

# OPTIMIZING THE SEEDING RATE IN SUBSOILING FOR DRYLAND WHEAT (*TRITICUM AESTIVUM* L.): A KEY TO IMPROVING WATER USE EFFICIENCY AND NITROGEN USE EFFICIENCY IN THE LOESS PLATEAU OF CHINA

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**Abstract.** The effects of seeding rate and tillage on water use and nitrogen use efficiencies were studied based on a field experiment carried out from 2012 to 2016. The results showed that subsoiling significantly increased the soil water storage before sowing in all years. The water consumption (ET) during the four years was, on average, 461 and 301 mm for subsoiling (SS) and CK, respectively. The average yield of SS was 4821 kg/ha, which was 944 kg/ha higher than that of CK. The average yield was highest at the mid-seeding rate for both SS and CK, with values of 5115 and 4394 kg/ha, respectively. Since the nitrogen fertilizer application rate was the same, a higher yield indicates a higher nitrogen use efficiency (NUE). Contribution analysis showed that the higher seeding rate led to a lower contribution of nitrogen uptake efficiency (UPE) and a higher contribution of NHIp to NUEp. In summary, subsoiling during summer fallow period increased the soil water retention and improved the wheat yield and WUE. It also increased nitrogen uptake and NUEp. The mid-seeding rate (approximately 90 kg/ha) under subsoiling is optimal for improving water use efficiency (WUE) and NUE in the Loess Plateau.

**Keywords:** *dryland farming, contribution analysis, water use efficiency, soil tillage, nitrogen fertilizer*

## Introduction

In dryland farming areas, water is a limiting factor for crop production. In most regions of the Loess Plateau, the groundwater is deep, and no irrigation water can be obtained; hence, the crops are rain-fed (Kang et al., 2002). Winter wheat (*Triticum aestivum* L.) is one of the main crops in this area. With a continental monsoon climate, the rainfall in the Loess Plateau is low and mainly falls in July, August, and September (Wang et al., 2011). However, this period occurs during the fallow period of winter wheat, which grows from early October to the following June. The rainfall during the wheat growth season is insufficient for optimal crop growth; approximately 30-40% of the required water comes from the soil water stored before sowing (Zhang et al., 2013).

A higher temperature in the fallow period makes it easier for the soil water to be lost by evaporation (Han et al., 2015). To conserve more water in the soil for wheat growth, the precipitation storage efficiency (PSE) should be increased during that period. In agronomy, there are two main types of practices to increase the PSE: reduce soil evaporation and increase soil infiltration (Nielsen and Vigil, 2010). To reduce evaporation, soil surface mulching techniques can be applied, among which plastic mulching and straw mulching are widely used (Zhang et al., 2013). Research shows that plastic film increases soil moisture in topsoil by 12.9% (Ma et al., 2018). Soil infiltration is related to soil physical properties. Tillage modifies the soil physical properties, such as the soil bulk density, which will further influence soil infiltration (Gómez et al., 1999). Subsoiling is a tillage practice that decreases the soil bulk density

and increases the amount of water infiltration. Previous studies have shown that subsoiling increases the water storage in drylands (Bhatt and Khera, 2006). In the Loess Plateau, soil water storage was increased by 76 mm in the 0-200 cm layer under subsoiling during the summer fallow period (Liao et al., 2002).

Nutrients represent another limiting factor in dryland farming. The nitrogen fertilizer use efficiency (NUE) is low in dryland farming areas (Zhu and Chen, 2002). Low soil moisture decreases nutrient availability and impacts the uptake of nutrients by crops; thus, the NUE in the dryland farming area is low (Guntiñas et al., 2012). The improved soil water conditions under subsoiling may improve the nutrient conditions in the field by making nutrients such as nitrogen more available for crops (Zhu et al., 2018), which providing crops with a better growth environment and increases productivity (Basso et al., 2010).

The seeding rate influences the wheat population, which further influences the use of soil water and nutrients and finally influences wheat growth and yield formation (Kühling et al., 2017). Wheat yield increases with the increase in seeding rate under the low sowing rate and peaks at a certain threshold value, after which it might not increase and may even cause a decrease in grain yield (Bhatta et al., 2017). Whether the optimum seeding rate changes due to the application of subsoiling still need to be addressed.

The process of nitrogen use by winter wheat can be simplified into two stages (Sadras and Lawson, 2013). In the first stage, plants uptake N from the soil and store it in leaves and stems. In this process, the N availability impacts its uptake. In winter, wheat N uptake represents 75 to 90% of the total N in the plant at harvest (Delogu et al., 1998). In the second stage, N is translocated to grains during grain filling. Many previous studies have focused on the uptake and translocation of nitrogen. However, few studies have focused on how nitrogen absorption and transportation respond to subsoiling and seeding rates. To clarify this issue, a field experiment on subsoiling in the fallow period and different wheat seeding rates was carried out from 2012 to 2016 in the Loess Plateau of China.

## Materials and methods

### *Site description*

The study was conducted at the experimental station of Shanxi Agricultural University in Wenxi County, Shanxi Province, China (35°20'N, 111°17'E, and elevation 639 m), from 2012 to 2016. The experimental site is a dryland area, with an average precipitation of 484 mm, 60-70% of which is concentrated during the fallow period of winter wheat. To improve the water use, all the experiment was carried out based on plastic film mulch. The basic nutrient properties of the soil in the experimental field in 2012 are shown in *Table 1*.

### *Crop management*

After harvesting the previous wheat, wheat stubble with a height of 20-30 cm was left in the field until mid-July. Subsoiling was performed during the fallow period by a subsoiler (IS-200, Xiuyuan Agricultural Machinery Co.) to a depth of 30-40 cm in mid-July, followed by rotary tillage to crumble large soil lumps and to level the field around 20 August. The winter wheat variety used in this study was 'Yunhan20410', which was

the recommended variety by the local agricultural extension department due to its drought stress resistance ability. The suggested sowing rate of Yunhan20410 is 90 kg/ha, if the sowing date is delayed due to climate condition, the sowing rate may be increased to 105 kg/ha. During the four experimental years, wheat was sown in late September or early October and harvested around 20 June. Before sowing, chemical fertilizer was applied at a rate of 150 kg ha<sup>-1</sup> nitrogen, 150 kg ha<sup>-1</sup> P<sub>2</sub>O<sub>5</sub> and 150 kg ha<sup>-1</sup> K<sub>2</sub>O. Since no irrigation was applied during the experiment, no fertilizer was applied during the entire growth period. Weeds and pests were controlled by herbicides as needed.

**Table 1.** Main soil chemical properties before sowing in 2012

Soil nutrients	Content
Organic matter (g kg <sup>-1</sup> )	11.88
Total nitrogen (g kg <sup>-1</sup> )	0.61
Alkali-hydrolysis nitrogen (mg kg <sup>-1</sup> )	38.62
Available phosphorous (mg kg <sup>-1</sup> )	14.61
Available potassium (mg kg <sup>-1</sup> )	238.16
pH	8.08

### Experimental design

The experiment was conducted with a two-factor split plot design, taking the tillage practice as a main factor and the planting density as a sub-plot factor. The two tillage practices were the subsoiling (SS) and the no tillage (NT) condition, which was the control. Under each tillage method, three planting densities, low (L, 60-75 kg seed ha<sup>-1</sup>, < 190 × 10<sup>6</sup> plants ha<sup>-1</sup>), mid (M, 90-105 kg seed ha<sup>-1</sup>, 190-260 × 10<sup>6</sup> plants ha<sup>-1</sup>), and high (H, 112.5-120 kg seed ha<sup>-1</sup>, > 320 × 10<sup>6</sup> plants ha<sup>-1</sup>) were used in the experiment. Seeds were sown at rates of 67.5, 90 and 112.5 kg ha<sup>-1</sup>, after which a 3-leaf stage planting density of 190, 260 and 320 plants m<sup>-2</sup> was attained by thinning. Each treatment was repeated three times with a total of 18 plots. Each sub-plot (150 m<sup>2</sup>) was 50 m long and 3 m wide with a line spacing of 30 cm.

### Measurements

#### Soil water storage

The soil was sampled every 20 cm to a depth of 300 cm and soil water content was determined gravimetrically before planting and after harvest. The precipitation data were obtained from the meteorological station at the experimental site (Table 2).

**Table 2.** Precipitation and mean temperature in fallow period and in growth stage during the experiment (mm)

	Stage	2012-2013	2013-2014	2014-2015	2015-2016
Precipitation (mm)	Fallow period	188	288	284	95
	Growth stage	167	202	190	292
Temperature (°C)	Fallow period	24.9	26.7	24.8	24.7
	Growth stage	10.4	10.7	10.5	10.0

As the plots were on a flat experimental field with ridges around them, the plots were not influenced by surface runoff. Moreover, the influence of groundwater can be ignored because the groundwater level is low in this region. The evapotranspiration (ET) and water use efficiency (WUE) were obtained through *Equations 1* and *2* (Li et al., 2013):

$$ET = P + \Delta W \quad (\text{Eq.1})$$

$$WUE = \frac{Y}{ET} \quad (\text{Eq.2})$$

where  $\Delta W$  is the soil water depletion during the wheat growing stage, and  $Y$  is the grain yield.

### *Nitrogen content*

Plant nitrogen content was determined using the semi-micro Kjeldahl method, and wheat protein content was obtained by multiplying the N content (%) by 5.7 (Halvorson et al., 2004).

### *Grain yield*

At maturity, plants from three 1 m<sup>2</sup> size sample plots were harvested from each plot to determine the grain yield (kg ha<sup>-1</sup>).

### *Contribution analysis*

In this research, because soil available nitrogen was not measured, we focused on the use efficiency of nitrogen from fertilizer and then the NUE, which is defined as the ratio of the grain yield ( $Y$ ) and nitrogen fertilizer application rate ( $N_f$ ) (Moll et al., 1982). The nitrogen fertilizer use efficiency for protein (NUE<sub>p</sub>) is defined as the ratio of the grain nitrogen ( $N_g$ ) and nitrogen fertilizer application rate. The NUE can be partitioned into the components of UTE (the ability of the plant to convert the absorbed N into harvested grain yield,  $Y/N_t$ ) and UPE (nitrogen uptake efficiency,  $N_t/N_f$ ). NUE<sub>p</sub> can be separated into the components of UPE and NHI (nitrogen harvest index,  $N_g/N_t$ ) (Van Sanford and Mackown, 1986). *Equations 3* and *4* express the relationship between these indexes.

$$NUE = UPE \times UTE \quad (\text{Eq.3})$$

$$NUE_p = UTE \times NHI \quad (\text{Eq.4})$$

To analyse the contribution of the components to NUE, we calculated the natural log of the three components using *Equation 5*:

$$\ln NUE = \ln UPE + \ln UTE \quad (\text{Eq.5})$$

Then, both individual components of NUE can be regressed with respect to NUE:  $\ln UPE = a_1 + b_1 \ln NUE$ ;  $\ln UTE = a_2 + b_2 \ln NUE$ ; ( $b_1 + b_2$ ) must be = 1 and thus

explains the complementary contribution of each component to NUE (Giuliani et al., 2011). Similarly, the contribution of each component to NUE<sub>p</sub> can be calculated by this means.

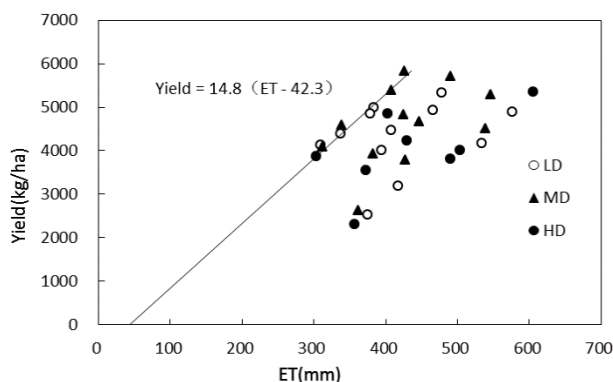
### Statistical analysis

An analysis of variance was conducted on the experimental data using SAS 9.3 (SAS Institute Inc., Cary, NC, USA) to study the main effects of mulching methods and their interactions. The least significant difference (LSD) test was performed to calculate the significance of differences between means at  $P < 0.05$ .

## Results

### Yield and water use

Based on the boundary function concept proposed by French and Scultz (1984) and the improved boundary function establishment method developed by Lin and Liu (2016), we obtained the winter wheat boundary function of yield-ET in the Loess Plateau (Fig. 1). The upper boundary of the yield-ET relationship can be fitted using the function  $\text{Yield} = 14.8 (\text{ET} - 42.3)$ , which means that under plastic film mulch in this area, the maximum transpiration efficiency is  $14.8 \text{ kg ha}^{-1} \text{ mm}^{-1}$ .



**Figure 1.** Yield and ET relationship under different seeding rates. The boundary line was generated according to (Lin and Liu, 2016) and shows the maximum yield under different ET

The results show that compared with CK, SS increased the soil water storage by an average of 58 mm during the 4 years ( $p < 0.001$ ). The average yield under SS was 4821 kg/ha, which was 950 kg higher than the 3877 kg/ha of CK ( $p < 0.001$ ). Higher soil water storage provided more water for crop use during the growth period; hence, the ET for SS was significantly higher than that of CK. The WUEs for SS and CK were 10.6 and 10.2 kg ha mm, respectively, without a significant difference. The WUE<sub>p</sub> for SS was significantly higher than that of CK (Table 3).

To evaluate the seeding rate impact on the yield and water use of winter wheat, we calculated the data based on the seeding rate (Table 4). The results showed that the wheat yields were 4324, 4787 and 3998 kg/ha for the low-, mid- and high-seeding rate treatments, respectively ( $p < 0.05$ ). No significant difference was observed for ET among different seeding rates. The difference in WUE and WUE<sub>p</sub> under different

seeding rates was much the same as that of yield, i.e., highest at the mid-seeding rate, second in the low-seeding rate and lowest in the high-seeding rate.

**Table 3.** Yield, water consumption and WUE under different tillage measures

Tillage	Yield (kg/ha)	Soil water storage before sowing (mm)	ET (mm)	WUE (kg ha <sup>-1</sup> mm <sup>-1</sup> )	WUE <sub>P</sub> (kg ha <sup>-1</sup> mm <sup>-1</sup> )
SS	4821	526	461	10.6	11.3
CK	3877	468	391	10.2	9.1
Prob	0.041**	0.045**	0.045**	0.064	0.041**

\*\*Significant difference between SS and CK based on t test at the  $p < 0.05$  significance level; ns: no significant difference was observed

**Table 4.** Yield, water consumption and WUE under different seeding rates. L, M, and H represent low-, mid- and high-seeding rates, respectively. Values followed by different letters within the same row are significantly different ( $P < 0.05$ )

Seeding rate	Yield (kg/ha)	ET (mm)	WUE (kg ha <sup>-1</sup> mm <sup>-1</sup> )	WUE <sub>P</sub> (kg ha <sup>-1</sup> mm <sup>-1</sup> )
L	4324 b	421 a	10.5 b	10.1 b
M	4787 a	431 a	11.3 a	11.1 a
H	3998 c	433 a	9.4 c	9.4 c
LSD <sub>0.05</sub>	301	12.5	0.7	0.7

### Nitrogen uptake and translocation

Under subsoiling, the NUE was 31.31, 34.10 and 30.43 kg/ha for the low-, mid- and high-seeding rates (Table 5). Under CK, the NUE decreased to 25.32, 26.51 and 21.91 kg/kg, respectively. The UTE for SS was significantly higher than that of CK under all seeding rates. However, the situation among different seeding rates was not the same for the NUE. The NUEs were highest under the mid-seeding rate. The UTE was highest at a low-seeding rate under SS and highest at a high-seeding rate under CK. The UPE is a component of both NUE and NUE<sub>P</sub>, and it was highest at the mid-seeding rate, with values of 1.06 and 1.01 in SS and CK, respectively (Table 5). However, for CK, there was no significant difference among seeding rates. The NUE<sub>P</sub> tended to be lower under CK than under SS. Under the same tillage method, the mid-seeding rate showed the highest NUE<sub>P</sub>. The average NHI was approximately 0.82, and no significant difference was observed between treatments.

### Contributions of NUE and NUE<sub>P</sub>

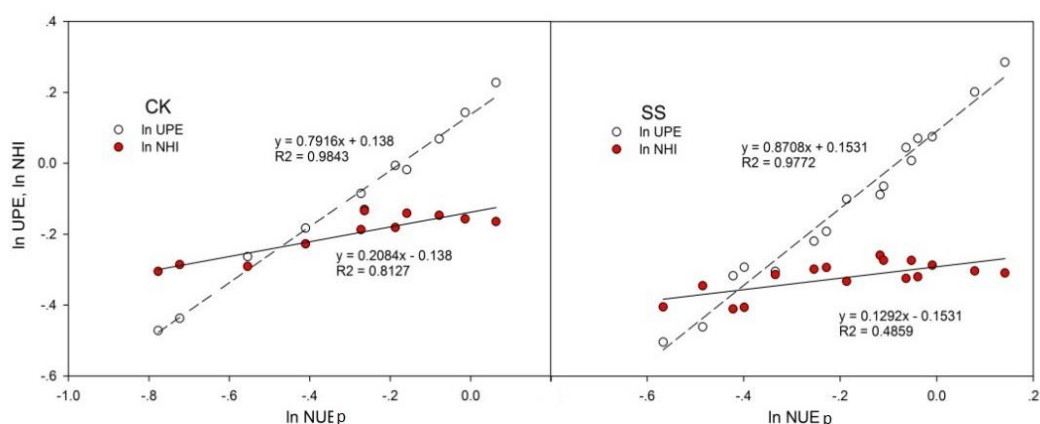
Figure 2 shows the calculation process for NUE<sub>P</sub> under SS and CK. The slope of the regression function is the contribution of each component to NUE<sub>P</sub>. The contribution of NHI to NUE<sub>P</sub> was 20.84%, and under CK, it decreased to 12.92%. The contribution of UPE to NUE<sub>P</sub> was 79.16%, and under CK, it increased to 87.08%. Hence, SS led to a higher contribution of UPE and a lower contribution to NHI.

The contribution of UPE to NUE<sub>P</sub> was 84.96%, 81.12% and 76.59% for the high-, mid- and low-seeding rates, respectively (Table 6). The contribution of UPE to NUE was 67.05%, 48.95% and 36.06% for the high-, mid- and low-seeding rates,

respectively (Table 7). The contribution of NHI to NUEp was 15.04%, 17.87% and 23.41% for the high-, mid- and low-seeding rates, respectively. The contribution of UTE to NUE increased as the seeding rate increased, ranking 32.95%, 51.05%, 63.94% for the high-, mid- and low-seeding rates, respectively.

**Table 5.** N use efficiency and its components.  $NUE = Y/N_f$ ,  $NUE_p = N_g/N_f$ ,  $UPE = N_t/N_f$ ,  $UTE = Y/N_t$ ,  $NHI = N_g/N_t$ . L, M, and H represent low-, mid- and high-seeding rates, respectively. Values followed by different letters within the same row are significantly different ( $P < 0.05$ ). \*\*Significance at  $p < 0.05$

Tillage	Seeding rate	NUE (kg/kg)	UTE (kg/kg)	UPE (kg/kg)	NUEp (kg/kg)	NHI (kg/kg)
SS	Low	31.31 b	33.50 a	0.96 b	0.80 b	0.83 a
	Mid	34.10 a	32.47 b	1.06 a	0.90 a	0.84 a
	High	30.43 c	31.09 c	0.98 b	0.82 b	0.84 a
CK	Low	25.32 e	26.82 e	0.95 b	0.79 b	0.82 ab
	Mid	26.51 d	26.36 e	1.00 b	0.83 b	0.82 ab
	High	21.91 f	27.88 d	0.78 c	0.63 c	0.80 b
ANOVA SS						
Tillage ( $F_T$ )		296.4**	275.6**	0.18**	0.12**	0.03
Seeding rate ( $F_S$ )		75.7**	87.5**	0.15**	0.10**	0.02
$F_T \times F_S$		26.8**	32.3**	0.03	0.05	0.02



**Figure 2.** Linear regression of nitrogen uptake efficiency (UPE) and nitrogen utilization for protein (NHIp) components on total nitrogen use efficiency for protein (NUEp) in CK and SS

**Table 6.** NUEp and its components under different seeding rates. L, M, and H represent low-, mid- and high-seeding rates, respectively. Values followed by different letters within the same row are significantly different ( $P < 0.05$ )

D	NUEp (kg/kg)	UPE	Contribution	NHI	Contribution
L	0.80 b	0.95 b	84.96%	0.83 a	15.04%
M	0.87 a	1.04 a	81.12%	0.84 a	17.87%
H	0.74 c	0.89 c	76.59%	0.82 a	23.41%
LSD <sub>0.05</sub>	0.59	0.05	-	0.03	-

**Table 7.** NUE and its components. L, M, and H represent the low-, mid- and high-seeding rates, respectively. Values followed by different letters within the same row are significantly different ( $P < 0.05$ )

D	NUE (kg/kg)	UPE	Contribution	UTE	Contribution
L	28.92 b	0.95 b	67.05%	30.83 a	32.95%
M	31.06 a	1.04 a	48.95%	30.02 b	51.05%
H	26.78 c	0.89 c	36.06%	29.72 b	63.94%
LSD <sub>0.05</sub>	1.58	0.05	-	0.55	-

## Discussion

### *Seeding rate and wheat water yield potential*

The boundary analysis results show that most of the dots close to the boundary line were the mid-seeding rate treatment and low-seeding rate treatment (*Fig. 1*). This result means that a high seeding rate is not appropriate for making full use of water resources in this region. The intercept of the boundary line represents the minimum soil evaporation in this area (Sadras and Angus, 2006). In this research, the intercept is 42.3 mm, which was lower than the value of 60 mm reported by Zhang (2013). The main reason is that plastic film was used in this research, and plastic is effective in reducing soil evaporation (Li et al., 2005).

### *Subsoiling influence on wheat yield and WUE*

In SS, the ET and yield increased significantly, but no significant difference was observed in the WUE (*Table 3*). However, this does not mean that SS had no impact on water resource use in dryland wheat. SS increased precipitation infiltration into the soil in the summer period; hence, more water was stored in the soil before sowing (Williams et al., 2006), which means that more water was available for crop growth and soil evaporation. Hence, the ET was increased (Lin et al., 2016). Because ET and yield were increased in a similar ratio under SS in this research, the WUE remained the same. However, in dryland farming, a high WUE should be considered, but it makes no sense if the high WUE is based on a low yield and low ET. The effective use of water should be the goal to improve the crop yield in dryland areas (Blum, 2009). In the Loess Plateau, without irrigation and groundwater supplementation, soil water is supplied by precipitation; hence, precipitation is the only source of water for crop growth (Lin et al., 2019). However, more water was used under SS because more water was within reach for the crop. We further calculated the WUE of precipitation (WUE<sub>p</sub>) in a hydrological year (fallow period + growth period) and found that the WUE<sub>p</sub> under SS increased significantly (*Table 3*). SS significantly used the limited precipitation available in the dryland farming area.

Fang (2010) found that ET increased as the seeding rate increased. In this study, although ET showed an increasing trend as the seeding rate increased, no significant difference was found in the ET values among the different seeding rate treatments. This difference may be due to differences in the environment at the experimental sites. Compared with Fang's research, precipitation was lower in this research. Under a high-seeding rate, the large population calls for more water for transpiration use, but the shading effect of higher shoot coverage may reduce the soil evaporation; under a low-seeding rate, less water is used by transpiration, but more soil is exposed to the air



directly, and hence more water is evaporated (Li et al., 2013). Iqbal et al. (2012) found that the mid-seeding rate helped obtain a high yield. In this research, we found a similar result. The wheat yield was highest in the mid-seeding rate treatment and lowest in the high-seeding rate treatment. Thus, a suitable seeding rate is important for achieving a high yield. This may be the reason why similar ET values were found among the different seeding rates in this study.

### ***N uptake and utilization***

SS increased the soil water content and improved the soil air condition, which increased the availability of nutrients and eased the uptake of nutrients by roots (Zhu et al., 2018); hence, UPE was higher in SS than in CK (*Table 1*). The higher UPE further led to a higher NUEp for SS, although there was no significant difference in the NHI among treatments. Contribution analysis showed that the contribution to NUEp was  $CK < SS$  for UPE and  $CK > SS$  for NHI. Giuliani et al. (2011) found that the contribution of UPE to NUEp was lower in dry years than in wet years. In this research, SS improved the soil water condition before sowing, which resembled a wetter condition compared with that in CK. A higher contribution of UPE means that the increased NUEp under SS was mainly due to the increased UPE.

NUE and NUEp were highest for the mid-seeding rate treatment. This result means that a moderate planting density helps make full use of nitrogen (Arduini et al., 2006). In agreement with several previous studies (Van Sanford and Mackown, 1986; Giuliani et al., 2011), the contribution of UPE to NUEp was higher than that of NHI under all seeding rates (*Table 6*). The contribution of UPE to NUEp decreased as the seeding rate increased, and the contribution of NHI increased as the seeding rate increased. For NUE, the contribution of UPE was higher than that of UTE at low-seeding rates, similar at mid-seeding rates and lower at high-seeding rates.

In this study, because the available soil N before seeding was not measured, nitrogen from fertilizer (Nf) was used instead of the nitrogen supply (Ns, expressed as Nf plus available soil nitrogen). This represents a limitation of this study. However, fertilizer N is an important N source for wheat growth; hence, the results still make sense for wheat production in dryland areas.

### **Conclusions**

In order to make full use of the limited water resources and improve nitrogen fertilizer use efficiency (NUE) in the dryland farming area, the effects of seeding rate and tillage on water use and nitrogen use were analyzed. We found that under plastic film mulch, soil evaporation is effectively reduced for the winter wheat in the Loess Plateau. Subsoiling during the summer fallow period increased soil water retention and improved wheat yield and WUEp. It also increased nitrogen uptake and NUEp. The mid-seeding rate (approximately 90 kg/ha) increased the wheat yield and WUE and increased the contribution of NHI to NUEp but decreased the contribution of UPE to NUEp, which led to the highest NUEp. The results of this study focused on the overall use of N fertilizer absorption and utilization, to make a full understanding about how seeding rate and subsoiling influence N utilization process, N concentration in plant and enzymatic activity related to N enzymatic activity should be measured in future study.

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