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Subsoiling and Sowing Time Influence Soil Water Content, Nitrogen Translocation and Yield of Dryland Winter Wheat

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Abstract: Dryland winter wheat in the Loess Plateau is facing a yield reduction due to a shortage of soil moisture and delayed sowing time. The field experiment was conducted at Loess Plateau in Shanxi, China from 2012 to 2015, to study the effect of subsoiling and conventional tillage and different sowing dates on the soil water storage, Nitrogen (N) accumulation, and remobilization and yield of winter wheat. The results showed that subsoiling significantly improved the soil water storage (0–300 cm soil depth) and increased the contribution of N translocation to grain N and grain yield (17–36%). Delaying sowing time had reduced the soil water storage at sowing and winter accumulated growing degree days by about 180 °C. The contribution of N translocation to grain yield was maximum in glume + spike followed by in leaves and minimum by stem + sheath. Moreover, there was a positive relationship between the N accumulation and translocation and the soil moisture in the 20–300 cm range. Subsoiling during the fallow period and the medium sowing date was beneficial for improving the soil water storage and increased the N translocation to grain, thereby increasing the yield of wheat, especially in a dry year.

Keywords: dryland wheat; subsoiling; sowing date; nitrogen accumulation; nitrogen translocation; yield

1. Introduction

Wheat is the dominant crop in the Loess Plateau, accounting for 35% of the total planting area [1,2]. Dryland wheat production in Loess Plateau is highly dependent on the timing and extent of rainfall, whereas most of the precipitation is mainly concentrated during the summer fallow period. Moreover, significant climatic changes have been observed in this area, such as average precipitation is decreasing by 3 mm and the average temperature is increasing by 0.6 °C per decade with the sudden incidence of drought [3,4]. These climatic changes are causing the unstable wheat production in dryland areas of Shanxi province due to extreme variation in precipitation and low water retention capacity of soil [5]. In the Loess Plateau, a short summer fallow of about three months is practiced after the harvest of the previous winter wheat in late June and planting of the succeeding crop in late September to conserve soil water. Available soil moisture at sowing time depends on the tillage method used during the fallow period [6–8]. Thus, improving soil water conservation is crucial to increase the yield of dryland wheat.

The sowing date also has a significant effect on the yield response of wheat [9,10]. Sowing time influences the accumulating temperature before winter, and affects the nutrient uptake and transportation of plants, and ultimately affects the yield [11]. Sowing date strongly influences the use of environmental resources and optimal sowing can make full use of resources such as pre-winter light, heat, nutrient, and water to develop strong seedlings and promote yield formation [12]. Under irrigation, the sowing time can be adjusted whereas in rain-fed dryland farming the sowing time might be delayed due to the scarcity of residual soil moisture under erratic rain condition [13]. Furthermore, the conventional tillage method also results in excessive soil disturbance and drying of surface soil. Therefore, saving the residual soil moisture from precipitation during the fallow season and the adjustment of the sowing date become key determining factors for yield determination of dryland winter wheat [6].

Yield formation of rain-fed winter wheat is effected to a different extent under early and late sowing [13]. Sun et al. [14] studied the impact of different sowing dates on yield in the North China Plain and found that the yield of wheat sown after October 10 was significantly reduced with the delay in sowing date. Zhou et al. [5] showed that late planting could increase the pre-anthesis accumulation of nitrogen in the vegetative organs and the contribution rate of nitrogen to the grain. In contrast, Qu et al. [15] showed that the pre-anthesis transport and translocation of nitrogen in the vegetative organs, and contribution rate of nitrogen to grain were decreased with the delay of sowing date and the grain yield was increased significantly under delayed sowing time and increasing density.

Subsoiling has previously proved a promising technique for increasing water storage, reducing water loss, enhancing water availability, and saving energy, as well as increasing wheat yield. Liu et al. [16] showed that subsoiling improved soil moisture content in the 0–160 cm soil layer before sowing than traditional tillage. Wang et al. [17] showed that during the fallow period, the subsoiling improved the soil water storage capacity of 0–180 cm by 9–24 mm before sowing. Wang et al. [18] showed that subsoiling can effectively accumulate precipitation during the fallow period, significantly increased soil water storage capacity from 0 to 200 cm before sowing, improving water use efficiency by 39%, and finally increasing yield.

In addition, different tillage methods could also affect the uptake and accumulation of nitrogen in plants by affecting soil moisture. Zheng et al. [19] have shown that subsoiling can increase the nitrogen accumulation of wheat after jointing and the translocation of nitrogen to grain during the maturity period, and obtain a high grain yield. Wang et al. [20] also reported that subsoiling can improve the efficiency of nitrogen utilization, and increased wheat yield by enhancing the distribution and translocation of nitrogen from vegetative organs to grain after flowering. The amount of nitrogen in the vegetative organs before flowering and its contribution to grain were found highest in leaves, followed by glume + cobs and the lowest was in stem + leaf sheaths. Furthermore, different tillage practices had increased the soil moisture, which increased the amount of nitrogen uptake than no-tillage and in turn increased the final yield [21].

It can be seen that tillage and sowing time can affect the translocation of plant nutrients thus affecting the yield. The need is to further explore how to adjust the sowing time to realize the increase of production under the premise of realizing the water storage. Therefore, the aim of the present research was to explore the effects of different sowing times on the changed source-sink ratio, accumulation and translocation of N and its contribution to yield of dryland wheat and condition of water storage in soil under subsoiling, in order to provide a theoretical basis for the realization of yield increase in dryland.

2. Materials and Methods

2.1. Site Characteristics and Description

The experiment was carried out from 2012 to 2015 at the dryland wheat experimental station of Shanxi Agricultural University, located at Wenxi (35°20′ N, 111°17′ E), Shanxi Province, China. Rain-fed agriculture is popular in this area due to unavailable irrigation conditions. Winter wheat is usually planted in early October and no irrigation was supplied. After the harvesting of wheat, the field was left fallow until the next sowing.

2.2. Meteorological Conditions

The experimental area is a hilly arid land with a semiarid climate typical of the Northeast Loess Plateau, where 60%–70% precipitation occurred in the summer months during the fallow season (July–September). Precipitation during the experimental years for 2012–2015 is shown in Table 1.

Table 1. Precipitation distribution of the experimental site from 2009–2015, during the fallow season and the growth stages of winter wheat (Source: Meteorological Observation of Wenxi County, Shanxi Province, China).

Precipitation (mm)	2012–2013	2013–2014	2014–2015
Fallow period	188.4	283.7	365.6
Sowing-wintering	32.8	43.7	21.5
Wintering-jointing	22.4	19.3	50.8
Jointing-anthesis	12.0	63.8	61.2
Anthesis-maturity	100.1	63.7	17.6
Total	355.7	474.2	516.7

Fallow period: from the last 10 days of June to the last 10 days of September; Sowing–wintering: from the first 10 days of October to the last 10 days of November; Wintering–Jointing: from the first 10 days of December to the first 10 days of April in the following year; Jointing–Anthesis: from the middle 10 days of April to the first 10 days of May; Anthesis–Maturity: the middle 10 days of May to the middle 10 days of June.

The average rainfall of the site from 2009 to 2014 was 487.6 mm. Therefore, the annual precipitation in 2012–2013 growth season was lower than usual and 188.4 mm rainfall was during the fellow period and 167.3 mm in the growth period. The total precipitation during 2013–2014 was close to the average annual precipitation, from which 283.7 mm rain occurred during the fallow period and 242 mm during the growth period.

The accumulated growing degree days (GDD) at wintering, jointing, booting, and maturity were calculated by using the following equation [22]:

$$\mathrm{GDD} = \sum_{i=1}^{n} [\left(\frac{Tmax + Tmin}{2}\right) - Tb] \quad (1)$$

where n is the number of days taken for the completion of a particular growth phase, $Tmax$ and $Tmin$ are the daily maximum and minimum air temperature respectively in °C, Tb is the minimum base temperature (threshold temperature) for a crop (°C) and for wheat, Tb = 4.0 °C

2.3. Field Trial Management and Experimental Design

The experiment consisted of two tillage methods, i.e., subsoiling (SS) and conventional tillage (CT), and three sowing dates, i.e., early (T_1), conventional (T_2), and late sowing (T_3) times. The experiment was arranged as a split-plot design in randomized complete block design (RCBD), taking tillage methods as main plots and sowing dates as sub-plot factors and each treatment was replicated three times. Former wheat stubble (20–30 cm) which was left in the field was shredded, followed by tillage in mid-July. Tillage practices were performed during the fallow season. Subsoiling (SS) was conducted with a subsoiling chisel plow at the depth of 30–40 cm on the 15th of July in 2012, 2013 and 2014. Local conventional tillage (CT) was taken as a control. Rotary tillage was used to crumble large lumps and level the fields on 25 August 2012 and 23 August 2013 and 2014. The area of each plot was 150 m^2 (50 m × 3 m).

The wheat variety 'Yunhan 20410' provided by the Agriculture Bureau Wenxi, was sown on three different dates: 20 September (T_1, early sowing), 1 October (T_2, conventional normal sowing), and 10 October (T_3, late sowing) in 2012, 2013 and 2014. Seeds were sown at a density of 2.25 × 10^6 seeds ha^{-1} in rows spaced 30 cm apart. Before planting, 150 kg N ha^{-1} (Urea, 46%), P_2O_5 (150 kg ha^{-1}) and K_2O (150 kg ha^{-1}) were broadcasted evenly on the surface of plots. No top fertilizer was applied during the growth period. Basic soil properties were determined from a 0–20 cm soil layer and soil was classified as silty clay loam. Soil properties recorded on 10 June 2012 were: organic matter 11.9 g kg^{-1}, available nitrogen 38.6 mg kg^{-1}, and available phosphorus 14.6 mg kg^{-1}, whereas soil properties recorded on 10 June 2013 were: organic matter 10.2 g kg^{-1}, available nitrogen 39.3 mg kg^{-1}, and available phosphorus 16.6 mg kg^{-1}.

2.4. Sampling and Measurements

2.4.1. Soil Moisture Content

Soil samples were collected from 0–300 cm soil depth with soil drilling after every 20 cm soil layer. The samples were weighed and dried at 105 °C until constant weight and soil moisture was measured at 30 (after harvest), 112 (pre-sowing), 185 (overwintering period), 301 (joining stage), 312 (booting stage), 327 (flowering stage) and 365 (maturity) days after the harvest of the former wheat. Soil water storage was calculated from the following formula:

$$\text{Soil water storage capacity (mm)} = [(\text{wet soil weight} - \text{dry soil weight})/\text{dry soil weight} \times 100\%] \times \text{soil thickness} \times \text{soil bulk density} \quad (2)$$

2.4.2. Total Nitrogen Content and Nitrogen Accumulation

Dry matter and total nitrogen content of plant were measured at overwintering, jointing, booting, flowering and maturity stages. Twenty whole plants were sampled from each plot and at the jointing and booting stages divided into two parts (stems and leaves sheath), at the flowering stage plants were divided into three parts (leaves, stems, and ears), and at the maturity stage were divided into four parts (leaves, stems + sheath, glumes + spikes, and grains). The samples were kept at 105 °C for 30 min and at 75 °C until constant weight, after which they were weighed, ground, and the total nitrogen content was determined by using the Kjeldahl method. The parameters, related to translocation, accumulation, and remobilization of nitrogen within the wheat plant were calculated by using the following equations:

$$\text{Pre-anthesis N translocation} = \text{N content in vegetative organ at anthesis} - \text{N content in vegetative organ at maturity} \quad (3)$$

$$\text{Contribution of pre-anthesis N to grain N (\%)} = (\text{pre-anthesis N translocation})/(\text{grain N content at maturity}) \times 100 \quad (4)$$

$$\text{Post-anthesis N accumulation} = \text{N content of the whole plant at maturity} - \text{N content of the whole plant at anthesis} \quad (5)$$

$$\text{Contribution of post-anthesis remobilized N to grain N (\%)} = (\text{post-anthesis remobilized N})/(\text{grain N content at maturity}) \times 100 \quad (6)$$

2.4.3. Yield and Yield Component

Plants from 20 m^2 were harvested from each plot and the grains were air-dried to determine plot yield at 12% moisture content and economic output was calculated.

2.5. Statistical Analysis

Data were analyzed using SAS 9.0 (SAS Corp., Cary, NC, USA) software to determine the statistical significance and the differences between the treatments were analyzed by LSD (least significant difference) test at $p < 0.05$, and graphs were constructed using Microsoft Excel 2003 and SigmaPlot 12.5 (Systat Software Inc., San Jose, CA, USA).

3. Results

3.1. Effects of Tillage Practices and Sowing Timing on Soil Water Storage

Soil water storage in 0–300 cm layer storage was more under the subsoiling practices as compared to conventional tillage (Figure 1). Under subsoiling, the soil water storage in the 0–300 cm soil layer increased by 35, 55 and 68 mm in 2012–2013 and 40, 35 and 52 mm in 2013–2014 at T_1, T_2 and T_3 sowing dates respectively, as compared to conventional tillage.

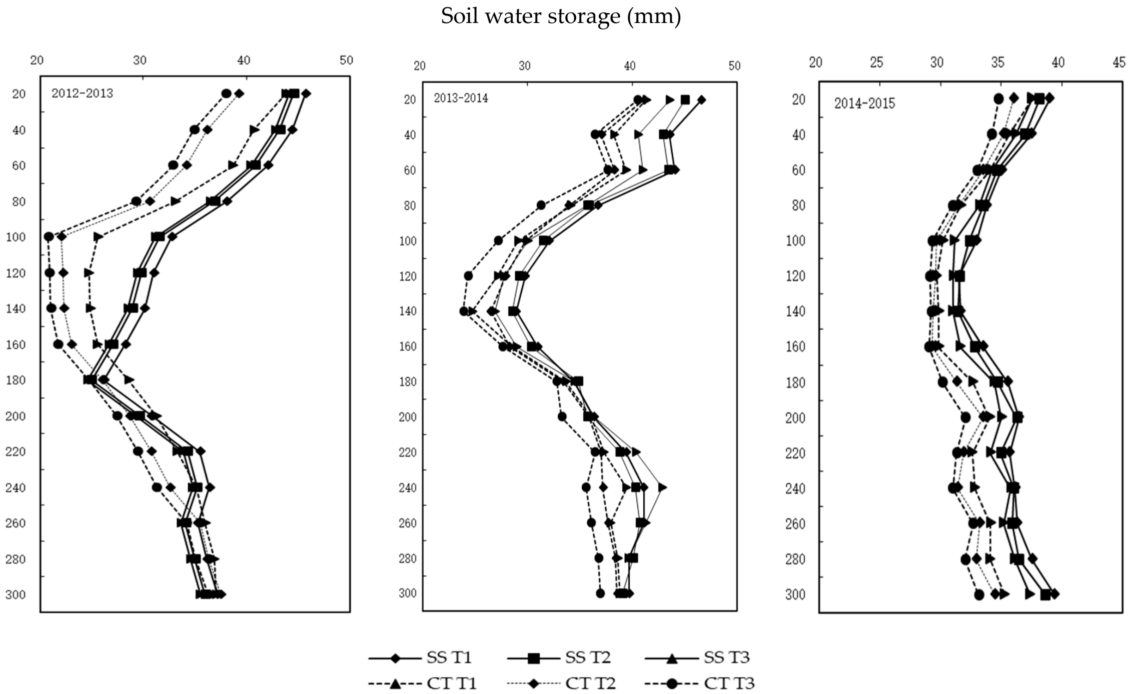

Figure 1. Effect of subsoiling and sowing date on soil water storage during 2012–2015. SS: Subsoiling during the fallow period; CT: Conventional tillage; T_1: Early sowing date; T_2: Timely sowing; T_3: Late sowing. Values followed by different small letters indicate significant difference at 0.05 level.

Furthermore, soil water storage was highest under early sowing as compared to medium and late sowing (Figure 1). Subsoiling especially increased the soil moisture in 0–160 cm and 200–240 cm soil layers in 2012–2013, and in 0–160 cm and 220–300 cm soil layers during 2013–2014. Maximum soil water storage in 0–300 cm during all three years was observed at early sowing. With the delay of the sowing date, soil water storage was decreased as compared to early and timely sowing. Soil water storage was significantly lower in the later planting than early and medium sowing period, especially 60–140 and 240–300 cm soil layer during 2013–2014.

3.2. Effects of Subsoiling and Sowing Time on the Number of Tillers at Different Stages of Winter Wheat and the Effect of Sowing Time on Accumulated Growing Degree Days

Accumulated growing degree days were decreased with the delay of sowing time. The accumulated growing degree days of late sowing was reduced by 379 °C and 172 °C than in the early and conventional sowing time of winter wheat, respectively (Figure 2). The number of tillers under subsoiling was significantly higher than that in conventional tillage. The highest number of tillers was recorded in conventional sowing time (T_2), but during the wintering stage, the difference was not significant with early sowing time (T_1), whereas in the joining, booting and maturity stages, the number of tillers were significantly higher in T_2 than T_1 and T_3. Under medium sowing time (T_2), subsoiling resulted in an average 13% increase in tillage number as compared to conventional tillage. Late sowing resulted in a 17% and 15% reduction in the number of tillers as compared to medium sowing time under subsoiling and conventional tillage respectively. Early sowing (T_1) and the conventional medium sowing (T_2) times were favorable to the formation of more tiller in winter, but the medium sowing is more favorable to the formation of an effective spike number, thus increasing the yield.

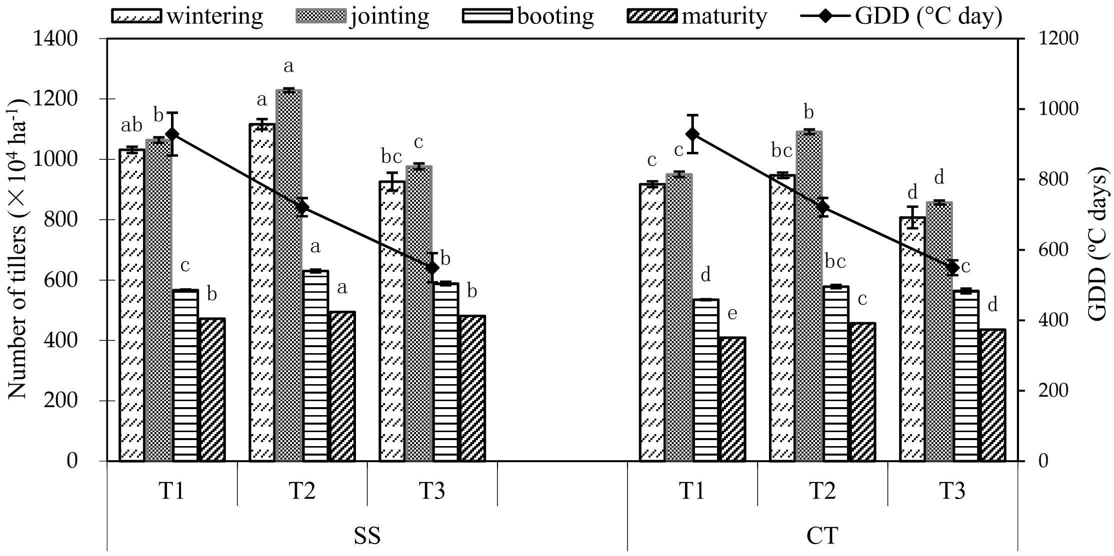

Figure 2. Effect of subsoiling and different sowing times on number of tillers ($\times 10^4$ ha^{-1}) and winter accumulated growing degree days (GDD) at different stages of winter wheat during 2013–2014. SS: Subsoiling during fallow period; CT: Conventional tillage; T_1: Early sowing date; T_2: Timely sowing; T_3: Late sowing.

3.3. Effect of Subsoiling and Sowing Time on N Accumulation and Translocation

3.3.1. Pre-Anthesis N Translocation and Post-Anthesis N Accumulation

The contribution rate of N translocation in the plant before anthesis (about 75%) was greater than the contribution rate of N accumulation after anthesis (about 25%) to the grain N (Table 2). Under subsoiling, the pre-anthesis N translocation was significantly increased. Pre-anthesis nitrogen translocation was increased by 21–25 kg ha^{-1}, whereas the contribution rate to grain N was non-significantly increased by 2%–7% by subsoiling as compared to conventional tillage. It can be seen that under the conditions of subsoiling in the fellow period, the pre-anthesis N translocation, N contribution to grain, and the amount of N accumulation after anthesis was higher at a medium sowing time as compared to early and late sowing times. At late sowing time the N translocation, contribution of N translocation and post-anthesis N accumulation were decreased as compared to medium sowing time, whereas the post-anthesis contribution of N accumulation to grain N was increased.

Table 2. Effect of subsoiling and sowing dates on pre-anthesis nitrogen translation and post-anthesis nitrogen accumulation to grain nitrogen.

Year	Tillage	Sowing Date	Pre-Anthesis		Post-Anthesis	
			NT (kg ha^{-1})	Contribution of NT to Grain N (%)	NA (kg ha^{-1})	Contribution of NA to Grain N (%)
2012–2013	SS	T_1	43.46 c	81.27 c	10.21 e	18.73 d
		T_2	54.55 a	83.30 a	10.93 b	16.70 f
		T_3	41.41 d	79.20 d	11.08 b	20.80 c
	CT	T_1	40.81 e	78.92 e	10.62 c	21.08 b
		T_2	50.50 b	81.55 b	11.38 a	18.45 e
		T_3	38.54 f	78.79 e	10.41 d	21.21 a
2013–2014	SS	T_1	96.74 b	76.67 ab	29.43 b	23.33 cd
		T_2	111.94 a	78.16 a	31.27 a	21.84 d
		T_3	86.25 d	75.93 bc	27.34 d	24.07 bc
	CT	T_1	73.98 e	74.45 c	25.39 e	25.55 b
		T_2	91.01 c	75.92 bc	28.86 c	24.08 c
		T_3	61.61 f	69.30 d	27.29 d	30.70 a
2014–2015	SS	T_1	55.66 b	75.60 c	17.97 c	24.40 c
		T_2	57.70 a	75.66 c	18.56 b	24.34 c
		T_3	53.84 c	73.83 e	19.08 a	26.17 a
	CT	T_1	50.71 e	74.57 d	17.29 d	25.43 b
		T_2	52.97 d	80.95 a	12.47 e	19.05 e
		T_3	48.21 f	79.56 b	12.39 e	20.44 d
ANOVA (*F*-values)	Year		261.06 **	223.78 **	4079.69 **	27.69 *
	Tillage		39.13 **	6.25 ns	48.49 **	7.01 ns
	Date		28.12 **	10.08 **	15.99 **	4.27 *
	Year × Tillage × Date		33.33 **	10.07 **	4.32 ns	4.26 *

NT, N translation; NA, N accumulation; SS, subsoiling; CT, conventional tillage; T_1, early sowing date; T_2, timely sowing; T_3: late sowing. Different letters in the same column indicate significant difference at 0.05. ns indicated non-significant,* and ** indicated significance at $p < 0.05$ and $p < 0.01$, respectively.

3.3.2. Pre-anthesis N Accumulation and Translocation in Various Plants Parts

The accumulation and translocation of N before flowering and contribution to grain were highest in the stem + leaf sheath, and the lowest in the glume + spike (Table 3). In leaf, N accumulation and N translocation and contribution to grain were less than the stem + sheath and higher than in glume + spike. Compared with the control, subsoiling during the fellow time significantly increased the accumulation and translocation of N in plants parts and its contribution to grains before flowering. Nitrogen accumulation was increased by 4–7 kg ha^{-1}, 13–18 kg ha^{-1}, and 3–4 kg ha^{-1}, and the amount of nitrogen translocation was increased by 6–7 kg ha^{-1} and 12–14 kg ha^{-1}, and 3–4 kg ha^{-1} in leaves, stems + sheaths, glume + spike respectively.

Accumulation and translocation of N in all plant parts were highest under medium sowing time, while the late and early sowing significantly decreased the N accumulation and translocation in leaf, stems + sheaths, glume + spike (Table 3). Contribution rate to the grain was highest in medium sowing time for leaf and stem + sheath. Under subsoiling conditions, the early and late sowing time has decreased the contribution of leaf and stem + sheath to grain as compared to medium sowing time, whereas there was no significant difference between sowing times in glume + spike. It can be seen that the medium sowing time is beneficial for the translocation of N in the leaves and stems + sheath under subsoiling practice during the fallow period.

Table 3. Effect of subsoiling in the fallow period and different sowing date on nitrogen accumulation, translocation, and contribution ratio to the grains of wheat before anthesis.

	Tillage	Sowing Date	Leaf			Stem + Sheath			Glume + Spike		
			NA (kg h^{-1})	NT (kg ha^{-1})	Contribution of NT to Grain N (%)	NA (kg h^{-1})	NT (kg ha^{-1})	Contribution of NT to Grain N (%)	NA (kg h^{-1})	NT (kg ha^{-1})	Contribution of NT to Grain N (%)
2012–2013	SS	T_1	20.55 c	17.97 c	33.54 a	38.16 c	23.63 c	44.12 c	7.25 c	5.38 c	20.55 c
		T_2	23.07 a	20.21 a	30.86 e	44.70 a	32.38 a	49.42 a	8.26 b	5.82 b	23.07 a
		T_3	22.75 b	19.97 b	32.02 c	43.85 b	25.95 b	41.59 d	8.59 a	6.76 a	22.75 b
	CT	T_1	17.55 e	15.90 e	32.50 b	31.85 f	22.26 d	45.47 b	5.38 e	3.80 d	17.55 e
		T_2	18.65 d	16.50 d	31.82 d	34.69 d	18.71 e	36.07 f	6.29 d	5.20 c	18.65 d
		T_3	17.39 f	15.42 f	30.58 e	33.06 e	18.83 e	37.34 e	5.78 e	3.97 d	17.39 f
2013–2014	SS	T_1	27.48 c	24.12 b	19.11 b	80.98 b	60.42 b	47.88 b	19.85 b	12.21 b	27.48 c
		T_2	32.35 a	28.88 a	20.17 a	86.69 a	69.08 a	48.24 a	23.44 a	13.98 a	32.35 a
		T_3	28.48 b	21.86 d	19.25 b	76.38 c	53.49 c	47.09 b	18.06 c	10.89 c	28.48 b
	CT	T_1	22.71 d	17.77 e	17.88 c	63.03 d	47.30 d	47.60 b	16.20 d	9.90 d	22.71 d
		T_2	28.27 b	22.60 c	18.86 b	72.77 c	57.28 b	47.79 b	20.08 b	11.13 c	28.27 b
		T_3	21.12 e	14.54 f	16.36 d	57.93 e	39.14 e	44.02 c	14.90 e	6.93 e	21.12 e
2014–2015	SS	T_1	22.90 c	20.77 c	36.90 a	40.51 c	27.43 c	47.48 c	9.60 b	7.18 c	22.90 c
		T_2	25.42 a	22.01 a	33.61 f	47.05 a	34.18 a	52.17 a	10.61 a	7.62 b	25.42 a
		T_3	25.10 b	21.77 b	34.90 d	46.20 b	28.25 b	44.47 d	10.94 a	8.56 a	25.10 b
	CT	T_1	19.90 e	16.70 e	36.17 b	34.20 f	21.06 d	49.15 b	7.73 e	5.15e	19.90 e
		T_2	21.00 d	19.30 d	35.29 c	37.04 d	28.51 e	39.54 f	8.64 c	6.00 c	21.00 d
		T_3	19.74 e	17.22 e	34.15 e	35.41 e	20.63 e	40.90 e	8.13 d	5.77 d	19.74 e
ANOVA (*F*-values)	Year		293.6 **	265,077 **	1341.0 **	12,802.0 **	34,823.8 **	20.3 *	5333.4 **	2597.0 **	156.7 **
	Tillage		9124.0 **	1001.2 **	0.90 ns	3678.2 **	3428.6 **	50.13 **	228.0 **	195.1 **	7.62 ns
	Date		45.4 **	60.2 **	3.75 *	76.8 **	218.2 **	16.9 **	44.3 **	60.1 **	1.46 ns
	Year × Tillage × Date		0.86 ns	1.05 ns	0.26 ns	3.30 *	13.08 **	5.47 **	0.67 ns	0.98 ns	4.29 *

Different letters in the same column indicate significant difference at 0.05. NT, N translation; NA, N accumulation; SS, subsoiling; CT, conventional tillage; T_1, early sowing date; T_2, timely sowing; T_3: late sowing. ns indicated non-significant, * and ** indicated significance at $p < 0.05$ and $p < 0.01$, respectively.

3.4. Correlation Coefficients between Soil Moisture and Nitrogen Accumulation and Translocation in Plant Parts before Anthesis

Under subsoiling and different sowing periods, the soil water storage in the 0–300 cm soil layers during the fallow period was positively correlated with the accumulation and translocation of nitrogen in plant parts before flowering (Table 4). A significant and positive correlation was found for nitrogen accumulation in leaf and glume + spike and soil moisture in 100–200 cm soil layer. Correlation between N accumulation in stems + sheaths and soil water storage was significant in the 0–300 cm soil layer. The N translocation in leaf and glume + spike and soil water storage in the 20–300 cm soil layer was significantly related. It was shown that the N translocation of glume + spike was closely related to the 40–300 soil layer.

Table 4. Correlation coefficients between soil water storage at different soil depth and nitrogen accumulation and translocation in different organs before anthesis.

Soil Depth (cm)	Leaf		Stem + Sheath		Glume + Spike	
	NA	NT	NA	NT	NA	NT
0–20	0.65	0.75	0.85 *	0.74	0.64	0.63
20–40	0.68	0.78 *	0.86 *	0.77 *	0.68	0.69
40–100	0.75	0.85 *	0.91 **	0.85 *	0.74	0.88 **
100–200	0.81 *	0.89 **	0.93 **	0.90 **	0.81 *	0.92 **
200–300	0.77	0.81 *	0.89 **	0.80 *	0.67	0.85 *

* = significant at $p < 0.05$; ** = significant at $p < 0.01$; NT, N translation; NA, N accumulation.

3.5. The Relationship between Nitrogen Translocation and Grain Yield before Flowering

3.5.1. Relationship between N Translocation and Grain Production

A significant linear positive correlation was found between grain yield and pre-anthesis N translocation (Figure 3). For N translocation in the leaves and glume + spike, the fitting equations were y = 89.933x + 2834.6 (r = 0.887) and y = 179.15x + 2867.5 (r = 0.876). There was a significant relationship between the N translocation in stem + sheath and grain yield, and the fitting equation was y = 40.92x + 2551.6 (r = 0.842).

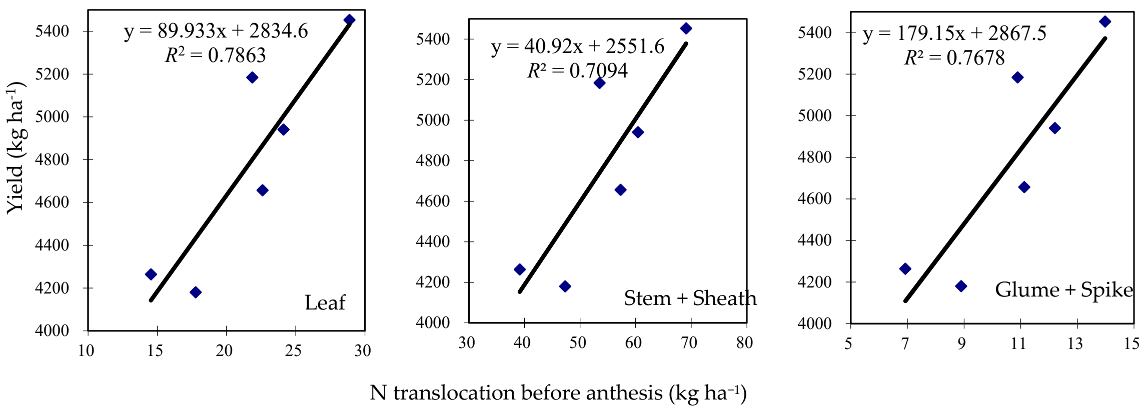

Figure 3. Relationship of yield with nitrogen translocation before anthesis (2013–2014), solid lines are linear regressions, dashed lines are the 95% confidence intervals.

3.5.2. The Contribution of Subsoiling to Increase Nitrogen Translocation

Subsoiling during the fallow period significantly increased the yield by 19%–36% (2012–2013), 17%–22% (2013–2014) and 20%–24% (2014–2015) compared with the conventional tillage (Table 5). Under subsoiling, the maximum yield was recorded at the medium sowing time. Under the conventional tillage, in 2012–2013 the highest yield was attained in early sowing treatment, but the difference between early and medium sowing treatment was not significant, however, in 2013–2014, and 2014–2015, maximum yield was attained at medium sowing time which was 7%–11% and 5%–9% higher than the early and late sowing.

Table 5. Effect of subsoiling at different sowing dates on the contribution of N translocation before anthesis on yield.

Year	Tillage	Sowing Date	Yield (kg ha^{-1})	ΔNT (kg ha^{-1})			△Y (kg ha^{-1})	△Y/△NT		
				Leaf	Stem + Sheath	Glume + Spike		Leaf	Stem + Sheath	Glume + Spike
2012–2013	SS	T_1	3353.4 b	4.91 c	7.05 a	2.31 c	537.2	109.4 b	76.20 b	232.9 b
		T_2	3796.7 a	5.14 a	5.66 c	3.35 a	1015.0	198.0 a	179.4 a	302.7 a
		T_3	3283.2 b	5.01 b	6.41 b	2.96 b	827.7	165.5 b	129.1 b	279.2 b
	CT	T_1	2816.3 c	—	—	—	—	—	—	—
		T_2	2781.7 c	—	—	—	—	—	—	—
		T_3	2455.5 d	—	—	—	—	—	—	—
2013–2014	SS	T_1	4940.6 c	6.34 b	13.11 b	3.31 b	760.63	119.9 b	58.03 b	235.2 b
		T_2	5453.0 a	6.28 c	11.80 c	2.85 c	796.20	127.4 a	67.57 a	282.6 a
		T_3	5184.3 b	7.32 a	14.35 a	3.96 a	920.60	125.9 b	64.35 b	246.1 b
	CT	T_1	4180.0 e	—	—	—	—	—	—	—
		T_2	4656.8 d	—	—	—	—	—	—	—
		T_3	4263.7 e	—	—	—	—	—	—	—
2014–2015	SS	T_1	4806.5 b	4.07 a	6.37 b	2.03 b	939.82 a	231.5 b	149.54 b	463.1 b
		T_2	4999.9 a	2.71 b	5.67 c	1.62 c	844.36 b	312.7 a	156.34 a	524.9 a
		T_3	4818.7 b	4.55 a	7.62 a	2.79 a	862.52 b	197.9 b	120.12 b	314.7 b
	CT	T_1	3866.7 e	—	—	—	—	—	—	—
		T_2	4155.6 c	—	—	—	—	—	—	—
		T_3	3956.2 d	—	—	—	—	—	—	—

Different letters in the same column indicate significant difference at $p < 0.05$. SS, subsoiling; CT, conventional tillage; ΔY, changes in grain yield; ΔNT, changes in N translocation; △Y/△NT, contribution of N translocation to grain yield.

The contribution of N translocation to grain yield was maximum in glume + spike, followed by the leaf and the minimum was in the stem + sheath. Medium sowing time significantly increased the contribution of the amount of N in each organ to the yield as compared to early and late sowing. It can be seen that the practice of subsoiling during the fallow period and medium sowing time (1 October) was beneficial to the pre-anthesis N translocation in plant organs and contribution of N to the yield and the effect was more prominent during the drier year (2012–2013).

4. Discussion

The results of this experiment showed that the subsoiling during the fallow period significantly increased the soil water storage from 0 to 300 cm soil before sowing, especially in 2012–2013 (Figure 1). Previous reports also showed that subsoiling during the fallow period promoted the water storage capacity in the deeper horizons of the soil profile in dryland areas [8,23,24]. Hou et al. [25] showed that subsoiling during the fallow period improved the water storage capacity of 0–200 cm soil before the sowing in dryland wheat field. Fu et al. [26] reported that subsoiling accumulated 50% of the summer rainfall in dryland wheat fields, and increased the soil water storage capacity by 76.2 mm in 0–200 cm soil before sowing. Mao et al. [27] showed that subsoiling during the fallow period in the dryland wheat field increased the soil water storage capacity of 0–300 cm by 21 mm and increased the yield by 5.5%. Ren et al. [28] found that subsoiling during the fallow period increased the water storage capacity of 0–300 cm soil in dryland wheat (especially in the 80–160 cm soil layer). These indicated that subsoiling can accumulate precipitation during the fallow period and increase the soil moisture reserve in the fallow period, favoring timely sowing and subsequent germination of dryland winter wheat [8,29].

Adequate soil moisture is conducive for the growth and development of wheat, which directly affects the accumulation and translocation of N, thus affecting the yield. The results of this experiment showed that subsoiling during the fallow period can significantly increase the amount of N of various organs before flowering, especially in leaves and stems + sheaths (Table 3). The contribution rate of N translocation to grain before flowering and nitrogen accumulation after flowering were significantly improved. This may be due to the improvement of effective soil water storage capacity to promote water and N absorption. Previous studies have shown that subsoiling practice increased the uptake of N after anthesis and further improve the N accumulation of grain by enhancing the absorption of water and nutrients by roots and increasing the supply of N metabolism substrates in the aboveground parts [15,20]. Zheng et al. [19] showed that subsoiling + rotary tillage and subsoiling + strip rotary tillage significantly increased N accumulation at flowering and N translocation from vegetative organs to grain after flowering, compared with the rotary tillage and strip rotary tillage and thereby increasing yield. Wang et al. [30] showed that subsoiling had increased N accumulation after flowering and its contribution to grain by 50% and 38%, respectively.

On the basis of a suitable sowing date, the growth of the root system was promoted, further improving the absorption capacity of soil nitrogen and fertilizer in dryland wheat and promoting the vegetative and reproductive growth promoted the transport of N stored in the leaves, stems and sheaths to the grain, which increased the amount of N before the flowering and the contribution rate to the grain, thereby increasing the yield [8]. Ren et al. [31] showed that the soil storage capacity of 0–300 cm was positively correlated with the accumulation of N in the vegetative organs and the amount of the biomass before anthesis.

Subsoiling during the fallow period significantly increased the yield (17%–36%) compared with the conventional tillage (Table 5). Wang and Shangguan [7] reported that wheat yield in the Loess Plateau region is sensitive to soil water content at plantation and grain yield increased linearly with the soil water at planting, under subsoiling, and other tillage methods. Subsoiling increased yield by improving N accumulation and translocation to grain. The amount of N mobilization in stem + sheath had a significant effect on grain yield [32]. The activities of key nitrogen metabolism enzymes and intermediate products of nitrogen assimilation were significantly higher by subsoiling than the rotary tillage and conventional tillage methods [20,33]. Subsoiling tillage had a higher translocation of N from vegetative organs to grain, higher absorption of N after flowering and higher contribution from absorbed N after flowering to grain than the other two tillage methods. As compared to subsoiling, the amount of translocation of N, translocation efficiency and N absorption after flowering, and N accumulation and distribution rate in grain were lower under rotary tillage. Therefore, subsoiling tillage could promote N assimilation and improve nitrogen use efficiency to attain high-efficient and high-yield of wheat [20].

Present results indicated that soil water in 40–200 cm showed a highly significant correlation with N accumulation and translocation in the stem + sheath and N translocation in leaf and glume + spike (Table 4). This may be related to the distribution of wheat roots in the soil and consistent with the results of Zhang et al. [32]. The soil water content at sowing stage in 0–300 cm depth was positively correlated to the N mobilization amount before anthesis and N accumulation amount after anthesis [32]. Subsoiling improves the depth of rooting in deeper soil by minimizing the compaction of soil and allowing the accumulation of water reserve, which in turn improves water and nutrients uptake and drought resistance [34].

Suitable sowing is the main measure to match the growth and development of wheat and the local climate, which is conducive to achieving a stable yield [14]. This experiment showed that by delaying the sowing time for 10 days the accumulated growing degree days before winter is reduced by about 180 °C. Xu et al. [12] and other studies have shown that with the delay of the sowing date, the accumulated temperature in winter was reduced, which significantly affected the growth of wheat before winter, and decreased the number of tillers. For each 6-day delay in sowing date, the average daily temperature from sowing to emergence decreased by 1.0–2.5 °C, and the number of tillers decreased by 100–150 million ha^{-1}. In the present study, both early sowing and medium sowing were beneficial for the formation of more group tillers in winter, but the medium sowing was more favorable for the formation of an effective number of tillers, so as to increase the yield. Sun et al. [14] reported that the delayed sowing time would affect the growth duration and reduced the dry matter mobilization efficiency of winter wheat as compared with the medium sowing time. Tillering is a determining factor for optimum wheat yield because of excessive production of tillers under well-fertilized soil ended in increased competition for light and resources leading to tillers mortality and reduced the number of effective tillers and grain yield [35].

Sowing at the appropriate time can increase the effective accumulative temperature, prolong the effective growth period of wheat, and increase the accumulation of N in grains [15,36,37]. The results of the present experiment showed that medium sowing time significantly increased the contribution of the amount of N in each organ to the yield as compared to early and late sowing (Table 5). Late and early sowing significantly decreased the N translocation. Accumulation and translocation of N in all plant parts were highest under medium sowing time, while the late and early sowing significantly decreased the N accumulation and translocation in leaf, stems + sheaths, glume + spike (Table 3). Medium and late sowing time significantly increased the dry matter accumulation in the vegetative organs before flowering to the grain, thereby increasing yield. Under subsoiling, the normal sowing timing significantly increased the yield by 13%–16% and 5%–10%, in 2012–2013 and 2013–2014 respectively as compared to early and late sowing. The delay in sowing tended to decrease the oncoming heading and flowering stage and shorten the duration of the grain filling stage, which caused less dry matter mobilization efficiency and reduced biomass and grain yield [14,38].

Early and late sowing significantly decreased the N accumulation and translocation before anthesis (Table 2). The contribution rate of N to the grain after anthesis was decreased at early and medium sowing, whereas the contribution rate of N accumulation for grain was significantly improved by late sowing at post-anthesis. This may be because late sowing increases the proportion of N translocation from the glume + spike to grain, and improves the ability of the plant to use already absorbed N for grain production.

Ding et al. [39] showed that the accumulation of N in leaves and stems was significantly linearly correlated with grain yield at the flowering stage, and N translocation from the leaves and the stem + sheath was significantly linearly positively correlated with grain yield. The results of this experiment showed that the relationship between the amount of N in various organs before flowering and grain yield was consistent with a significant linear positive correlation. There was a significant relationship between the amount of N translocation in the leaf, stem + sheath, and glume + spike and the grain yield. For every 1 kg ha^{-1} of N transported from the leaves, the yield was increased by 109–198 kg ha^{-1}; for every 1 kg ha^{-1} of N transported by the stem + sheath, the yield was increased by 58–179 kg ha^{-1}; for each kg ha^{-1} N translocation from glume + spike, the increase of 233–302 kg ha^{-1} of grain yield could be achieved.

5. Conclusions

Subsoiling during the fallow period can make full use of precipitation, which contributes greatly to the yield of dryland wheat. Subsoiling during the fallow period significantly increased the yield (17%–36%) compared with the conventional tillage. SS increased yield by improving N accumulation and translocation to grain. A significant linear relationship was found for N translocation and grain yield and N translocation from glume + spike contributed most for yield increment followed by leaves. Medium sowing time (1 October) significantly increased the contribution of the amount of N in each organ to the yield as compared to early and late sowing.

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