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Effect of subsoiling on tillers, root density and nitrogen use efficiency of winter wheat in loessal soil

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Abstract: A 2-year field experiment was carried out in loessal soil in a semi-humid climate to research winter wheat (*Triticum aestivum* L.) growth and nitrogen use efficiency. The result showed that subsoiling increased root penetration and promoted deep soil water absorption, which resulted in high resilience to the adverse dry climate. Soil NO_3^--N residue throughout the profile was decreased but increased in rotary tillage. Grain yield was significantly increased by 21.9% and 11.3% in 2016 and 2017, respectively, mainly due to the significantly larger spikes per hectare and grains per spike. Nitrogen use efficiency was significantly improved by 26.7% in 2016 and 13.8% in 2017. For loessal soil in semi-humid climate, breaking the plough pan was necessary, and it was useful for the increase of grain yield and nitrogen use efficiency.

Keywords: farming system; nitrate nitrogen; profile distribution; root growth; tillage method

Well-drained, light, and medium textured loessal soils are the primary soil types in the Loess Plateau region and rain-fed farming systems of North Shaanxi province in China (Huang et al. 2011). They cover an area of 491.1 million hectares, accounting for about 80% of the total farmland in North Shannxi province, and are therefore important for agricultural production (Huang 1987). However, due to a long-term mechanized and shallow tillage, a thick 'plough pan' on the farmlands are beginning to restrict local agricultural productivity (Zhai et al. 2016).

The high soil strength of plough pans limited root propagation and thus also limited plant utilization of resources in the subsoil (Bengough et al. 2011). In dry years, compaction became more severe; restricted root growth could lead to increasing moisture stress and decreased yields (Motavalli et al. 2003). In wet years, soil compaction increased nitrogen (N) losses due to increased rates of runoff and denitrification under anaerobic conditions (Torbert and Wood 1992).

Subsoiling without turning or mixing soil horizons aims at loosening the soil structure, breaking plough pan, and decreasing the bulk density of the subsoil. Therefore, subsoiling could increase root penetration, which could improve grain yield, the ability to utilize subsoil water and nutrients, and increase nutrients use efficiency (Gajri et al. 1994). Baumhardt et al. (2008) also found that subsoiling could enhance water storage, improve soil fertility, enhance deep root growth, and increase crops yield. By loosening the soil structure, subsoiling might improve drought resistance by increasing the soil water holding capacity (Cai et al. 2014) and the plant-available water reservoir (Schneider et al. 2017).

However, some researches had also found that deep tillage could decrease nutrient availability and depress crop yield due to nutrient leaching by high infiltration rates (Schneider et al. 2017). Deep tillage could increase infiltration rates, reduce waterlogging and run-off, and increase water recharge (Baumhardt et

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Table 1. Means of soil properties in different layers

Soil layer	Treatment	Depth (cm)	pH	BD (g/cm^3)	FC (cm^3/cm^3)	WP (cm^3/cm^3)	SOC (g/kg)	AN (mg/kg)	AP (mg/kg)	AK (mg/kg)
Topsoil	RT	0–12	8.2^b	1.29^b	0.34^b	0.13^b	7.0^a	3.3^c	12.6^a	101.2^a
	ST	0–35	8.1^b	1.25^b	0.33^b	0.12^b	6.5^a	2.8^c	11.6^a	93.2^a
Plough pan	RT	12–28	8.3^b	1.60^a	0.39^a	0.15^a	5.9^a	6.2^b	12.9^a	98.9^a
	ST	35–50	8.3^b	1.56^a	0.36^a	0.14^a	6.4^a	5.5^b	9.2^a	100.3^a
Eluvial soil	RT	28–75	8.7^a	1.37^b	0.32^b	0.12^b	5.0^a	11.2^a	2.7^b	81.7^b
	ST	50–110	8.5^a	1.38^b	0.33^b	0.13^b	5.3^a	7.7^b	3.1^b	88.3^b
Subsoil	RT	75–120	8.0^b	1.43^b	0.34^b	0.12^b	4.1^a	15.9^a	1.9^b	81.4^b
	ST	110–120	8.1^b	1.41^b	0.32^b	0.11^b	4.2^a	13.9^a	2.0^b	87.5^b

pH (1:2.5 soil/water, w:w); BD – bulk density; SOC – soil organic carbon, measured by the potassium dichromate titrimetric method; FC/WP – filed capacity/wilting point, determined by soil water retention curve, at –0.01 MPa and –1.5 MPa, respectively; AN – available N, determined by alkaline hydrolysis diffusion method; AP – available P, determined by Olsen method; AK – available K, measured by flame-photometer method. Means followed by the same letter within a column are not significantly different at the 0.05 probability level according to the *LSD* (least significant difference) test. The same as below

al. 2008). As a result, the increased infiltration rates, especially preferential-water flow in macropores, might lead to nutrients leaching (Jarvis 2007).

Schneider et al. (2017) found that the opposite conclusions resulted from the difference in soil types and climates; therefore, the influences of subsoiling on crop yields differed in different regions. In the South Chinese Loess Plateau, irrigation or heavy rainfall always occurs due to the semi-humid climate. It is necessary to find out the influences of subsoiling on winter wheat in loessal soil. Therefore, the first objective is to compare the effects of rotary tillage and subsoiling on winter wheat growth. The second objective is to determine whether nitrogen use efficiency increased or not.

MATERIAL AND METHODS

Experimental site. Field experiments on winter wheat were carried out in 2016 and 2017 in the town Zhangqiao, Fuping county, Shannxi province, China (34°46'N, 107°22'E; 430 m a.s.l.), located in South Loess Plateau. The region is characterized by a semi-humid climate with a mean annual precipitation of approximately 580 mm (Zheng et al. 2013). Based on the WRB (World Reference Base for Soil Resources), loessal soil is Calcici Cambisols. Generally, soil pH is higher than 8.0. Soil texture is loam or sand loam (Huang 1987). The arable loessal soil profile can be divided into four layers in sequential order, from the top of the soil with increasing depth: topsoil, plough pan, eluvial soil, and subsoil. Soil properties are shown in Table 1.

Precipitation. Cumulative precipitation from stem elongation (1 March) to ripening (10 June) was 101.6 mm in 2016 and 173.3 mm in 2017 (Figure 1). Additionally, there was a long absence of precipitation from the mid-booting to anthesis stage in 2016, in

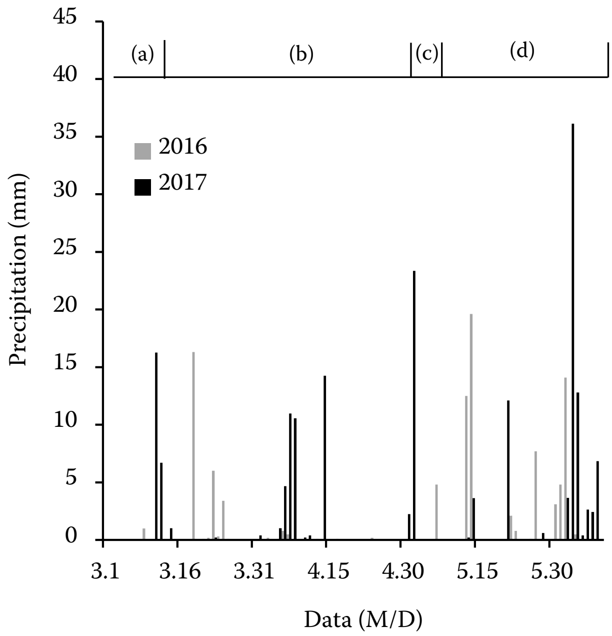

Figure 1. Precipitation after spring reviving in 2016 and 2017. (a) Stem elongation; (b) booting and inflorescence emergence; (c) anthesis, and (d) milk development, dough development, and ripening

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the critical period of water demand, which adversely affected winter wheat growth.

Experimental design. The experiment consisted of two tillage methods, rotary tillage (RT) and subsoiling, a kind of deep tillage, followed by rotary tillage (ST). Two fertilization rates, 225 and 0 kg/ha nitrogen, were labeled as RT225, ST225, ST0 and RT0, each replicated 3 times. The ST0 and RT0 were designed for nitrogen use efficiency calculations to reduce the influence by tillage methods, which were given the same amounts of P and K, but no nitrogen fertilizers. The 12 plots were arranged in a randomized block design. The plot for each replication measured 20 m × 12 m.

The RT was tilled to a depth of 10–15 cm with a rotocultivator before sowing both in 2015 and 2016. The ST was tilled to a depth of 35 cm with a vibrating deep loosening shovel with 35 cm space only in 2015 and was rotated in 2016. According to the local experiences, the RT225 and ST225 were given a basal dose of compound fertilizer (N:P:K = 20:20:5) 750 kg/ha just before rotation, and followed by a topdressing of urea 163 kg/ha when the crop irrigated at reviving stage in the spring and the total N application was 225 kg/ha in the growing season.

Winter wheat (cv. Xiaoyan No. 22) was sown at the rate of 150 kg/ha in 20 cm wide rows. Winter wheat was irrigated 2 times, in winter (10 January 2016 and 13 January 2017) and after reviving in spring (1 March 2016 and 4 March 2017). A single amount of about 90 mm of irrigation was applied by sprinkler irrigation.

Measurement. Three sampling points were randomly selected in each plot of the four treatments (ST225, RT225, ST0, and RT0), and soil of depths (0–10, 10–20, 20–30, 30–40, 40–60, 60–80 and 80–100 cm) were collected using soil drilling (depth, 100 cm; internal diameter, 4.4 cm). Soil samples were taken before cultivation treatment, reviving, jointing, grain-filling, and maturity stage of the winter wheat in 2016 and 2017. Each treatment at each different soil depth was replicated 3 times. Gravimetric soil water content (SWC) was measured by oven-drying method. Volume SWC was the product of bulk density and gravimetric SWC. Each sample was mixed and divided into two parts. One part was frozen and transferred to the lab to determine NO_3^--N by indophenol blue colorimetry and dual-wavelength ultraviolet spectrophotometric method (Norman et al. 1985). The other part was air-dried and available nitrogen, available phosphorus, and available potassium were measured (Table 1). At the flowering stage, root length density data were obtained from soil cores (depth, 100 cm; diameter, 10 cm and height, 10 cm). Root samples were taken both within and between crop rows in each plot. Roots collected from each soil layer were scanned and analyzed using WinRHIZO root analyzer system (Regent, Quebec, Canada).

In each plot, after reviving, plant density was counted every 7 days. At the maturity stage, grain yield was achieved by harvesting all winter wheat in each plot. Ear length, grain per spike, spike per ha, and 1000-grain weight were measured. Twenty whole plants were sampled and divided into four parts (leaf, stem + sheath, glume + spike, and grain). These plant samples and soil samples (before and after treatments) were prepared for total nitrogen determination using Kjeldahl method.

Calculations. The following parameters were derived according to the previous study (Raun and Jackson 1999):

Grain yield at a given N rate represents the sum of the yield without N inputs (Y_0) plus the incremental increase in grain yield (ΔY) that results from N application. And, ΔN_p is the increase in plant N accumulation that results from N application (N_a).

The recovery efficiency of nitrogen use efficiency (NUE, %) can be expressed as:

$$NUE = \Delta N_p/N_a \times 100$$

ΔN_p in RT225 or ST225 is equal to N accumulation in RT225 or ST225 minus N accumulation in RT0 or ST0, respectively.

Agronomic efficiency (AE, kg/kg): $AE = \Delta Y/N_a$

Physiological efficiency (PE, kg/kg) means that the plant utilizes the N acquired from applied inputs to produce more grain:

$$PE = \Delta Y/\Delta N_p$$

Statistical analysis. The data for this study were analyzed using SPSS 16.0 (SPSS, Inc., Chicago, USA) and *LSD* (least significant difference) test was used to detect significant differences at the 5% level.

RESULTS AND DISCUSSION

Soil water profile distribution. At the reviving stage, SWC was higher in the ST225, especially in the deep (Figure 2b). More water was in storage because of the subsoiling tillage. Additionally, the lowest SWC was found in the ST225 at the harvest (Figure 2b), which resulted from the promoted water absorption in the deep (> 50 cm).

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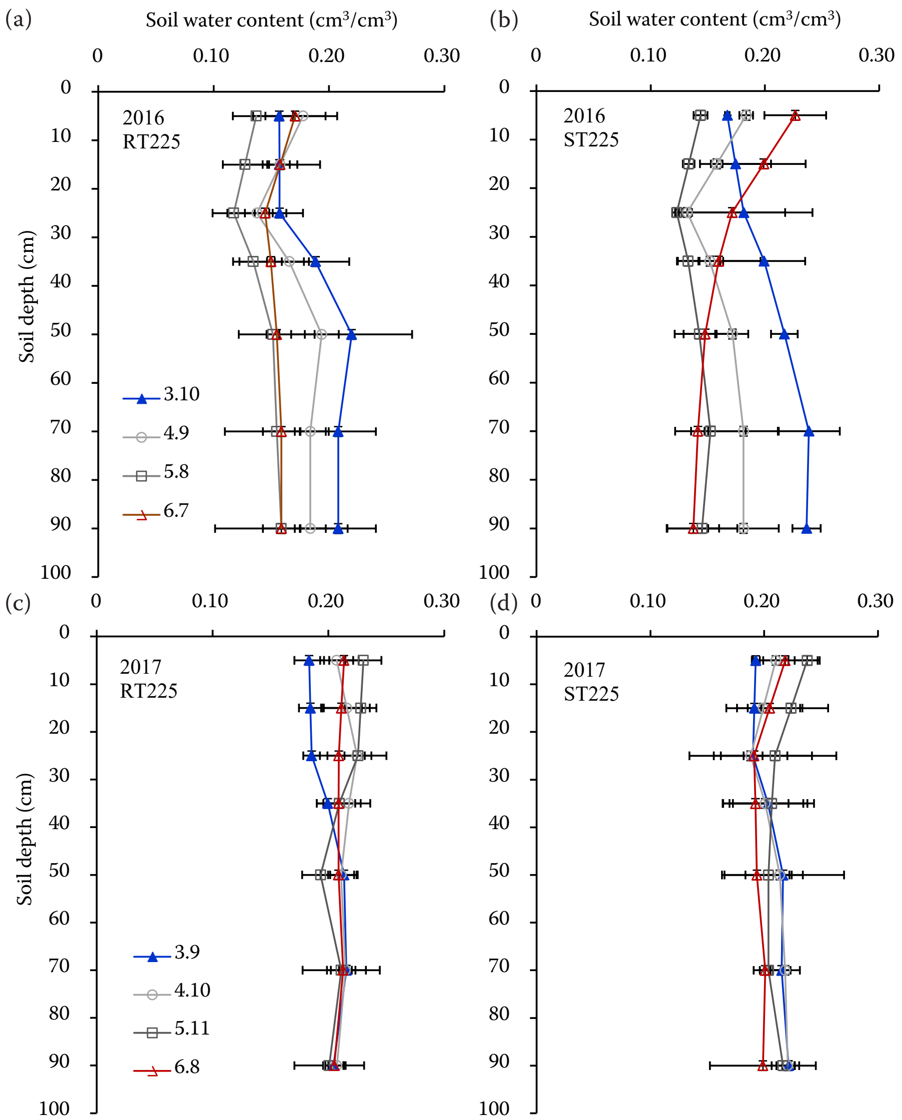

Figure 2. Soil water profile distribution in 2016 and 2017 (Date: M/D)

As depicted in Figure 2c,d, it was more obvious that soil water absorption in the deep was limited because of the large amount of precipitation in 2017. In the ST225, water absorption in the deep was smaller than that in 2016.

In the RT225 in 2016, SWC at 50 cm and 70 cm depth at 8 May were lower than those at 6 June (Figure 2a). It meant that some water leached to these depths caused by large rainfall (Figure 1), which might result in the nitrate-nitrogen deeply distribution.

Breaking the shallow plough pan helped maximize water use in the subsoil, and it was helpful to improve the resilience to drought stress caused by longtime rainfall absence, especially in 2016. Additionally, water leaching deeper was prevented because of the lower SWC in the deep. Subsoiling did not only help to promote water adsorption in the deep, but also to prevent water from leaching.

Tiller density. The effective tillers had a notable influence on grain yield. As depicted in Figure 3a, tiller density decreased from 31 March to 20 May 2016 but increased up to 28 March, the decreasing up to 20 May 2017 (Figure 3b). Tiller density was significantly higher in 2017 than in 2016. The long absence of precipitation in 2016 resulted in the death of more tillers in jointing and grain-filling stages. Tiller density was significantly higher in the ST225 in both 2016 and 2017 ($P < 0.05$), and therefore the ST225 showed increased drought resistance.

Root profile distribution. Subsoiling aims to loosen the soil structure by destroying hard soil pans (Baumhardt et al. 2008). This may also improve root

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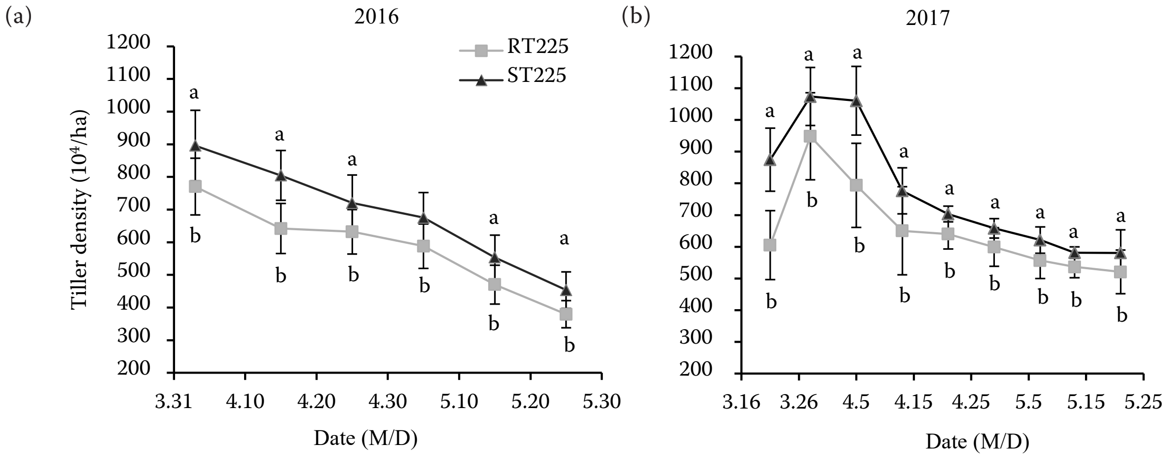

Figure 3. Tiller density in 2016 and 2017 winter wheat season

penetration as plough pan acted as root-restricting barrier to vertical root growth (Gao et al. 2016). As a result, the root profile distribution changed. As depicted in Figure 4a, root length density in the ST225 was about 1.4–2.2 times greater than that in the RT225 throughout the profile. The root length density in the ST225 was about 1.2–5.4 times greater than that in the RT225 in 2017 (Figure 4b). In the deep, it was only 0.08 cm/cm^3 in 90–100 cm depth in the RT225, but 0.41 cm/cm^3 in the ST225.

Subsoiling helped to produce more roots in the deep layer (Sun et al. 2017), which may serve to facilitate access to additional water and nutrients in the subsoil thereby improving crop performance. As result, subsoiling tillage had the high potential to increase the grain yield and improve the resilience to adverse climate conditions.

Nitrate nitrogen profile distribution. Generally, plough pan could decrease water infiltration and reduce soil aeration (Ishaq et al. 2001), which will directly influence the transformation and migration of soil nitrogen. Subsoiling destroyed or deepened plough pan, which might lead to nutrient leaching by high infiltration rates (Schneider et al. 2017). However, at maturity stage, NO_3^--N content in the ST225 was lower than that in the RT225 (Figure 5). The phenomena might due to higher adsorption throughout the profile, especially in the subsoil, which resulted from the higher root length density (Figure 4) caused by plough pan destruction by subsoiling. Conversely, the amount of NO_3^--N in the RT225 increased in the deep, which was mainly due to the low plant adsorption in the subsoil and NO_3^--N deep leaching.

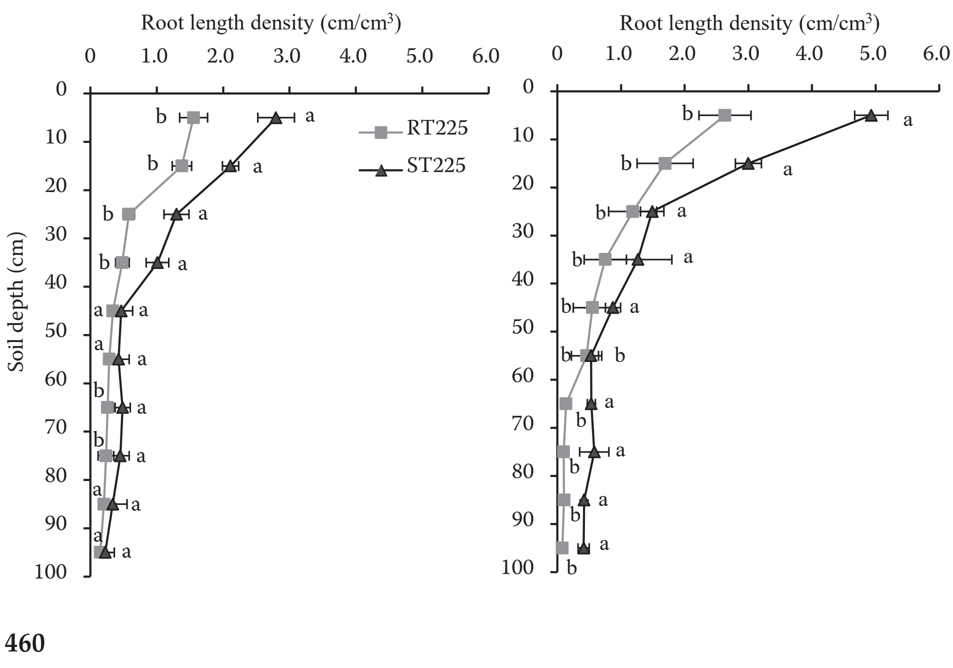

Figure 4. Root profile distribution at the flowering stage in 2016 and 2017

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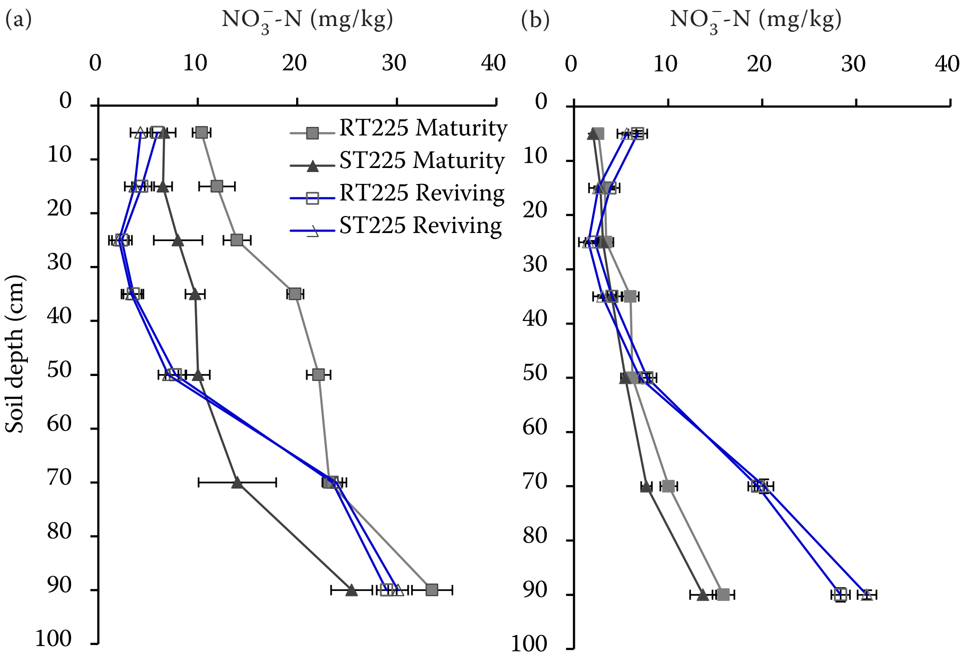

Figure 5. NO_3^--N profile distribution in (a) 2016 and (b) 2017

There was significantly higher NO_3^--N content throughout the soil profile at the maturity in 2016 compared with 2017. This was because of deficient precipitation during the critical water demand period in 2016, which decreased the N absorption because of the lower tiller density, root length density, and grain yield. Therefore, with the same amount of N application, more residue soil NO_3^--N in adverse climate year as 2016 was found.

Grain yield and nitrogen use efficiency. Table 2 showed the grain yield components. Grain per spike and spike per hectare both appeared significant difference ($P < 0.05$) by subsoiling, increased by 5.8% and 7.6%, 14.2% and 10.3% in 2016 and 2017, respectively. As a result, grain yield in the ST225 was significantly increased by 21.9% and 11.3% in 2016 and 2017, respectively. Compared with 2016, grain yield increased by 51.1% and 27.5% in 2017 in the RT and ST, respectively. Grain yield in the ST showed the stable and significantly higher grain yield.

Nitrogen use efficiency was demonstrated as NUE, AE, and PE. Both in 2016 and 2017, significantly higher values for the NUE and AE were found in the ST225 compared with the RT225 (Table 3). NUE in the ST225 was increased by 26.7% in 2016, and 13.8% in 2017, respectively. These results were consistent with the grain yield (Table 2) and nitrate nitrogen profile distribution (Figure 5). Therefore, subsoiling helped increase NUE and grain yield (Liang et al. 2019). Subsoiling, breaking the plough pan, showed the great value to be popularized in this area.

Table 2. Grain yield components in 2016 and 2017

Treatment	Ear length (cm)	Grains per spike	Spike ($\times 10^4$/ha)	1000-grain weight (g)	Grain yield (kg/ha)
2016					
RT225	6.0^a	43.4^b	379.6^b	35.1^a	4750.1^b
ST225	6.3^a	45.9^a	433.5^a	36.7^a	5790.4^a
2017					
RT225	8.1^a	44.7^b	520.6^b	42.0^b	7176.7^b
ST225	8.8^a	48.1^a	580.4^a	45.0^a	7983.9^a

Table 3. Effects of different tillage practices on nitrogen use efficiency

Year	Treatment	NUE (%)	AE (kg/kg)	PE (kg/kg)
2016	RT225	35.9^b	10.1^b	28.1^a
	ST225	45.5^a	12.8^a	28.0^a
2017	RT225	39.8^b	12.7^b	31.8^a
	ST225	45.3^a	14.0^a	31.0^a

NUE – nitrogen use efficiency; AE – agronomic efficiency; PE – physiological efficiency

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