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RESEARCH

Long-term no-tillage enhanced maize yield and potassium use efficiency under spring drought year

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ABSTRACT

Tillage is an important management tool for tackling and promoting water conservation and improving crop yield. As one of the important nutrients in plant growth, K is involved in important processes such as osmoregulation, photosynthesis and metabolite transport, and plays a particularly critical role in improving crop yield and quality. In the long-term positioning platform of the tillage method, a 2-yr field experiment was conducted in 2019-2020 in maize (*Zea mays* L.) Three tillage methods: conventional tillage (CT), subsoil tillage (ST), and no-tillage (NT) and two planting densities 6×10^4 (D1) and 9×10^4 plants ha^{-1} (D2) were set up in the experiment. The results showed that yield and K translocation efficiency (KTE) were significantly higher in NT than in CT at D1 (by 4.7% and 12.2%) and D2 (by 14.0% and 13.9%), respectively. At maturity stage in 2019, population DM accumulation after silking (DMA) was significantly higher in NT (by 11.0% and 16.9%) than in CT at D1 and D2. Correlation analysis revealed that yield was significantly positive correlated with ears (r = 0.57***) and DMA (r = 0.64***). Potassium translocation and K harvest index were positively correlated with KTE. Under spring drought year, the long-term no-tillage had a significant yield increase, mainly through the increase in 1000-kernel weight. The increase in K efficiency was mainly through the influence of DM accumulation and distribution, and K accumulation in grain.

Key words: Dense planting, no-tillage, potassium efficiency, spring drought, yield.

INTRODUCTION

Maize (*Zea mays* L.) is one of the most important staple food crops in China, occupies an important position in China's food security system (Han et al., 2020). The northeast spring-sown maize area, as one of the main maize-producing areas in China, its planting area and production account for about 31.4% and 32.8% of China's total area and production. It also plays a crucial role in ensuring food security in China (Qiu et al., 2014). However, changes in water resources, climate, and soil fertility threaten maize yield. In recent years, many factors have limited the improvement of maize yields in Northeast China, among them the deterioration soil tillage structure (Sun et al., 2018b) and planting density conditions (Timlin et al., 2014).

Tillage is a basic agricultural practice in which mechanical forces act on the soil to adjust the tillage layer and provide a suitable soil environment for crop growth (Bian et al., 2016; Sun et al., 2018b). As one of the major grain-producing areas in China, the spring maize region in the northeast has long been dominated by the traditional monoculture method of rototilling (Piazza et al., 2020). Conventional tillage has caused certain impacts on soil properties, including soil erosion, soil structure degradation, thickening of the plow base layer, and loss of soil organic matter and nutrients (Scarpare et al., 2019; Zhai et al., 2021). Conservation agriculture practices such as subsoil tillage and no-tillage, which have been proposed as sustainable and effective soil management measures (Shi et al., 2016). Therefore, conservation tillage measures have been proposed to reduce soil structure damage and nutrient loss to increase crop yields. Compared to conventional tillage, such tillage strategies are useful for improving soil structure, regulating surface temperature, reduce surface evaporation, and protecting the soil and preventing water loss (Sun et al., 2018a; Scarpare et al., 2019). Changes in the physical and chemical properties of the soil, which nourish the growth and development of the maize root, ultimately affect maize yield (Das et al., 2019). Previous studies have reported that long-term no-tillage improves soil water retention capacity, increases soil nutrient and soil organic matter content, improves soil fertility, improves soil structure and aeration, and increases water use efficiency of crops (Alskaf et al., 2021; Dai et al., 2021). Soil properties are key to early root growth and development, and different tillage create different soil environments, which in turn affect root growth and distribution, and crop growth (Wang et al., 2020a). Therefore, no tillage provides an important guarantee for early crop root growth in spring drought years.

In addition, reasonable density planting is one of the key techniques to improve high maize yield (Niu et al., 2020). Currently, the increase in maize yield is still dependent on the increase in planting density, in other words, increasing the number of plants per unit area is used to compensate for the decrease in yield per plant (Timlin et al., 2014). Constructing a reasonable group structure can significantly improve the comprehensive utilization of light, temperature, water and fertilizer, which can bring into play the yield potential of maize groups and thus obtain high yields (Anders et al., 2020; Wang et al., 2021). However, if plant permeability is poor, increasing planting density restricts the growth space of individuals within the population, which can increase competition between individual maize and cause yield reduction (Burton and Kemanian, 2022). The intercropping effect between different tillage methods and planting density also contributes significantly to the improvement of crop yield.

Potassium is one of the essential phytonutrients in crop growth and plays a key role in the synthesis of cells, enzymes, proteins, starch, cellulose and vitamins, translocation and uptake of nutrients, enhancement of crop stress resistance and improvement of crop quality (Yang et al., 2014). In addition, K is involved in osmoregulation, photosynthesis, metabolite transport and enzyme activation in cells. In the past, the soil K content in northeast China was relatively high (Yang et al., 2014). However, with the widespread application of high-yielding crop varieties and the long-standing neglect of K fertilization by farmers, soil K deficits have occurred in recent years in the northeastern region, negatively impacting crop production (Tan et al., 2012). At present, people pay more attention to N and P fertilizers than to K fertilizers, and less attention is paid to the absorption and accumulation of K. High yielding and efficient production of maize is mainly predicated on high biomass, which in turn is influenced by nutrient uptake and transport (Zhao et al., 2021). The absorption, accumulation, distribution and translocation efficiency of N, P and K by maize plants are closely related to maize yield formation (Li et al., 2014). Previous studies have shown that the study of the accumulation dynamics and the distribution and transport characteristics of N, P and K are important to improve the high yield and efficient production of maize (Ning et al., 2013). Since more studies have focused on the accumulation characteristics of N and P, we should pay more attention to the accumulation and transport characteristics of K in order to better promote high yield and efficient production of maize.

Long-term no-tillage greatly improves soil water retention capacity and organic matter content, promoting maize emergence and early growth especially in spring drought years. In the present study, we hypothesize that tillage changes the soil environment to regulate root growth, and combined with reasonably dense planting dual regulate crop root-crown structure, and finally promote maize yield. The main objectives of this study were to (1) clarify the influence of tillage method and dense planting on crop yield formation, material production and distribution, and (2) investigate the effect of tillage method and dense planting on K uptake and transport.

MATERIALS AND METHODS

Study site and experimental design

The study was conducted in 2019 and 2020 at a long-term (since 1983) tillage experiment site at Gongzhuling Experimental Station (43°31′44″ N, 124°49′7″ E) of the Agricultural Academy of Jilin Province in Gongzhuling County, Jilin Province, China. This region is located in central Jilin Province, and the station experiences a temperate sub-humid continental monsoon climate with long winters. The mean annual temperature is 5.6 °C, and the mean annual precipitation is 594.8 mm, with more than 70% occurring in June, July, and August (based on data from the past 30 yr). The annual frost-free period averages 144 d. Meteorological data during the growing seasons of 2019 and 2020 were measured as shown in Figure 1 (weather data were accessed from the China Meteorological Data Sharing Service System, http://cdc.cma.gov.cn/home.do). The soil is a typical Mollisol (USDA soil taxonomy) with silty clay loam texture. In 2019, nutrient content of soil at 0-20 cm plow layer for conventional tillage (CT), subsoil tillage (ST) and no-tillage (NT) were 1.51, 1.56, 1.83 g kg^{-1} total N, 0.52, 0.49, 0.57 g kg^{-1} total P, 21.97, 21.59, 21.85 g kg^{-1} total K, 20.2, 14.9, 23.1 mg kg^{-1} available P, 110.0, 124.0, 97.7 mg kg^{-1} available K, respectively.

A long-term field experiment was set up to compare CT, ST and NT methods in a maize (*Zea mays* L.) field, and two density levels were applied 6×10^4 (D1) and 9×10^4 plants ha^{-1} (D2). The experiment was laid out in a randomized block design with three replicates of each treatment, and each plot was of 200 m^2 (20 m long × 10 m wide). Conventional tillage consisted of equal row spacing planting (65 cm). Fertilizer is applied when sowing and combined with middle tillage for topdressing when jointing. Subsoil tillage was wide and narrow row planting with wide row 90 cm and narrow row 40 cm. Deep loosening was carried out between wide rows when jointing (30-35 cm), and fertilizer was applied at sowing and jointing. For the NT, with no soil disturbance except for planting using a no-till planter. Equal row spacing planting with 65 cm line spacing. Details of treatments and management practices are given in Table 1. The commonly used maize 'Xiangyu 998' was tested. Nitrogen, P, and K fertilizers were applied at rates of 243 kg N ha^{-1}, 92 kg P_2O_5 ha^{-1}, and 80 kg K_2O ha^{-1}.

Figure 1. Temperature and precipitation during the two growing seasons of maize.

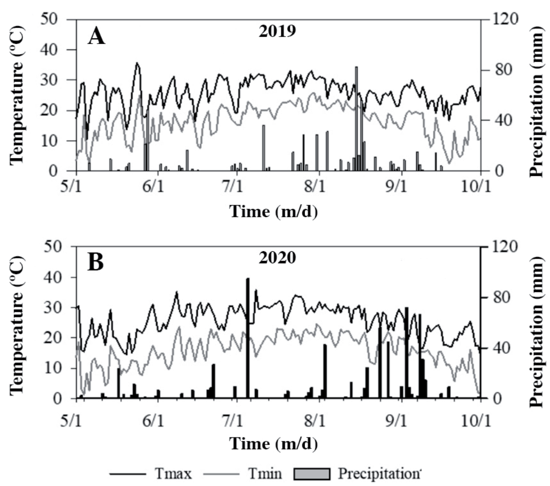


Table 1. Operation methods of different tillage methods in maize field.

Tillage methods	Operation methods
Conventional tillage (CT)	Equal row spacing planting with 65 cm line spacing. Fertilizer is applied when sowing in spring, and combined with middle tillage for topdressing when jointing. The remaining straw was removed after harvest, and then carried on shallow rotary cultivated land with rotary tiller (20 cm).
Subsoil tillage (ST)	Wide and narrow row planting with wide row 90 cm and narrow row 40 cm. Deep loosening was carried out between wide rows. Sowing in the wide row of the previous year in spring, and fertilizer was applied at the same time. Topdressing and deep loosening (30-35 cm) were carried out at corn jointing. After harvest stubble height 40-45 cm and the remaining straw was removed after harvest. The wide row is used as a bed for the next year after rotary tillage.
No-tillage (NT)	Equal row spacing planting with 65 cm line spacing. Sowing in spring with no-tillage planter and side fertilization. Topdressing of maize during jointing. After harvest stubble height 40-45 cm and the remaining straw was removed after harvest.

Grain yield

At the maturity stage (PM), grain was harvested from three plots (each plots area measuring 10 m × 3 rows). The total number of plants, number of grains per ear and 1000-grain weight were recorded. The grain's moisture content was determined in real-time by grain moisture meter (PM-8188, Kett Electric Lab., Tokyo, Japan), and the grain yield was expressed at 14% moisture content.

Dry matter accumulation and distribution

At silking (VT) and PM stages, three maize plants were randomly sampled from each plot, and separated into leaf, stem and grains. All of the plant samples were oven-dried at 105 °C for 30 min, dried at 70 °C to determine aboveground biomass. The calculation equations were as follows:

$$\text{DM accumulation after VT (DMA, kg ha}^{-1}\text{)} = \text{DM at maturity} - \text{DM at VT}$$

$$\text{DM translocation (DMT, kg ha}^{-1}\text{)} = \text{DM at VT} - \text{DM of vegetative plant parts at PM}$$

$$\text{Contribution of DMT to grains (DMTC, \%)} = \text{(DMT/DM of grain at PM)} \times 100$$

$$\text{DM translocation efficiency (DMTE, \%)} = \text{(DMT/DM at VT)} \times 100$$

K accumulation and distribution

The plant samples were ground and sieved (2 mm sieve) for nutrient determination. The maize plant and grain samples were digested by H_2SO_4-H_2O_2 mixture and the K concentration was measured by a flame photometer procedure. The calculation equations are as follows:

$$\text{K accumulation (kg ha}^{-1}\text{)} = \text{DMA} \times \text{K concentration}$$

$$\text{K translocation (KTA, kg ha}^{-1}\text{)} = \text{K accumulation at VT} - \text{K accumulation of vegetative parts at PM}$$

$$\text{K translocation efficiency (KTE, \%)} = \text{K translocation/K accumulation at VT} \times 100$$

$$\text{K harvest index (KHI, \%)} = \text{Grain K accumulation/Total K accumulation in the plant}$$

$$\text{Partial factor productivity of K (PFP}_K\text{, kg kg}^{-1}\text{)} = \text{Grain yield (kg ha}^{-1}\text{)/Applied K fertilizer rate (kg ha}^{-1}\text{)}$$

Statistical analyses

The statistical analyses consisted of ANOVA. For multiple comparisons, Fisher's protected least significant differences (LSD) at the 5% level of probability was used. All statistical analyses were conducted using the R platform (R Foundation for Statistical Computing, Vienna, Austria), and graphs were generated using SigmaPlot 14.0 (Inpixon, Palo Alto, California, USA).

RESULTS

Precipitation before and after sowing

We analyzed the precipitation amount per 10 consecutive days from 1st April to 20 May for 2019, 2020, and the average of the last 20 yr (Table 2). The results showed that the rainfall in 2019 was lower than that in 2020 before and after sowing; 2019 was considered a spring drought year.

Yield and yield components

The results showed that tillage, planting density and year significantly affected maize yield (Table 3). Increasing density under different tillage significantly increased maize yield, the yields of CT, ST, and NT were higher in D2 ($P < 0.05$). In 2019, at D1 and D2, three tillage methods showed higher yields for the NT treatment with the highest yields of 12 431.1 and 13 845.5 kg ha^{-1}, respectively. Grain yield of NT was 4.7% and 14.0% higher in CT at D1 and D2, respectively ($P < 0.05$). Consistent with grain yield, 1000-kernel weight of NT was 1.4% and 5.0% higher than the CT at D1 and D2. In 2020, the grain yield was significantly higher in ST (by 5.6%) than in CT at D1. The grain yield of NT was not significantly different from that of CT ($P > 0.05$), kernels per ear of NT was significantly lower than in CT, while the 1000-kernel weight of NT was significantly higher than in CT at D1 ($P < 0.05$). At D2 in 2020, there were no differences in grain yield, kernels per ear, and 1000-kernel weight among the tillage methods.

Table 2. Precipitation from 1 April to 20 May in 2019 and 2020.

Year	Precipitation				
	1-10 April	11-20 April	21-30 April	1-10 May	11-20 May
	mm				
2019	0.0	0.0	0.3	6.3	13.5
2020	0.1	9.9	5.4	2.4	32.0
2001-2020	7.0	10.1	10.4	15.3	22.0

Table 3. Effects of planting density increase on grain yield and its components of maize under different tillage methods.

Year	Density	Tillage	Grain yield	Ears	Kernels per ear	1000-kernel weight
			kg ha^{-1}	× 10^4 ear ha^{-1}		g
2019	D1	CT	11 840.9 ± 202.8b	5.77 ± 0.13a	578.5 ± 7.2ab	365.8 ± 2.1b
		ST	11 998.1 ± 196.8b	5.90 ± 0.44a	564.7 ± 6.2b	367.6 ± 1.4ab
		NT	12 431.1 ± 90.1a	5.98 ± 0.15a	583.4 ± 12.9a	371.0 ± 1.8a
	D2	CT	12 354.1 ± 272.0b	8.89 ± 0.39a	439.6 ± 6.3b	341.8 ± 3.2b
		ST	12 421.5 ± 118.7b	8.59 ± 0.13a	454.3 ± 4.3a	345.2 ± 3.5b
		NT	13 845.5 ± 314.4a	8.80 ± 0.15a	457.0 ± 8.1a	359.0 ± 4.4a
2020	D1	CT	11 407.2 ± 291.9b	5.90 ± 0.09a	577.0 ± 6.7a	362.3 ± 2.9b
		ST	11 942.3 ± 164.7a	5.90 ± 0.09a	571.1 ± 5.1a	361.4 ± 3.0b
		NT	11 263.9 ± 283.4b	5.95 ± 0.18a	551.9 ± 3.2b	369.9 ± 2.2a
	D2	CT	12 224.4 ± 819.0a	8.97 ± 0.09a	394.6 ± 8.0a	353.4 ± 2.6b
		ST	12 550.6 ± 385.4a	8.92 ± 0.15a	400.0 ± 10.3a	361.5 ± 1.1a
		NT	12 151.0 ± 220.9a	8.92 ± 0.31a	405.1 ± 9.0a	356.7 ± 1.2b
P-value	Year (Y)		***	ns	***	**
	Density (D)		***	***	***	***
	Tillage (T)		**	ns	ns	***
	Y×D		ns	ns	***	***
	Y×T		***	ns	*	*
	D×T		ns	ns	**	ns
	Y×D×T		ns	ns	*	***

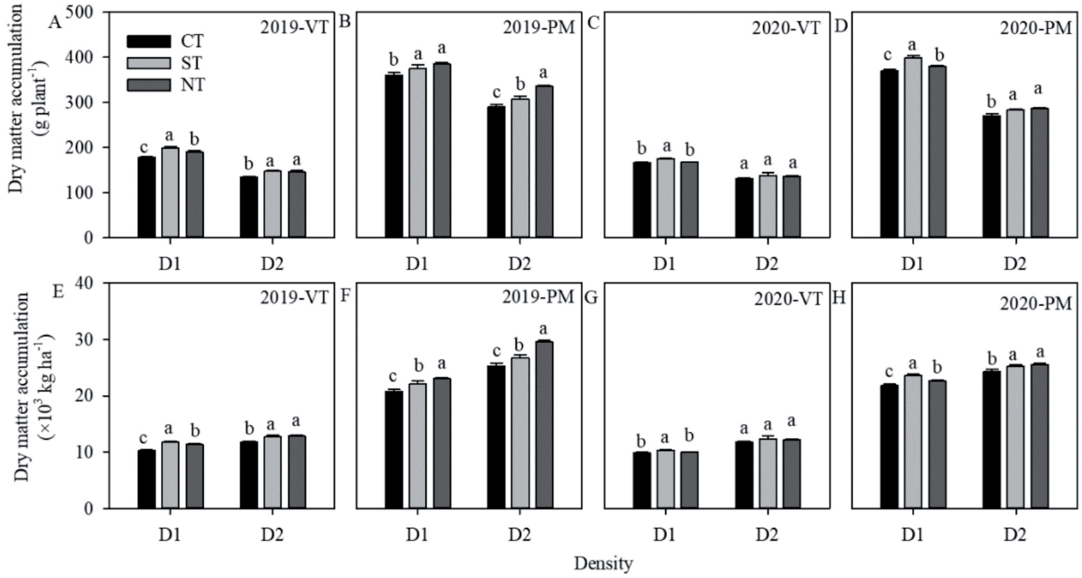
Values within a column followed by different lowercase letters are significantly different at the 0.05 probability level among different treatments.
*, **, ***Significant at $P < 0.05$, $P < 0.01$, and $P < 0.001$, respectively; ns: nonsignificant.
D1: 6×10^4 plants ha^{-1}; D2: 9×10^4 plants ha^{-1}; CT: conventional tillage; ST: subsoil tillage; NT: no-tillage.

Dry matter accumulation and distribution

Different tillage and density regulation significantly affected maize DM ($P < 0.05$). The high density significantly increased population DM accumulation (DMA) and decreased individual plant DMA (Figure 2). At VT in 2019, DMA of ST and NT was significantly higher than CT at both D1 and D2 ($P < 0.05$). At VT in 2020, DMA was significantly higher in ST than in the CT at D1, while there was nonsignificant difference between tillage methods at D2 ($P > 0.05$). At PM in 2019, population DMA was significantly higher in ST (by 6.5% and 5.8%) and NT (by 11.0% and 16.9%) than in CT at D1 and D2. At PM in 2020, population DMA was significantly higher in ST (by 8.2% and 4.0%) and NT (by 4.0% and 5.3%) than in CT at D1 and D2.

In 2019, DM translocation (DMT) of NT was significantly higher than in CT at D1 and D2 (by 11.3% and 23.5%) (Table 4). The DMT and DMT efficiency (DMTE) were significantly higher in ST than in CT at D1, while DMT, contribution of DMT to grains (DMTC) and DMTE were significantly higher in the ST than in CT at D2, with values of 23.2%, 13.5% and 14.7%, respectively. In 2020, DMA was significantly higher in NT and ST than in CT at D1 (by 10.9% and 6.6%), while DMT, DMTC and DMTE were significantly lower than CT. At D2, DMA was increased by 6.9% in NT compared with in CT treatment ($P < 0.05$), and ST and NT had a higher DMTC and DMTE than in CT.

Figure 2. Effects of planting density increase on DM accumulation of maize under different tillage methods at silking (VT) and maturity (PM) stages.



Values within a column followed by different lowercase letters are significantly different at the 0.05 probability level among different treatments. D1: 6×10^4 plants ha^{-1}; D2: 9×10^4 plants ha^{-1}; CT: conventional tillage; ST: subsoil tillage; NT: no-tillage.

Table 4. Effects of planting density increase on DM remobilization during grain filling after silking of maize under different tillage methods.

Year	Density	Tillage	DMA	DMT	DMTC	DMTE
			kg ha^{-1}		%	
2019	D1	CT	10531.0 ± 426.4b	3024.6 ± 246.2b	29.4 ± 2.1a	26.1 ± 2.4b
		ST	10382.2 ± 399.8b	3982.5 ± 322.3a	33.8 ± 2.4a	32.2 ± 2.5a
		NT	11718.7 ± 351.2a	3606.1 ± 299.1a	31.7 ± 2.1a	27.3 ± 2.2b
	D2	CT	13513.7 ± 416.6b	2992.3 ± 177.5b	25.4 ± 1.6b	22.0 ± 1.9b
		ST	13972.8 ± 402.9b	3686.8 ± 172.6a	28.8 ± 1.6a	25.2 ± 1.7a
		NT	16685.4 ± 426.1a	2940.3 ± 193.2b	22.8 ± 1.8b	17.8 ± 0.8c
2020	D1	CT	11910.9 ± 346.8b	1497.9 ± 61.8a	15.2 ± 0.7a	12.6 ± 0.5a
		ST	13209.3 ± 223.2a	991.0 ± 130.4b	9.6 ± 1.2b	7.8 ± 1.1b
		NT	12695.4 ± 175.8a	1033.5 ± 149.8b	10.4 ± 1.5b	8.4 ± 1.2b
	D2	CT	12481.2 ± 336.7b	1912.4 ± 93.1a	16.2 ± 0.6a	14.9 ± 0.8a
		ST	12907.8 ± 475.4ab	1608.2 ± 151.3b	13.0 ± 0.8b	12.8 ± 1.4b
		NT	13344.2 ± 326.0a	1653.7 ± 150.9ab	13.6 ± 1.4b	12.4 ± 0.8b

Values within a column followed by different lowercase letters are significantly different at the 0.05 probability level among different treatments.
DMA: DM accumulation after silking; DMT: DM translocation; DMTC: contribution of DMT to grains; DMTE: DMT efficiency; D1: 6×10^4 plants ha^{-1}; D2: 9×10^4 plants ha^{-1}; CT: conventional tillage; ST: subsoil tillage; NT: no-tillage.

K accumulation, allocation and translocation efficiency

Different tillage methods and planting densities significantly affected K accumulation and allocation in all organs of the maize (Table 5, Figure 3). At VT in 2019, compared with in CT at D1, K accumulation in stem was increased by 7.5% and 16.4% in ST and NT, respectively. Potassium accumulation in leaf of ST (by 8.2%) and NT (by 25.0%) was significantly lower than CT ($P < 0.05$), while K accumulation in stem was significantly higher in ST than in CT at D2. At VT in 2020, K accumulation in stem was significantly higher in ST than in CT at D1 and D2 (by 11.9% and 44.2%). Compared with the CT treatment, NT significantly increased K accumulation in leaf at D1, and ST and NT significantly increased K accumulation in stem and leaf at D2. At PM in 2019, K accumulation in grain was significantly higher in NT (by 19.1% and 38.1%) than in CT at D1 and D2, respectively. At PM in 2020, there are nonsignificant difference in K accumulation in grain between tillage methods ($P > 0.05$). The ST and NT significantly increased K accumulation in stem and leaf at D1 and D2 compared with CT ($P < 0.05$).

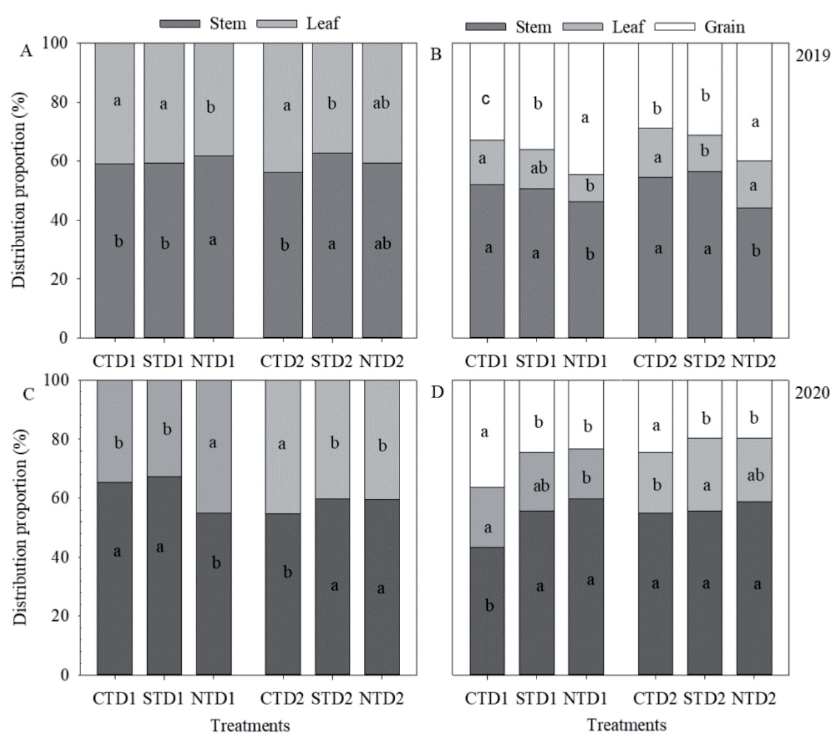
At VT in 2019 (Figure 3A), the proportion of K accumulation in stem was significantly higher in NT and ST than in CT at D1 and D2, respectively. At VT in 2020 (Figure 3C), the NT treatment accounted for the highest percentage of K accumulation in leaf at D1, while the proportion of K accumulation in stem was significantly higher in ST and NT (by 9.7% and 7.9%) than in CT. At PM in 2019 (Figure 3B), the proportion of K accumulation in grain of NT was 35.3% and 38.0% higher than CT in D1 and D2, respectively. At PM in 2020 (Figure 3D), the proportion of K accumulation in grain was significantly lower in ST (by 32.4% and 20.4%) and NT (by 35.6% and 19.6%) than in CT at D1 and D2, respectively.

Table 5. Effects of planting density increase on K accumulation in various maize organs under different tillage methods at silking and maturity stages.

			Silking		Maturity		
Year	Density	Tillage	Stem	Leaf	Stem	Leaf	Grain
2019	D1	CT	81.83 ± 0.94a	56.52 ± 0.81a	61.06 ± 3.28a	17.69 ± 0.37a	38.65 ± 0.50c
		ST	75.69 ± 0.58b	51.88 ± 1.59b	57.99 ± 1.84a	15.31 ± 1.99b	41.55 ± 1.11b
		NT	68.40 ± 0.93c	42.40 ± 3.48c	47.71 ± 3.54b	9.57 ± 0.28c	46.04 ± 1.69a
	D2	CT	77.46 ± 4.89b	60.25 ± 2.97a	74.16 ± 2.38b	22.43 ± 1.37a	39.34 ± 0.59c
		ST	92.11 ± 1.63a	54.85 ± 2.01b	89.04 ± 5.22a	19.38 ± 1.02b	49.05 ± 0.77b
		NT	73.40 ± 4.06b	50.43 ± 1.34c	59.95 ± 2.84c	21.72 ± 1.45ab	54.33 ± 2.73a
2020	D1	CT	92.37 ± 1.59b	49.24 ± 0.55b	53.28 ± 6.13b	24.98 ± 3.10b	44.48 ± 2.19a
		ST	103.36 ± 4.81a	50.55 ± 6.33b	92.94 ± 4.08a	33.16 ± 2.74a	40.84 ± 0.93b
		NT	78.48 ± 5.61c	64.22 ± 2.38a	101.11 ± 8.62a	28.69 ± 1.90ab	39.41 ± 1.31b
	D2	CT	84.76 ± 7.09c	69.96 ± 4.62b	82.38 ± 6.08b	30.62 ± 4.88c	36.80 ± 0.79a
		ST	122.20 ± 6.24a	82.57 ± 7.01a	114.91 ± 5.09a	50.87 ± 1.65a	40.36 ± 2.97a
		NT	104.32 ± 2.95b	70.85 ± 0.75b	118.20 ± 2.54a	42.94 ± 0.42b	39.70 ± 1.80a

Values within a column followed by different lowercase letters are significantly different at the 0.05 probability level among different treatments. D1: 6×10^4 plants ha^{-1}; D2: 9×10^4 plants ha^{-1}; CT: conventional tillage; ST: subsoil tillage; NT: no-tillage.

Figure 3. Distribution proportion of K accumulation in various maize organs under different tillage methods and planting density.



Values within a column followed by different lowercase letters are significantly different at the 0.05 probability level among different treatments. D1: 6×10^4 plants ha^{-1}; D2: 9×10^4 plants ha^{-1}; CT: conventional tillage; ST: subsoil tillage; NT: no-tillage.

Table 6 showed the effects of tillage methods and planting densities on K translocation, K translocation efficiency (KTE), K harvest index (KHI) and partial factor productivity of K (PFP_K). In 2019, K translocation and KHI of ST were lower than CT at D1, while the KTE of NT was higher than CT at D1 and D2 ($P < 0.05$). The KHI was significantly higher in NT than in CT at both D1 and D2, with values of 35.7% and 37.9%, respectively. The PFP_K of NT was 5.0% and 12.1% higher than CT in D1 and D2, respectively. In 2020, K translocation, KTE, and KHI were significantly lower in ST (by 56.1%, 59.6% and 32.4%) and NT (by 79.6%, 79.6% and 35.6%) than in CT at D1, respectively. The KTE and KHI were also significantly lower in ST and NT than in CT at D2 ($P < 0.05$).

Correlations of yield and KTE with each item

To further analyze the effects of different tillage on maize yield, DMA and distribution, and KTE, correlation analyses were conducted between maize yield and KTE and each index, respectively (Table 7). Correlation analysis revealed that there was a storage positive correlation between yield and ears (r = 0.57***), and significant correlation with DMA (r = 0.64***) and DMT (r = 0.35*). However, a strong negative correlation between yield and kernels per ear was observed (r = -0.44**). Kernels per ear, DMT, DMTC, DMTE, KTA, and KHI were positively correlated with KTE (r = 0.50**, 064***, 0.72***, 0.69***, 0.95***, and 0.87***). However, there were negative correlations between ears, DMA, and KTE (r = -0.40* and -0.37*).

Table 6. Effects of planting density increase on K remobilization of maize under different tillage methods.

Year	Density	Tillage	K translocation	KTE	KHI	PFP_K
			kg ha^{-1}	%		kg ha^{-1}
2019	D1	CT	59.6 ± 2.4a	43.1 ± 2.1b	32.9 ± 1.3c	148.0 ± 2.5b
		ST	54.3 ± 3.4b	42.5 ± 2.3b	36.2 ± 0.4b	150.0 ± 2.5b
		NT	53.5 ± 1.8b	48.3 ± 1.4a	44.6 ± 0.6a	155.4 ± 1.1a
	D2	CT	41.1 ± 2.7a	29.9 ± 2.1b	29.0 ± 0.5b	154.4 ± 3.4b
		ST	38.5 ± 2.6a	26.2 ± 2.2b	31.2 ± 1.0b	155.3 ± 1.5b
		NT	42.2 ± 3.0a	34.0 ± 1.7a	39.9 ± 1.7a	173.1 ± 3.9a
2020	D1	CT	63.4 ± 3.3a	44.8 ± 2.6a	36.2 ± 0.9a	142.6 ± 3.6b
		ST	27.8 ± 4.7b	18.1 ± 3.1b	24.5 ± 1.2b	149.3 ± 2.1a
		NT	12.9 ± 4.0c	9.1 ± 3.1c	23.3 ± 1.0b	140.8 ± 3.5b
	D2	CT	41.7 ± 6.6a	26.9 ± 2.3a	24.6 ± 0.6a	152.8 ± 10.2a
		ST	39.0 ± 2.0a	19.0 ± 1.1b	19.6 ± 1.2b	156.9 ± 4.8a
		NT	14.0 ± 5.5b	8.0 ± 3.0c	19.8 ± 0.9b	151.9 ± 2.8a

Values within a column followed by different lowercase letters are significantly different at the 0.05 probability level among different treatments.
KTE: K translocation efficiency; KHI: K harvest index; PFP_K: partial factor productivity of K; D1: 6×10^4 plants ha^{-1}; D2: 9×10^4 plants ha^{-1}; CT: conventional tillage; ST: subsoil tillage; NT: no-tillage.

Table 7. Correlation of maize yield and K translocation efficiency (KTE) with each item.

Items	Ear	Kernels per ear	1000-kernel weight	DMA	DMT	DMTC	DMTE	K translocation	KHI	PFP_K
Yield	0.57***	-0.44**	-0.24ns	0.64***	0.35*	0.24ns	0.19ns	0.07ns	0.27ns	1.00***
KTE	-0.40*	0.50**	0.21ns	-0.37*	0.64***	0.72***	0.69***	0.95***	0.87***	0.10ns

*, **, ***Correlation are significant at 0.05, 0.01, and 0.001 lever, respectively; ns: nonsignificant.
DMA: DM accumulation after silking; DMT: DM translocation; DMTC: contribution of DMT to grains; DMTE: DMT efficiency; KHI: K harvest index; PFP_K: partial factor productivity of K.

DISCUSSION

Yield formation and material production and distribution in response to different tillage

Different long-term tillage practices have certain effects on the soil environment, including water, heat and nutrients (Dai et al., 2021). The implementation of reasonable tillage can improve the physical and chemical properties of the soil, combined with intensive planting control to maximize the role of the crop root, improve the absorption of water and nutrients in the soil, thereby increasing crop productivity (Cai et al., 2014; Timlin et al., 2014). Different tillage methods disturb the soil to different degrees and change the soil environment at the surface, especially soil temperature and soil moisture are particularly important from seeding to emergence stage (Ma et al., 2015; Wang et al., 2018). Previous studies have shown that no-tillage and subsoil tillage significantly increase soil moisture throughout the crop reproduction process, which in turn promotes crop growth and development (Wang et al., 2020b). No-tillage methods can increase soil water storage capacity, improve soil properties, and significantly increase crop yields, especially in dry years (Dai et al., 2021). In our study, maize received low precipitation and severe spring drought before and after seeding in 2019 (Table 2). Dry matter accumulation and grain yield of NT were significantly higher than those of CT, which indicated that to some extent NT was more favorable for maize growth and development in spring drought years (Table 3, Figure 2). The main reason may be that the soil moisture variation is not only affected by tillage method, but also closely related to precipitation.

Reasonably dense planting increases the leaf area of the maize population and increases the accumulation of photosynthetic products in the population, which in turn affects material accumulation (Yang et al., 2021). In addition, DMA is the basis of grain yield; therefore, grain yield is significantly increased by reasonable density planting (Niu et al., 2020). The results in the present study were consistent with previous study in that different tillage methods and planting densities were responsible for increasing maize yield and population DMA. Our study found that NT significantly increased DMA and DMT at D1 in 2019 (Table 4). These results indicated that long-term no-tillage increased maize grain yield, DMA and DMT in spring drought year.

Effect of different tillage on K accumulation and translocation efficiency

Potassium is the most abundant mineral cation in plants, and although K is not involved in organ composition, it is mainly involved in enzyme activation and cellular osmotic potential regulation (Li et al., 2014). Potassium nutrient availability is one of the important factors limiting high maize yields, and redistribution of nutrient K is important for grain quality (Shi et al., 2016). Studies have also found that K application can greatly increase the grain yield of maize (Li et al., 2020). Moreover, optimal K application may contribute to sustainable high yields and efficiency. Effective precipitation promotes root growth, increases the concentration of fast-acting K in the soil, and increases the assimilation of renewed K, which is extremely important for above-ground biomass production and nutrient assimilation during early maize reproduction (Li et al., 2012). The period from anthesis to maturity is a critical period for grain formation. Potassium uptake is mainly concentrated in the nutrient organs before anthesis and K in the grain mainly coming from nutrient organ retransfer (Ning et al., 2013). In the present study, K accumulation in grain was significantly higher in NT than in CT at PM in 2019 (Figure 3B), indicating that K accumulation in nutrient organs was gradually transferred to the grain at the post-anthesis. Moreover, KTE and KHI of NT were significantly higher than CT at D1 and D2 in 2019, indicating than NT had a higher KHI due to the increased KTA and KTE (Tables 5 and 6). Consistent with the results of previous studies, long-term NT improved KTE. The root absorbs K nutrient from the soil in transit to the plant during the crop growth. Moreover, the K absorbed by the plant is gradually translocated from the stems and leaves to the grain, which eventually promotes the improvement of grain yield.

CONCLUSIONS

The experiment assessed the effects of tillage and density on maize yield and K translocation efficiency. Comparing 2-yr of experiment, the result showed that the long-term no-tillage (NT) increased yield significantly under spring drought years. The grain yield of NT increased by 4.7% and 14.0% at planting densities of 6×10^4 (D1) and 9×10^4 plants ha^{-1} (D2) in 2019, respectively. There were positive correlations between grain yield and DM accumulation (DMA) after silking. The result indicated that the increase in yield was mainly due to the increase in DMA, especially DMA increase after silking. In addition, NT significantly improved K translocation efficiency (KTE) than conventional tillage (CT) at D1 and D2, with values of 12.2% and 13.9%, respectively. Meanwhile, K harvest index was also significantly higher in NT than CT in spring drought year. The KTE is achieved mainly by affecting the K accumulation and allocation in grain. Therefore, long-term NT improves maize yield under spring drought year mainly through simultaneous increase in plant biomass and KTE achieve high and efficient maize yield. In conclusion, it is evident that tillage methods, especially NT, are more effective in regulating dense maize planting under spring drought year.

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