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EFFECTS OF NITROGEN APPLICATION ON BIOMASS ACCUMULATION, REMOBILIZATION, AND SOIL WATER CONTENTS IN A RAINFED WHEAT FIELD

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ABSTRACT

This study examined the effects of different levels of N fertilization on dry matter accumulation and remobilization, and soil water contents in a rainfed winter wheat field. The experiments were carried out during growth seasons in 2009 – 2012 in a hilly region in Shandong Province, China. The N rates applied were 0 (N0, the control), 90 (N1), 120 (N2), 150 (N3), 180 (N4), and 210 (N5) kg N ha^{-1}. Our results showed that N fertilization significantly increased dry matter accumulation and post-anthesis assimilates compared with controls. At anthesis, total above-ground biomass increased significantly with increasing N rate up to 150 kg ha^{-1} and then leveled off in the 2009 – 2010 and 2011 – 2012 growth seasons. However, the biomass in the 2010 – 2011 growth season did not vary with different N rates. At maturity, the accumulation of dry matter in vegetative organs significantly increased with increasing N rate up to 150 kg ha^{-1} and then leveled off in all growth seasons. Of all the treatments, N3 and N4 had relatively higher total above-ground biomass at maturity. In contrast, dry matter remobilization efficiency showed a declining trend under increasing N rate. The higher post-anthesis assimilates and the contribution of pre-anthesis assimilates to grains were obtained at N rates of 150 and 180 kg ha^{-1} in all growth seasons. Soil water contents in 0 – 120, 0 – 100, and 40 – 160 cm soil layers during each growth season decreased significantly with increasing N rate up to 150 kg ha^{-1}. The maximum grain yields were obtained under N rate of 150 kg ha^{-1} in all growth seasons, with the highest grain yield being 7160.8 kg ha^{-1} in the 2011 – 2012 growth season. Our results suggested that N fertilization at 150 kg N ha^{-1} was optimal for grain production via promoting above-ground biomass and soil water consumption in deep soil layers. These results should help provide guidance for N fertilization management for optimal and sustainable wheat production in the said region.

Keywords: Dry matter accumulation, dry matter remobilization, grain yield, N application rate, rainfed winter wheat, soil water content,.

INTRODUCTION

Shandong Province, located in the Yellow River and Huai River Valleys, is a major wheat-growing region that accounted for 14.7% of total harvest area and 17.9% of total wheat production in China in 2009 (China Agriculture Statistical Report, 2010). However, approximately 1.3 million ha of wheat planting farmland in Shandong is rainfed, accounting for one third of total wheat planting area in this province (Wang et al., 2003). Nitrogen fertilization is one of the most effective means to promote wheat growth and improve grain yield, especially in rainfed dry farmland (Holger et al., 1997; Hao et al., 2007; Ryan et al., 2012). The optimum N fertilization rate depends on a variety of factors including residual N in soil, wheat cultivars, and local climate conditions, and may differ in different dryland areas. Ryan et al. (1998) reported that 40 kg N ha^{-1} was adequate for maximum dryland wheat yield in most areas of North Africa. Basso et al. (2010) recommended 60 kg N ha^{-1} for rainfed Mediterranean farmland considering both decreased nitrogen fertilizer losses and increased wheat yield. Halvorson et al. (2004) reported that 84 kg N ha^{-1} was optimal for no-till dryland in the central Great Plains under wheat–summer crop–fallow rotation. Li et al. (2000) showed that 138 kg N ha^{-1} was adequate for optimum wheat yield in a loess hilly dryland in the western part of Henan Province. However, the appropriate N rate for optimal water use efficiency and grain yield of winter wheat in the rainfed hilly areas in Shandong Province has rarely been studied.

In wheat plants, assimilates to grains originate from both current assimilation and remobilization of assimilates stored in vegetative organs (Austin et al., 1980; Pheleung and Siddique, 1991; Schnyder, 1993). Nitrogen can affect dry matter accumulation and remobilization after anthesis (Mainard and Jeuffroy, 2001; Ferrise et al., 2010). However, the findings of N fertilization studies on those have been inconsistent. Wang et al. (2010) found that maximum dry matter remobilization efficiency (DMRE) was obtained at different N rates in different genotypes of winter wheat. Zhang et al. (2010) reported that maximum post-anthesis dry matter accumulation was obtained at a relatively lower N rate. In addition, Bahrani et al. (2011) reported that dry matter remobilization (DMR) and DMRE increased with increasing N rate up to 80 kg N ha^{-1} but decreased at higher N rates in the Mediterranean climate. Similarly, Zhang et al. (2010) showed that DMRE decreased with N rate after N rates exceeded 94 kg N ha^{-1} in the Tai Lake region of China. These inconsistent results may be due to the different cultivar properties, soil fertility, and growing environments investigated. Although there have been a few studies on N fertilization for winter wheat production under climate conditions in Shandong Province of China, the effects of N rate on biomass accumulation and translocation in winter wheat under rainfed conditions in Shandong Province have rarely been explored.

In Shandong Province, annual rainfall ranges from 550 mm to 650 mm, and rainfall during the growth season of winter wheat ranges from 162 mm to 310 mm, which is significantly lower than the estimated wheat water requirements in Shandong Province (Wang et al., 2007). The annual yield of rainfed wheat significantly changes because of the different patterns in rainfall amount and distribution during the growth season. This significant change is not beneficial for maintaining and improving the total wheat production in this region. Research has shown that nitrogen fertilization also promoted wheat to utilize more soil water and improve its water use efficiency (WUE), especially under rainfed conditions (Holger et al., 1997). The effects of N rate on water use in wheat under irrigation conditions have been widely reported (Garabet et al., 1998; Timsina et al., 2001; Li et al., 2004). However, how N rate affects WUE in wheat under rainfed conditions, especially in the Yellow River and Huaihe River areas of China, remains largely unexplored.

The amount and timing of nitrogen fertilization needed for optimum crop yields are dictated by the potential yields for a specific environment, that is, climate, soils, crop varieties and management (Ryan et al., 2012). In the rainfed hilly of west Henan Province, China, nitrogen is applied before sowing at a recommended rate of 138 kg N ha^{-1} (Li et al., 2000). Chen et al. (2010) reported that 120 kg N ha^{-1} as a basal dressing would help maintain wheat yield and improve water use efficiency in the Weibei dryland of Loess Plateau. According to Li et al. (2011), top dressing of 30 kg N ha^{-1} on basic nitrogen application of 165 kg N ha^{-1} are important measures to increase yield of winter wheat in rainfed regions of southern Shanxi Province. In rainfed areas of middle Shandong Province, drought frequently occurs at revival and jointing stages of wheat growth (Wang et al., 2013), and farmers did not have the habit of fertilizer topdressing. Most previous studies tested fewer than five N rates to assess the effects of N rate on wheat production in rainfed dryland areas (Ehdaie and Waines, 2001; Halvorson et al., 2004; Ercolia et al., 2008). In the present study, we conducted a field experiment in a rainfed hilly dryland of Shandong Province to investigate the effects of N fertilization before sowing on winter wheat. The effects of six gradient N rates on biomass accumulation, remobilization, and water use characteristics were investigated. Our results provided an estimate of optimal level of nitrogen fertilization to help maintain high and stable winter wheat production in the said region.

MATERIALS AND METHODS

Experimental site

The field experiment was conducted in a hilly rainfed area in Bianhe Village (36°7′ N, 118°2′ E), Linzi, Shandong Province, China, during the growth seasons in 2009 – 2012. The average annual temperature and rainfall in the study area are 13.0°C and 746.8 mm, respectively, with 60% – 70% of rainfall occurring in the summer from June to August. The top 20 cm soil layer in the experimental field before sowing contained 12.1 g kg^{-1} of organic matter, 1.0 g kg^{-1} of total N, 73.5 mg kg^{-1} of alkali-hydrolyzable N, 27.0 mg kg^{-1} of available phosphate, and 115.8 mg kg^{-1} of available potassium during the growth seasons in 2009 – 2012. The precipitation data in different periods of wheat growth are shown in Table 1.

Table 1. Rainfall during different wheat growth periods during the 2009–2012 growth seasons

Growth seasons	Sowing to pre-winter	Pre-winter to revival	Revival to jointing	Jointing to anthesis	Anthesis to maturity	Total
2009-2010	57.9	37.7	35.6	7.9	99.8	238.9
2010-2011	5.0	0.0	20.0	9.5	71.1	105.6
2011-2012	105.6	12.7	23.2	25.1	11.6	178.2

Experimental design and crop management

The winter wheat cultivars Jimai 22 (the most widely planted cultivar in the Yellow River and Huai River Valleys of China), Shannong 16 (a widely planted dryland cultivar in Shandong Province), and Yannong 0428 (another widely planted dryland cultivar in Shandong Province) were studied in the three wheat growth seasons from 2009 – 2012, respectively. Six N rates were applied before sowing in each growth season: 0 (N0), 90 (N1), 120 (N2), 150 (N3), 180 (N4), and 210 (N5) kg N ha^{-1}. Each treatment was replicated three times in plots measured 3 m × 6 m each in a completely randomized block design.

Wheat seeds were sown on 3 October 2009, 4 October 2010, and 5 October 2011, and the plants were harvested on 15 June 2010, 11 June 2011, and 7 June 2012, respectively. Fertilizers applied in each growth season included urea (46.4% N), calcium triple superphosphate (46% P_2O_5), and potassium sulfate (50% K_2O). In each growth season, fixed amounts of P_2O_5 (150 kg ha^{-1}) and K_2O (150 kg ha^{-1}) were added with varying amounts of nitrogen fertilizer before sowing. The seeds were sown at a distance of 0.25 m per row and the seedling density was maintained at 225 plants per m^2 at the four-leaf stage. Irrigation was not performed in any growth season throughout the experiment. Other field managements followed those for general field production.

Measurements of variables

Dates of plant anthesis and maturity were recorded. Anthesis was defined as when anthers of the central spikelets of 50% of ears in a plot had extruded, whereas maturity was defined as when most of the ears in the plot showed complete loss of green color. At times of anthesis and maturation, 30 randomly selected culms were cut at the ground level and samples of stems + sheaths, leaves, glumes (spike axis and kernel husks), and grains (only at harvest) were collected. All plant samples were oven-dried at 75°C to constant weight for determination of above-ground biomass (Xu et al., 2005).

Various parameters of dry matter accumulation and remobilization were calculated using formula described by Papakosta and Gagianas (1991) and Arduini et al. (2006):

DMR during Grain Filling = Dry Matter of Vegetative Plant Parts at Anthesis − Dry Matter of Vegetative Plant Parts at Maturity

This formula is valid under the assumption that all dry matter lost from vegetative parts of the plant is translocated to the developing grain, as loss of dry matter owing to plant respiration during grain filling is so little that it is neglected.

DMRE = (DMR / Dry Matter of the Aerial Plant Part at Anthesis) × 100

The post-anthesis dry matter accumulation was calculated as the difference between the dry matter of the aerial parts of a plant at physiological maturity and that at anthesis:

Contribution of Post-anthesis Dry Matter Assimilate to Grain = (Post-anthesis Dry Matter Accumulation / Dry Matter of Grain at Maturity) × 100

Evapotranspiration (ET) was calculated using the water balance equation (Corbeels et al. 1998; Miranzadeh et al., 2011):

$$ET = (P + I + S_G) - (D + R) - \Delta S,$$

where P is the growth season rainfall (mm), I is irrigation (mm), S_G is groundwater contribution to plant available water (mm), D is downward drainage out of the root zone (mm), R is surface runoff (mm), and ΔS is the change in soil water stored in the upper 200 cm of soil between sowing and maturity (mm). In this experiment, the groundwater was 10 m below the surface and runoff was prevented from the experimental plots, such that S_G, D, and R were all negligible. In addition, I was assigned a zero value since irrigation was not performed throughout the growth period in this experiment.

Soil water content (SWC) in every 20-cm soil layer up to a depth of 200 cm was measured by the oven drying method, which was used to estimate the soil water consumption (ΔS). Soil core samples were randomly collected using a 50 mm diameter steel sampling tube. Soil cores were weighed, oven-dried at 105°C for 48 h, and re-weighed to determine the gravimetric water content. Gravimetric water content was converted to volumetric water units using measured bulk densities for the ten soil layers, respectively. Measurements of soil water contents were taken immediately before seeding and again immediately after harvesting (Yule, 1984; Gan et al., 2000).

WUE was calculated based on the following equation (Corbeels et al., 1998):

WUE = Grain Yield / ET

At maturity, plant samples were collected from two 1-m rows adjacent to each other in the center of each plot. The number of spikes per square meter was obtained from the collected samples (Hassan and Bedreldin, 1996; Villegas et al., 2010). The average number of grains per spike was determined from 20 randomly selected spikes (Hossein and Mohammand, 2009). The thousand-kernel weight was calculated from a randomly selected sample of 500 grains from each plot (Villegas et al., 2010). Grain yield was calculated based on 3-m^2 harvest areas in each plot and expressed at 12.5% grain moisture (Xue et al., 2006).

Statistical analysis

Statistical analysis was performed using SPSS Version 13.0 for Windows (SPSS, Chicago, Illinois, USA). All data presented were means over three replicates. Differences between means were analysed by ANOVA. The least significant difference test was used to compare differences in means among treatments at the 0.05 probability level.

RESULTS

Dry matter accumulation and partitioning at anthesis and maturity

Dry matter accumulation and partitioning into different parts at anthesis and maturity varied with N rates in each growth season (Table 2). At anthesis, the total above-ground biomass significantly increased with increasing N rate up to 150 kg ha^{-1} and then leveled off in growth seasons of 2009 – 2010 and 2011 – 2012. However, the total above-ground biomass at anthesis did not vary with N rates in 2010 – 2011, during which the amount of rainfall before anthesis was lower than those in the other two growth seasons. Our results showed that increasing N rate up to 150 kg ha^{-1} significantly improved dry matter accumulation at anthesis in growth seasons that had more rainfall before anthesis.

Table 2. Dry matter accumulation and partition (mg $culm^{-1}$) in different organs at anthesis and maturity under different N treatments during the 2009-2012 growth seasons

Treatment	Anthesis	Maturity		
	Total	Vegetative	Grain	Total
2009-2010				
N0	1287.11b	1011.44c	836.11c	1847.56d
N1	1317.67b	1025.67c	880.44b	1906.11c
N2	1347.78b	1049.33c	885.33b	1934.67c
N3	1414.11ab	1114.44a	990.22a	2104.67a
N4	1427.00a	1131.56a	984.67a	2116.22a
N5	1437.33a	1143.22a	872.89b	2016.11b
2010-2011				
N0	1000.89b	790.22c	663.89c	1454.11c
N1	1230.33a	922.11b	861.22b	1783.33b
N2	1222.56a	937.89b	872.56b	1810.44b
N3	1263.22a	1074.11a	951.78a	2025. 89a
N4	1249.44a	1054.67a	933.89a	1988.56a
N5	1247.00a	1062.33a	916.56a	1978.89a
2011-2012				
N0	1223.11d	910.67d	752.56c	1663.22c
N1	1420.44c	1088.67c	1044.44b	2133.11b
N2	1428.44c	1101.56c	1055.89b	2157.44b
N3	1582.67b	1207.56b	1122.89a	2330.44a
N4	1588.00ab	1224.56b	1112.56a	2337.11a
N5	1664.67a	1302.22a	1037.67b	2339.89a

Values are means over three replicates. Values in the same column with different letters in each growth season are significantly different (n = 3; $P < 0.05$).

At maturity, the accumulation of dry matter in vegetative organs significantly increased with increasing N rate up to 150 kg ha^{-1} and leveled off under higher N rates in all growth seasons. Dry matter accumulation in grains that received N3 or N4 treatments was significantly higher than those in grains under other treatments in 2009 – 2010 and 2011 – 2012. In 2010 – 2011, while dry matter accumulation in grains under N3, N4, or N5 treatments was significantly higher than those under other treatments, no significant differences were observed between N3, N4, and N5 treatments. Overall, N rates of 150 and 180 kg ha^{-1} showed the most prominent effect in enhancing dry matter accumulation in grains, which contributed to improved grain yield. In addition, the effect of N rate on total above-ground biomass at maturity was similar to that on dry matter accumulation in grains in each growth season.

DMR after anthesis

The DMR with different N rates varied in each growth season (Table 3). While DMR was not affected by N rate in 2009 – 2010, it significantly decreased with increasing N rate up to 150 kg ha^{-1} in 2010 – 2011. In 2011 – 2012, however, DMR significantly increased with increasing N rate up to 150 kg ha^{-1} before leveling off at higher N rates. Meanwhile, DMRE showed a declining trend with increasing N rate in all three seasons. Our results suggested that the effect of N rate on DMR is complex. Increasing N rate does not necessarily promote DMR. It may even reduce DMR under certain conditions.

Dry matter accumulation after anthesis significantly increased with increasing N rate up to 150 kg ha^{-1} in all growth seasons. The effect of N rate differed, however, under N rates higher than 150 kg ha^{-1}. Dry matter accumulation significantly decreased in 2009 – 2010 and 2011 – 2012, whereas it only leveled off in 2010 – 2011. The contribution of post-anthesis assimilates to grains under different N rates ranged from 58.5% to 80.1%, with the higher ones being obtained at 150 and 180 kg ha^{-1}, suggesting that post-anthesis assimilates were the main source of dry matter accumulation in grains. Taken together, N rates of 150 and 180 kg N ha^{-1} were most effective in promoting post-anthesis assimilates and dry matter accumulation in grains and ultimately the grain yield.

Table 3 DMR (mg culm^{-1}) under different N treatments during the 2009–2012 growth seasons

Treatment	Dry matter remobilization	Dry matter remobilization efficiency(%)	Dry matter accumulaiton after anthesis	Contribution of post-anthesis assimilates to grain(%)
2009-2010				
N0	275.67c	21.42ab	560.44c	67.03ab
N1	292.00a	22.16a	588.44b	66.83ab
N2	298.44a	22.14a	586.89b	66.29b
N3	299.67a	21.19ab	690.56a	69.74ab
N4	295.44a	20.70b	689.22a	70.008a
N5	294.11a	20.46b	578.78bc	66.31b
2010-2011				
N0	210.67b	21.05b	453.22c	68.27b
N1	308.22a	25.05a	553.00b	64.21c
N2	284.67a	23.28ab	587.89b	67.38bc
N3	189.11c	14.97c	762.67a	80.13a
N4	194.78c	15.59c	739.11a	79.14a
N5	184.67c	14.81c	731.89a	79.85a
2011-2012				
N0	312.44c	25.55a	440.11d	58.48c
N1	331.78b	23.36ab	712.67b	68.23ab
N2	326.89bc	22.88b	729.00ab	69.04a
N3	375.11a	23.70ab	747.78a	66.591ab
N4	363.44a	22.89b	749.11a	67.33ab
N5	362.44a	21.77b	675.22c	65.07b

Values are means over three replicates. Values in the same column with different letters in each growth season are significantly different ($n = 3$; $P < 0.05$).

SWC of the 0 – 200 cm soil layers at maturity

N rate had different effects on SWC of the 10 soil layers (20 cm each) at maturity in the three growth seasons (Figure 1). In 2009 – 2010, SWC of soil layers within 120 – 200 cm did not vary with N rate. SWC of soil layers within 0 – 120 cm significantly decreased with increasing N rate up to 150 kg ha^{-1}.

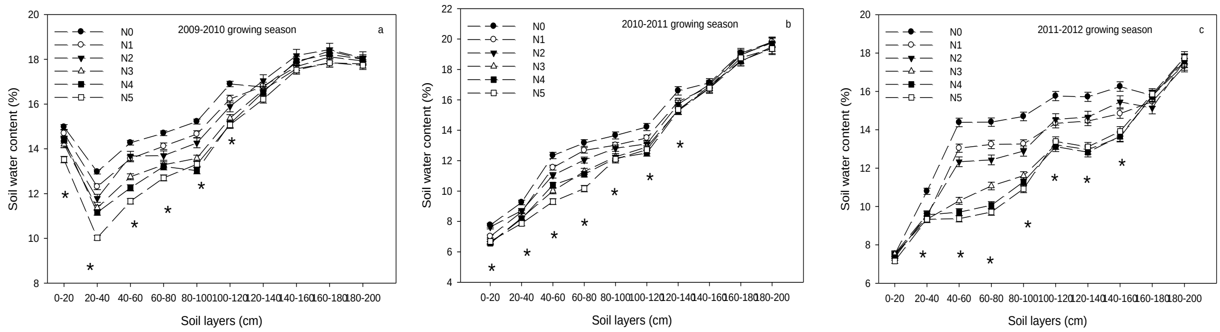

Figure 1. Changes in SWC in 0 – 200 cm soil layers at maturity under different N regimens during the growth seasons in 2009 – 2010 (a), 2010 – 2011 (b), and 2011 – 2012 (c). Values are means over three replicates. Bars represent ± SE. The asterisk (*) indicates significant differences between treatments ($P < 0.05$)

In addition, SWC of soil layers within 0 – 80 cm continued to decline significantly when N rate was raised from 150 to 210 kg ha^{-1}. In 2010 – 2011, SWC of soil layers within 0 – 140 cm was significantly lower than that of controls while SWC of soil layers within 140 – 200 cm was not affected by N rate. Particularly, SWC of soil layers within 20 – 80 cm significantly decreased with increasing N rate up to 210 kg ha^{-1}. In 2011 – 2012, SWC of soil layers within 20 – 160 cm was significantly lower than that of controls. SWC of soil layers within 40 – 160 cm significantly decreased with increasing N rate up to 150 kg ha^{-1}. Particularly, SWC of soil layers within 40 – 80 cm continued the significant declining trend under N rates above 150 kg ha^{-1}. Taken together, our results indicated that N rate of 150 kg ha^{-1} promoted soil water consumption of winter wheat, especially in deep soil layers (100 – 160 cm). In most cases, N rates higher than 150 kg ha^{-1} did not further promote soil water consumption.

Grain yield and its components

Grain yield and its components under different N rates during the 2009 – 2012 growth seasons are shown in Table 4. Grain yields under N3 and N4 treatments were significantly higher than those under other treatments in 2009 – 2010 and 2011 – 2012. In 2010 – 2011, grain yield significantly increased with increasing N rate up to 150 kg ha^{-1} before leveling off. The maximum grain yield was obtained under N rate of 150 kg N ha^{-1} in all three growth seasons, with the highest grain yield being 7160.8 kg ha^{-1} in 2011 – 2012. Compared with controls, the grain yield under N3 treatment (150 kg ha^{-1}) increased by 51.4%, 63.0%, and 66.6% in the three growth seasons, respectively. Our results suggested that 150 kg ha^{-1} was the optimal nitrogen application rate for wheat grown in the rainfed region investigated.

The number of spikes per square meter was not significantly affected by N treatments in all growth seasons. However, the number of grains per spike significantly increased with increasing N rate up to 150 kg ha^{-1} before leveling off in 2009 – 2010 and 2011 – 2012, whereas in 2010 – 2011 the number of grains per spike did not change with N rates. Grain weight significantly increased with increasing N rate up to 150 kg ha^{-1} in all three seasons. Under N rates above 150 kg ha^{-1}, grain weight declined in 2009 – 2010 and 2011 – 2012 but stayed the same as that obtained under 150 kg ha^{-1} in 2010 – 2011. These results indicated that 150 kg ha^{-1} was the optimal N rate for improving grain number per spike and grain weight.

Table 4 Grain yield and its components under different N treatments during the 2009–2012 growth seasons

Treatment	**Spike number ($\times10^4$ ha^{-1})**	**Grain number per spike**	**Weight per 1000 Kernels (g)**	**Grain yield (kg ha^{-1})**
2009-2010				
N0	429.34b	28.83c	32.32c	3807.80c
N1	573.34a	31.67b	33.79b	5327.90b
N2	578.67a	32.17b	34.13b	5402.53b
N3	581.34a	33.17a	35.43a	5765.12a
N4	584.00a	33.33a	35.25a	5718.18a
N5	586.67a	33.67a	33.51b	5445.97b
2010-2011				
N0	421.34b	20.38b	44.94b	2808.10c
N1	474.67a	23.10a	44.96b	4118.43b
N2	477.34a	23.20a	45.10b	4209.12b
N3	480.00a	23.37a	46.80a	4577.98a
N4	485.34a	23.44a	46.62a	4541.11a
N5	482.67a	23.36a	46.43a	4401.79a
2011-2012				
N0	570.67b	29.49c	30.21c	4298.80c
N1	626.67a	32.98b	33.83b	6598.32b
N2	632.00a	33.19b	33.94b	6775.26b
N3	637.34a	34.57a	35.56a	7160.75a
N4	642.67a	34.11a	35.40a	7152.41a
N5	648.00a	34.28a	34.14b	6753.92b

Values are means over three replicates. Values in the same column with different letters in each growth season are significantly different ($n = 3$; $P < 0.05$).

Relationships between grain yield, dry matter remobilization and accumulation, and water status

Significant positive linear correlations were found between grain yield and dry matter accumulation, both at and after anthesis (Figure 2). Significant positive correlation between grain yield and DMR was found in 2009 – 2010 and 2011 – 2012 but not in 2010 – 2011. Our data indicated that it may be a useful route for optimizing nitrogen application to achieve high yields by improving both dry matter accumulation at anthesis and post-anthesis assimilates.

Grain yield was found to have a significant relationship with ET when data were fitted to quadratic equations. Similar significant relationships were found between WUE and ET in each growth season (Figure 3). These results suggested that N rate might be optimized to achieve high grain yields and high WUE simultaneously.

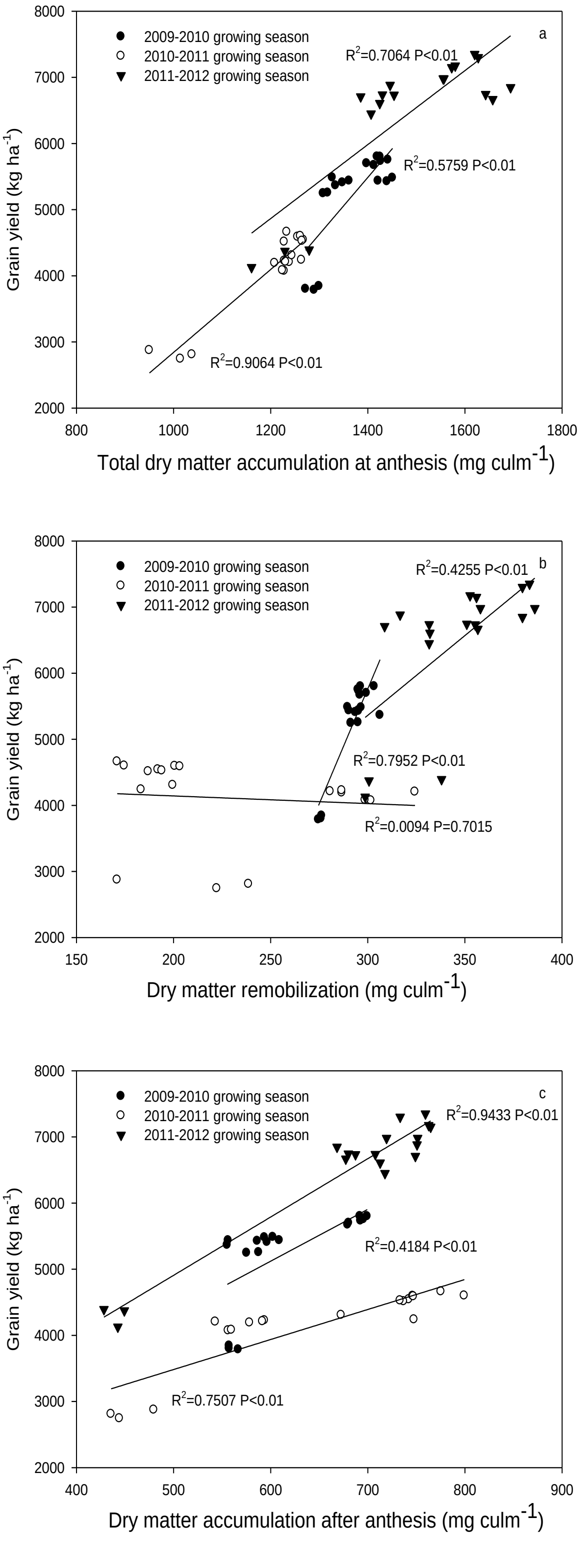

Figure 2. Relationships between grain yield and total dry matter accumulation at anthesis (a), between grain yield and DMR remobilization (b), and between grain yield and dry matter accumulation after anthesis (c) during the 2009 – 2012 growth seasons

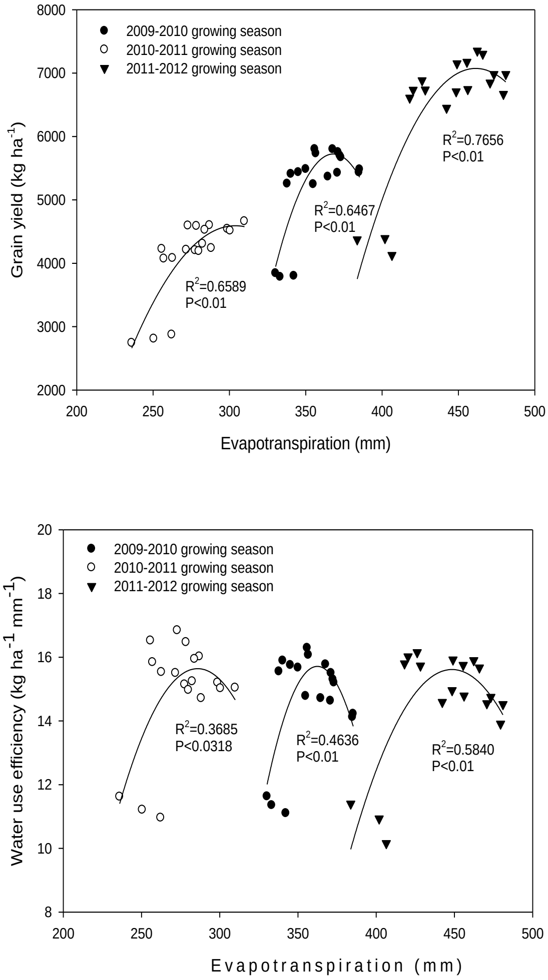

Figure 3 Relationships between grain yield and ET (a), and between WUE and ET (b) during the 2009 – 2012 growth seasons

DISCUSSION

It has been well established that N fertilization profoundly affects dry matter accumulation and partitioning in wheat. Garabet et al. (1998) found that N fertilization increased total dry matter accumulation at maturity. Fois et al. (2009) reported that 120 kg N ha^{-1} generated significant increases in above-ground dry matter accumulation at both anthesis and maturity. Dordas (2009) demonstrated that the accumulation of dry matter in grain at harvest was similar to that of vegetative parts (leaf, culm, and chaff) as well as that total above-ground biomass at anthesis and that at maturity both increased when the N application rate was 80 kg ha^{-1}. In the present study, dry matter accumulation and partitioning into different plant parts varied under different N rates. Increasing N rate to a certain level was beneficial for improving dry matter accumulation at both anthesis and maturity. In this study, the highest dry matter accumulation in grains was obtained at 150 kg N ha^{-1} in all growth seasons.

DMR can be affected by cultivars and prevailing growth conditions (Papakosta and Gagianas, 1991). Ma et al. (2007) showed that DMR first increased and then decreased with increasing N rate. In particular, DMRE in wheat was found to range from 10.2% to 23.4% under different N rates (Ma et al., 2007; Bahrani et al., 2011). In the present study, DMR was affected by N rate differently in different growth seasons. DMR increased with increasing N rate up to a certain level but excessive N rates did not help promoting DMR further. Meanwhile, values of DMRE, which ranged from 14.8% to 25.6%, were slightly higher than those reported previously, likely attributed to differences in cultivars and weather conditions. According to Zou et al. (2011), when nitrogen levels in soil were in the range of 225 – 300 kg ha^{-1}, wheat grain yield was mainly determined by photosynthetic assimilation of green organs after anthesis followed by distribution of dry matter accumulation before anthesis. Ercolia et al. (2008) found that post-anthesis dry matter accumulation under 180 kg N ha^{-1} was significantly higher than that under 120 kg N ha^{-1}. The contribution of post-anthesis assimilates to grains was reported to range from 53.6% to 82.4% under different N rates in wheat (Lu et al., 2007). In the present study, the contribution of post-anthesis assimilates to grains with different N rates ranged from 64.2% to 80.1%. These data suggested that dry matter accumulation after anthesis was a main source of dry matter accumulation in grains. N rate of 150 kg ha^{-1} enhanced post-anthesis dry matter accumulation and thus its contribution to grain yield, leading to higher grain production.

Soil water storage after wheat harvest has been reported to be lower under N fertilizer treatments compared with unfertilized treatments (Latiri-Souki et al., 1998; Angus and Herwaarden, 2001). In contrast, Gentile et al. (2005) found that N rates did not consistently affect seasonal soil water consumption in soils with adequate N supply. In the present study, N fertilizer application was found to improve soil water consumption. Patterns of soil water profile for control and N fertilized treatments are generally similar, and SWCs with significant differences in soil layers with N application rates may vary during different growth seasons (Corbeels et al., 1998). Similar results were obtained in the present study, with significant changes in SWCs being found in soil layers within 0 – 160 cm under different N rates in the third growth season. Xie et al. (2011) reported that SWC of soil layers within 80 – 200 cm was not affected by increasing N rate up to 165 kg ha^{-1} in the rainfed area of South Shanxi Province, China. In addition, Wang et al. (2007) reported that in soils supplied with 90 kg N ha^{-1} in the dryland of Loess Plateau, soil moisture contents in soil layers within 100 – 200 cm stayed stable. In the present study, SWC of deep soil layers (100 – 200 cm) did not change significantly with increasing N rate when the N rates were above 150 kg ha^{-1}.

Santiveri et al. (2004) reported that higher dry matter at anthesis was associated with higher yield in spring triticale. Ehdaie and Waines (2001) showed that grain yield was positively correlated with shoot biomass at anthesis in bread and durum wheat. Bahrani et al. (2011) found that grain yield was positively related to dry matter at anthesis in winter wheat grown in dryland. In the present study, significant positive linear correlations were found between grain yield and dry matter accumulation, both at and after anthesis. We also found that the relationship between grain yield and DMR varied in different growth seasons, in alignment with previous results reported by Przulj and Momcilovic (2001). It has been shown that quadratic functions were more suitable for analysis of relationships between seasonal ET and grain yield or WUE (Li et al., 2005; Zhang et al., 2005; Kang et al., 2002). In our analysis using quadratic functions, we found that grain yield and WUE had similar relationships with ET.

In the present study, three different cultivars were used among different growth seasons, which may make some effects in the analysis of the results among different growth seasons. Long-term effects of nitrogen fertilization on individual cultivar require further study to provide more reliable guidance for nitrogen management in the said region. According to Knaggs (2002), N additions had little effect on crop biomass or grain yield in soils that already had a high N supply. Further studies should be conducted to investigate whether or not the amount of applied nitrogen can be decreased without reducing crop yield after high N fertilizer rates have been applied for several years.

CONCLUSION

This study examined the effects of six levels of nitrogen fertilization on dry matter accumulation, remobilization, and SWCs in a rainfed winter wheat field in three growth seasons in Shandong Province of China. Nitrogen fertilization increased dry matter accumulation, both at anthesis and at maturity, and promoted post-anthesis assimilates. Dry matter accumulation in grains, total above-ground biomass at maturity, and post-anthesis assimilates all increased with increasing N rate up to 150 kg ha^{-1} in all growth seasons. Under N rates higher than 150 kg ha^{-1}, dry matter accumulation at anthesis and maturity, DMR, and post-anthesis assimilates did not appear to add up in all growth seasons. Application of 150 kg N ha^{-1} also promoted soil water consumption of winter wheat, especially in deep soil layers (100 – 160 cm). SWC of deep soil layers did not change significantly with increasing N rate under N rates above 150 kg ha^{-1}, suggesting that the capability of N fertilization to promote soil water consumption was saturated under high N rates. The maximum grain yield was obtained under 150 kg N ha^{-1} in all growth seasons, with the highest being 7160.6 kg ha^{-1} in the 2011 – 2012 growth season. These results were in alignment with our expectations considering that dry matter accumulation and soil water consumption are two key factors contributing to grain yield. Our results suggested that 150 kg ha^{-1} may be the optimal N application rate for high grain yield of winter wheat in the rainfed region in Shandong Province of China.

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LITERATURE CITED

Angus, J.F., A.F. Herwaarden. 2001. Increasing water use and water use efficiency in dryland wheat. Agron J. 93: 290-298.

Arduini, I., A. Masoni, L. Ercoli, M. Mariotti. 2006. Grain yield, and dry matter and nitrogen accumulation and remobilization in durum wheat as affected by variety and seeding rate. Eur J. Agron. 25: 309-318.

Austin, R.B., C.L. Morgan, M.A. Ford, R.D. Blackwell. 1980. Contribution to grain yield from pre-anthesis assimilation in tall and dwarf barley phenotypes in two contrasting seasons. Ann Bot. 45: 309-319.

Bahrani, A., H.H. Sharifabad, Z.T. Sarvestani, G.H. Moafpourian, A.A. Band. 2011. Remobilization of dry matter in wheat: effects of nitrogen application and post-anthesis water deficit during grain filling. New Zeal J. Crop Hort Sci. 39: 279-293.

Basso, B., D. Cammarano, A. Troccoli, D.L. Chen, J.T. Ritchie, 2010. Long-term wheat response to nitrogen in a rainfed Mediterranean environment: Field data and simulation analysis. Eur J. Agron. 33: 132-138.

Chen H.L., X.H. Tian, X.F. Wang, Y.X. Cao, Y.H. Wu, Z.H. Wang. 2010. Effects of cultivation models on soil water, soil temperature and yield during the winter wheat growth in the Weibei dry highland. Acta Ecol Sin. 30: 2424-2433.

Corbeels, M., G. Hofman, O.V. Cleemput. 1998. Analysis of water use by wheat grown on a cracking clay soil in a semi-arid Mediterranean environment: weather and nitrogen effects. Agr Water Manage. 38: 147-167.

Dordas, C. 2009. Dry matter, nitrogen and phosphorus accumulation, partitioning and remobilization as affected by N and P fertilization and source–sink relations. Eur J. Agron. 30: 129-139.

Ehdaie, B., J.G. Waines. 2001. Sowing date and nitrogen rate effects on dry matter and nitrogen partitioning in bread and durum wheat. Field Crops Res. 73: 47-61.

Ercolia, L., L. Lullib, M. Mariottib, A. Masonib, I. Arduini. 2008. Post-anthesis dry matter and nitrogen dynamics in durum wheat as affected by nitrogen supply and soil water availability. Eur J. Agron. 28: 138-147.

Ferrise, R., A. Triossi, P. Stratonovitch, M. Bindi, P. Martre. 2010. Sowing date and nitrogen fertilisation effects on dry matter and nitrogen dynamics for durum wheat: An experimental and simulation study. Field Crops Res. 117: 245-257.

Fois, S., R. Motzo, F. Giunta. 2009. The effect of nitrogenous fertiliser application on leaf traits in durum wheat in relation to grain yield and development. Field Crops Res. 110: 69-75.

Gan, Y.T., G.P. Lafond, W.E. May. 2000. Grain yield and water use: Relative performance of winter vs. spring cereals in east-central Saskatchewan. Can J. Plant Sci. 80: 533-541.

Garabet, S., M. Wood, J. Ryan. 1998. Nitrogen and water effects on wheat yield in a Mediterranean-type climate I. Growth, water-use and nitrogen accumulation. Field Crops Res. 57: 309-318.

Gentile, R.M., P.J. de Rocquigny, M.H. Entz. 2005. Soil water depletion by tall and semidwarf oat and wheat cultivars. Can J. Plant Sci. 85: 385-388.

Halvorson, A.D., D.C. Nielsen, C.A. Reule. 2004. Nitrogen fertilization and rotation effects on no-till dryland wheat production. Agron J. 96: 1196-1201.

Hao, M.D., J. F, Q.J.Wang, T.H. Dang, S.L. Guo, J.J. Wang. 2007. Wheat grain yield and yield stability in a long-term fertilization experiment on the Loess Plateau. Pedosphere. 17: 257-264.

Hassan, M.I., A.M. Badreldin. 1996. Phasic development of spring wheat and stability of yield and its components in hot environments. Field Crops Res. 46: 169-176.

Holger, M., L.H. Graeme, V.K. Herman, R. Rudy, A.K. Brian. 1997. Improving wheat simulation capabilities in Australia from a cropping systems perspective: water and nitrogen effects on spring wheat in a semi-arid environment. Eur J. Agron. 7: 75-88.

Hossein, S., J.B. Mohammad. 2009. Effects of crop residue and nitrogen rates on yield and yield components of two dryland wheat (*Triticum aestivum* L.) cultivars. Plant Prod Sci. 12: 497-502.

Kang, S.Z., L. Zhang, Y.L. Liang, X.T. Hu, H.J. Cai, B.J. Gu. 2002. Effects of limited irrigaiton on yield and water use efficiency of winter wheat in the Loess Plateau of China. Agr Water Manage. 55: 203-216.

Knaggs, P.J. 2002. Yield physiology, quality and soil water dynamics of a semidwarf and a tall oat (Avena sativa L.) cultivar. M.Sc. thesis, University of Manitoba, Winnipeg, MB. 168 pp.

Latiri-Souki, K., S. Nortcliff, D.W. Lawlor. 1998. Nitrogen fertilizer can increase dry matter, grain production and radiation and water use efficiencies for durum wheat under semi-arid conditions. Eur J. Agron. 9: 21-34.

Li, J.M., S. Inanag, Z.H. Li., A.E.Eneji. 2005. Optimizing irrigation scheduling for winter wheat in the North China Plain. Agr Water Manage. 76: 8-23.

Li T.L., Y.H. Xie, M.M. Ren, S.Y. Deng, J. Shan, Z.Y. Lei, J.P. Hong, C H Wang. 2011. Effects of fertilization and plastic film mulched ridge-furrow cultivation on yield and water and nitrogen utilization of winter wheat on dryland. Acta Ecol Sin. 31: 212-220.

Li, Y.Y., Y.J. Guo, M.A. Shao. 2000. The effect of fertilizer application on the growth and development and water use of winter wheat in hilly land of west Henan. Agric Res Arid Areas. 18: 15-21.

Li, Z.Z., W.D. Li, W.L. Li. 2004. Dry-period irrigation and fertilizer application affect water use and yield of spring wheat in semi-arid regions. Agr Water Manage. 65: 133-143.

Lu, Z.G., T.B. Dai, D. Jiang, Q. Jing, Z.G.Wu, P.N. Zhou, W.X. Cao. 2007. Effects of nitrogen strategies on population quality index and grain yield and quality in weak-gluten wheat. Acta Agron Sin. 33: 590-597.

Ma, D.H., Y.F. Wang, H. Zhou, H. Sun. 2007. Effect of post-anthesis soil water status and nitrogen on grain yield and canopy biomass accumulation and transportation of winter wheat. J. Triticeae Crops. 27: 847-851.

Mainard, S.D. and M.H. Jeuffroy. 2001. Partitioning of dry matter and nitrogen to the spike throughout the spike growth period in wheat crops subjected to nitrogen deficiency. Field Crops Res. 70: 153-165.

Ministry of Agriculture of the People’s Republic of China. 2010. China Agriculture Statistical Report. China Statistics Press, Beijing, China. pp, 26.

Miranzadeh, H., Y. Emam, P. Pilesjö, H. Seyyedi. 2011. Water use efficiency of four dryland wheat cultivars under different levels of nitrogen fertilization. J. Agr Sci Tech. 13: 843-854.

Papakosta, D.K. and A.A. Gagianas. 1991. Nitrogen and dry Matter Accumulation, remobilization, and losses for Mediterranean wheat during grain filling. Agron J. 83: 864-870.

Pheleung, P.C. and K.H.M. Siddique. 1991. Contribution of stem dry matter to grain yield in wheat cultivars. Aust J. Plant Physiol. 18: 53-64.

Przulj, N. and V. Momcilovic. 2001. Genetic variation for dry matter and nitrogen accumulation and translocation in two-rowed spring barley I. Dry matter translocation. Eur J. Agron. 15: 241-254.

Ryan, J., M. Abdel Monem, J.P. Shroyer, M. El Bouhssini, M.M. Nachit. 1998. Potential for nitrogen fertilization and Hessian fly-resistance to improve Morocco's dryland wheat yields. Eur J. Agron. 8: 153-159.

Ryan, J., R. Sommer, H. Ibrikci. 2012. Fertilizer best management practices: A perspective from the dryland West Asia–North Africa region. J. Agron Crop Sci. 198: 57-67.

Santiveri, F., C. Royo, I. Romagosa. 2004. Growth and yield responses of spring and winter triticale cultivated under Mediterranean conditions. Eur J. Agron. 20: 281-292.

Schnyder, H. 1993. The role of carbohydrate storage and redistribution in the source-sink relations of wheat and barley during grain filling a review. New Phytol. 123: 233-245.

Timsina, J., U. Singh, M. Badaruddin, C. Meisner, M.R. Amin. 2001. Cultivar, nitrogen, and water effects on productivity, and nitrogen-use efficiency and balance for rice-wheat sequences of Bangladesh. Field Crops Res. 72: 143-161.

Villegas, D., J. Casadesus, S.G. Atienza, V. Martos, F. Maalouf, F. Karame, I. Aranjuelo, S. Nogues. 2010. Tritordeum, wheat and triticale yield components under multi-local mediterranean drought conditions. Field Crops Res. 116: 68-74.

Wang, B., W.Z. Liu, T.H. Dang, C.Q. Gao, Z. Li, Z.T. Gan. 2007. Distribution features of soil water content in the profile of rainfed cropland with long-term fertilization. Plant Nutr Fert Sci. 13: 411-416.

Wang D., Z.W. Yu, Y.L. Zhang. 2007. Meteorological conditions affecting the quality of strong-gluten and medium-gluten wheat and climate division in Shandong Province. Chin J. Appl Ecol. 18: 2269-2276.

Wang F.Y., W.J. Feng, S.Y. Liu, Z.C. Wang, L. Mei, Y. Tang. 2013. Research and development of weather risk assessment model group for wheat in Shandong Province. Chin Agri Sci Bull. 29: 197-204.

Wang, G.L., Y.L. Ye, H.H. Li, Y.J. Zhu. 2010. Effect of nitrogen fertilizer application on grain yield and dry matter accumulation for different genotypes of winter wheat. J. Triticeae Crops. 30: 116-122.

Wang, Y.F., J.L. Cheng, B.J. Wang, Y.G. Wang, L.L. Wang, C.Q. Sui. 2003. Review and outlook to the production and development of wheat in dryland of Shandong. J. Laiyang Agric Coll. 20: 200-205.

Xie, Y.H., T.L. Li, J.P. Hong, L.Q. Liu, J. Pang, Q. Feng, S.Y. Deng, J. Shan. 2011. Effects of nitrogen application and ridge film furrow planting on water use of winter wheat in dryland of South Shanxi. Chin. J. Appl Ecol. 22: 2038-2044.

Xu, Z.Z., Z.W. Yu, D. Wang, Y.L. Zhang. 2005. Nitrogen accumulation and translocation for winter wheat under different irrigation regimes. J. Agron. Crop Sci. 191: 439-449.

Xue, Q.W., Z.X. Zhu, J.T. Musick, B.A. Stewart, D.A. Dusek. 2006. Physiological mechanisms contributing to the increased water-use efficiency in winter wheat under deficit irrigation. J. Plant Physiol. 163: 154-164.

Yule, D.F. 1984. Volumetric calculations in cracking clay soils. In: McGarity, J.W., Hoult, E.H., So, H.B. (Eds.), Properties and Utilization of Cracking Clay Soils. Reviews in Rural Science, vol. 5, University of New England, Armidale, NSW, Australia, pp. 136-140.

Zhang, B.C., F.M. Li, G.B. Huang, Y. Gan, P.H. Liu, Z.Y. Cheng. 2005. Effects of regulated deficit irrigation on grain yield and water use efficiency of spring wheat in an arid environment. Can J. Plant Sci. 85: 829-837.

Zhang, J.H., J.L. Liu, J.B. Zhang, F.T. Zhao, Y.N. Cheng, W.P. Wang. 2010. Effects of nitrogen application rates on translocation of dry matter and utilization of nitrogen in rice and wheat. Acta Agron Sin. 36: 1736-1742.

Zhang, M., D. Jiang, R.L. Miao, K. Xu, Y.Y. Liu, J. Zhang, H.C. Zang. 2010. Effects of different soil fertility levels and N application rate on wheat yield and matter production after rice. J. Triticeae Crops. 30: 330-336.

Zou, B., Z.R. Dong, J.S. Wang, J. Zhang, J. Tan, X.G. Xu, Y. Liu, X.W. Li. 2011. Response of post-anthesis assimilates remobilization and yield to nitrogen management in wheat cultivar with different spike-types. Chin Agric Sci Bull. 27: 63-67.