

Keywords:
Subsoiling
Rotary
Soil water storage capacity
Soil water consumption

ABSTRACT

We report the results of a six-year study (2007–2013) of tillage regimes for use in producing winter wheat (Jimai 22) on the North China Plain, with supplemental irrigation. The tillage regimes include: plowing for six years (P6); rotary for six years (R6); rotary after subsoiling with an interval of two years (S1R2); subsoiling with an interval of three years (S1R3); subsoiling with an interval of four years (S1R4); and subsoiling with an interval of five years (S1R5). In comparison with the P6 and R6 treatments, the S1R2 and S1R3 treatments improved water storage capacity, maintained higher soil moisture content in the 100–160 cm soil layers before sowing and significantly decreased soil moisture content in the 20–180 cm soil layers at maturity, in all years. Hence, S1R2 and S1R3 led to greater utilization of water stored in the 60–180 cm soil layers. Evapotranspiration (ETc), soil water consumption, and the ratio of soil water consumption to ETc for S1R2 and S1R3 were significantly higher than those for other treatments. Average grain yields for the six growth seasons were ranked as S1R2, S1R3 > S1R4 > S1R5 > P6 > R6, while water use efficiency was ranked in the order of S1R2, S1R3, S1R4 > S1R5, P6 > R6. Grain yields of S1R2 and S1R3 were 9.028 and 8.817 kg ha^{-2}, respectively, which are higher than the yield of R6 (conventional tillage) by 27.7% and 24.7%, respectively. Hence, rotary tillage after subsoiling with an interval of two or three years (S1R2 and S1R3) can be considered as a desirable tillage practice for increasing yields, while using water efficiently in this region.

1. Introduction

The North China Plain (NCP) is the most important wheat production area in China. A winter wheat and summer maize double-cropping system is widely implemented in this region (Li et al., 2007a,b). However, the monsoon climate with about 70–80% of the mean annual rainfall (550 mm) concentrated in the summer (July–September) affects rainfall during the wheat growth period and meets only 25–40% of the crop water requirement (Fang et al., 2010). Therefore, irrigation is necessary to achieve high grain yields of winter wheat in this region (Dong et al., 2011; Xiong et al., 2010).

Intensive conventional tillage (i.e., moldboard plowing) tends to increase soil bulk density and to reduce both energy efficiency and economics, thereby resulting in lower water and nutrient availability (Kumar et al., 2013; He et al., 2009a). Conservation tillage technologies, such as reduced tillage, no-tillage and surface covering organisms, can modify the energy and available water in the soil profile and improve soil conditions and crop yields. These measures can be highly effective for sustainable development of agricultural production (Fernández-García et al., 2013; Jemai et al., 2013; Aziz et al., 2013).

Subsoiling is a process by which the hardpan layer or compacted layer of the soil is broken without turning over the infertile subsoil at the top (Singh et al., 2013). This process can improve infiltration and water storage, enhance soil water retention in the summer fallow and increase the drought-resilience of crops, thereby increasing crop yield (Mao et al., 2010). As a remedial treatment method, subsoiling has been found to decrease soil bulk density, increase aeration porosity, reduce the inhibitory effect of

* Corresponding author at: Key Laboratory of Crop Ecophysiology and Farming System, Ministry of Agriculture, Shandong Agricultural University, 61 Daizong Road, Tai'an 271018, Shandong, China. Tel.: +86 538 8241484; fax: +86 538 8242226.
E-mail address: shiyu@sdau.edu.cn (Y. Shi).

http://dx.doi.org/10.1016/j.agwat.2014.11.011
0378-3774/

soil compaction on root growth and augment water availability for crops by facilitating root exploration (Mohanty et al., 2007). Subsoiling has been reported to result in better water storage during the summer fallow or rainy season in winter wheat fields (Wang et al., 2012). In addition, Hou et al. (2012b) find that soil water storage during the fallow period increases by 13.0% following subsoiling every two years, compared to conventional tillage.

While some studies suggest that subsoiling has little effect on plant growth and no effect on grain yield over three cropping seasons (Evans et al., 1996), others have reported that subsoiling can significantly improve the yield and water use efficiency (WUE) of wheat (He et al., 2007; Pikul and Aase, 2003). An experiment conducted in the wheat field of Weibei Highland showed that wheat yields from subsoiling were 5.5% and 6.3% higher, and WUEs from subsoiling were 4.3% and 11.6% higher, compared to those from deep plowing and no-tillage, respectively (Mao et al., 2010). No tillage for four years followed by single subsoiling reduced mechanical inputs by 62%, whereas annual subsoiling decreased them by only 25% (He et al., 2007).

The effect of interval subsoiling on soil moisture content and wheat yield has seldom been reported for irrigated conditions on the North China Plain. In the current study, the effects of tillage practices on soil water use and wheat yield under high-yield conditions were examined by implementing rotary tillage, ploughing tillage, and rotary tillage after subsoiling in different years during a six-year study in Yanzhou, Shandong. The findings provide a scientific basis for selecting suitable tillage practices to achieve high yields and water use efficiency in winter wheat on the North China Plain.

2. Materials and methods

2.1. Experimental site

Field experiments were conducted using the Jimai 22 wheat cultivar in Shiwang Village (35.41° N, 116.41° E), Yanzhou, Shandong Province, China during the 2007–2013. The cropping pattern of this area is largely a winter wheat-summer maize double-cropping system with rotary tillage for wheat and no-tillage for maize, which is typical on the North China Plain. The loam soil in this village, with a pH value of 7.6 and a texture of 29.6% clay, 37.3% silt, and 33.1% sand, has been cultivated intensively for many centuries. The nutrient condition of the soil in the top 20 cm are shown in Table 1, and soil moisture contents of the 0–200 cm soil layers before sowing in the autumn of 2007 are shown in Table 2. The monthly distribution of precipitation from 2007 to 2013 and mean annual precipitation for 40 years at the experimental site are shown in Table 3.

Table 1
Nutrient condition of the top soil (0–20 cm) at the experimental site, before sowing in the autumn of 2007.

Soil nutrient	Content
Organic matter ($g\,kg^{-1}$)	14.12
Total nitrogen ($g\,kg^{-1}$)	1.11
Hydrolysable nitrogen ($mg\,kg^{-1}$)	103.13
Available phosphorus ($mg\,kg^{-1}$)	49.44
Available potassium ($mg\,kg^{-1}$)	128.47

Table 2
Soil moisture content of the 0–200 cm soil layers before sowing in the autumn of 2007.

Soil layers (cm)	Soil moisture content (%)
0–20	18.89
20–40	18.97
40–60	19.52
60–80	21.56
80–100	22.09
100–120	21.71
120–140	21.61
140–160	22.01
160–180	21.89
180–200	21.62

2.2. Experimental design

The operational procedures of the tillage practices applied on the North China Plain are listed in Table 4. The tillage treatments designed in 2007–2013 are (Table 5): plowing for six years (P6); rotary for six years (R6); rotary after subsoiling with an interval of two years (S1R2): rotary after subsoiling for the first (2007–2008) and fourth (2010–2011) years and rotary without subsoiling for other years; subsoiling with an interval of three years (S1R3): rotary after subsoiling for the first (2007–2008) and fifth (2011–2012) years and rotary without subsoiling for other years; subsoiling with an interval of four years (S1R4): rotary after subsoiling for the first (2007–2008) and sixth (2012–2013) years and rotary without subsoiling for other years; and subsoiling with an interval of five years (S1R5): rotary after subsoiling for the first (2007–2008) year and rotary without subsoiling for the remaining five years. Before sowing, maize straw (about 10,000 $kg\,ha^{-1}$) was totally chopped and returned into the field. The field was prepared using a randomized block design with 3 replicates. The experimental plot was 40 m × 4 m, with a 2 m wide isolation area preventing water interpenetration between any two contiguous plots.

The 0–140 cm soil layers were tested for soil moisture content to calculate the required amount of supplemental irrigation. The

Table 3
Monthly distribution of precipitation from 2007–2013, and mean annual precipitation for 40 years (1966–2006) at the experimental site, in mm.

Months	2007–2008	2008–2009	2009–2010	2010–2011	2011–2012	2012–2013	Average of 2007–2013	Average of 40 years
July	114	197	195	152	130	172	160	184
August	251	50	127	211	81	103	137	142
September	16	56	32	80	198	38	70	65
October	15	14	25	5	16	15	15	42
November	0	4	16	0	102	18	23	16
December	13	4	1	0	16	37	12	9
January	8	0	0	0	2	4	2	8
February	3	20	21	27	1	10	14	9
March	4	22	13	0	25	8	12	21
April	78	57	26	15	28	9	35	32
May	13	33	61	52	1	123	47	49
June	49	96	91	18	15	13	47	82
Amount during wheat growth season	228	141	163	147	183	238	183	269
Total amount	564	553	608	560	615	551	574	660