Research Article

Received: 28 May 2021 Revised: 23 August 2021 Accepted article published: 8 October 2021

(wileyonlinelibrary.com) DOI 10.1002/jsfa.11571

# Conservation tillage improves the yield of summer maize by regulating soil water, photosynthesis and inferior kernel grain filling on the semiard Loess Plateau, China

Zhen Wang,[a] Jun Sun,[a] Yadan Du[a] and Wenquan Niu[b,c*]

## Abstract

**BACKGROUND: Poor inferior kernel grain filling is a challenge that limits summer maize yield. The effect and mechanism of conservation tillage on improving grain filling of inferior kernel in semi-arid rained areas remain uncertain and there has been little research on tillage management integrated with straw mulching to improve soil water content and photosynthesis in the Loess Plateau region. A 2 year (2019–2020) field experiment was established to study the impact of tillage practices on soil water content and summer maize root system morphology, photosynthetic capacity, inferior kernel grain filling, and grain yield. Treatments included reduced tillage (RT), no tillage (NT), and conventional tillage (CT).**

**RESULTS: Under RT and NT, the final 100-kernel weight and maximum and mean grain filling rates were higher than CT. Reduced tillage and NT increased soil water content at the jointing stage, silking stage and grain filling stage in comparison with CT. They increased root system morphology and dry matter accumulation, net photosynthetic rate, transpiration efficiency, and stomatal conductance in comparison with CT, and they also decreased intercellular $CO_2$ concentration, and they increased chlorophyll content and above-ground dry matter accumulation in comparison with CT. Reduced tillage and NT increased evapotranspiration of maize, and ultimately, increased grain yield by 17% and 14%, respectively, in comparison with CT.**

**CONCLUSION: Conservation tillage could promote summer maize photosynthetic capacity and grain filling of inferior kernels by regulating soil water content and root system morphology.**

**Keywords:** conservation tillage; grain filling; soil water content; photosynthesis; inferior kernel

## INTRODUCTION

Maize is the most widely grown food crop in China, and its yield is directly related to the nation's food security.[1] Maize yield depends on a combination of ears, grains, and final grain weight.[2] The quantity and weight of grains is determined by the grain filling rate and period;[3] thus, grain filling is a critical process if a high grain yield is to be achieved. Grain filling is divided into inferior and superior kernel filling, and inferior kernel filling is important for increased grain weight.[4] Grains with slow filling, poor filling, and low grain weight are considered to be inferior kernels[5] and are generally located at the apex of the ear.[6,7] Poor inferior kernel grain filling is a challenge restricting summer maize yield, and yield losses of more than 10% can be attributed to normal inferior kernel development failure or poor filling under dense planting conditions. Consequently, promoting inferior kernel establishment and filling is an important means of exploiting maize yield potential, and has become a key focus of research.[8] To date, research into inferior kernel grain filling characteristics has mainly focused on the impact of variety,[9] moisture,[6,10] nitrogen fertilizer,[11] and planting density,[12] whereas little research has focused on the impact of tillage practices.

Conservation tillage systems can improve soil physicochemical properties and increase soil water content (SWC).[13–15] However, in China, current research on tillage methods is more focused on subsoiling.[1,16–18] A 2 year study[19] showed that the process of subsoiling can loosen the soil, which increases the risk of wind and water erosion of soils and losses due to soil water evaporation. This can be detrimental to agricultural development, especially in semi-arid regions such as China's Loess Plateau area where soil erosion is already a serious issue. Subsoiling can also reduce soil organic matter and result in high greenhouse gas (GHG) emissions.[18] This can have a

---

* Correspondence to: W Niu, Institute of Soil and Water Conservation, Northwest A&F University, Yangling, 712100, China. E-mail: nwq@nwafu.edu.cn

a College of Water Resources and Architectural Engineering, Northwest A&F University, Yangling, 712100, China

b Institute of Soil and Water Conservation, Northwest A&F University, Yangling, China

c University of Chinese Academy of Sciences, Beijing, 100049, China

negative impact on the soil and air environment. No tillage (NT) and reduced tillage (RT) are becoming accepted as sustainable agricultural management practices. The area of NT agriculture was estimated to be $7.29 \times 10^7$ ha globally in 2016 (12.5% of the global agricultural area) and is increasing at a rate of $4.25 \times 10^6$ ha per year.[20] Reduced tillage and NT can improve SWC, facilitating improved root systems, increased nutrient uptake, and enhanced photosynthesis. A 3 year study[21] in a semi-arid region showed that NT significantly increased SWC at a depth of 0–90 cm, while the lowest SWC was observed with conventional tillage (CT). Increased SWC improves the chlorophyll content[1] and photosynthesis of leaves,[22,23] which correspondingly enhances grain filling.[24] Increased chlorophyll delays leaf senescence and increases the assimilation rate.[25] As effective grain filling is related to the ability to accommodate and absorb assimilates,[26] RT and NT may improve the photosynthetic characteristics and grain filling of the summer maize inferior kernel by regulating SWC.

China's Loess Plateau is a very important area for maize cultivation, producing $6.11 \times 10^7$ t in 2016 (approximately 10% of China's cereal yield).[27] However, the uneven distribution of rainfall and large evaporation losses (1500 mm) make soil water an important factor that limits agricultural sustainability in the region.[28,29] Techniques of conservation tillage to increase SWC are essential for sustainable intensification of crop production.[30] Conventional tillage management (frequent plowing without straw mulching) can also contribute to soil degradation and erosion.[31] Consequently, RT and NT may be effective for soil and water conservation in China's semiarid Loess Plateau.

In the present study, we hypothesized that RT and NT could increase grain yield by improving soil water content, summer maize photosynthetic capacity and inferior kernel grain filling. The objectives of the paper are to: (i) investigate the effects of RT and NT on SWC and root growth of summer maize in a semi-arid region, and (ii) study summer maize photosynthetic capacity and inferior kernel filling to reveal the effects and mechanisms of RT and NT on improving maize yield.

## MATERIALS AND METHODS

### Study site

The field experiment supported by the Ministry of Education was conducted at the Key Laboratory of Agricultural Soil and Water Engineering in Arid and Semiarid Areas (34° 20′ N, 108° 23 ′ E, 521 m a.s.l. ), Northwest A & F University, Yangling, Shaanxi Province, China. The site was located in the south-central region of the Loess Plateau, in a semi-arid and semi-humid climate zone with a mean annual precipitation of approximately 632 mm, a temperature of 12.9 °C, a frost-free period of 210 days, and 2163.8 h sunshine. The primary soil at the experiment station is medium loam with a 23–25% field water-holding capacity (0–100 cm), a pH of 8.1, organic matter content of 13.3 g $kg^1$, available nitrogen content of 69.0 mg $kg^{-1}$, available phosphorus content of 23.3 mg $kg^{-1}$, and available potassium content of 88.5 mg $kg^{-1}$.

Daily temperature and rainfall (Fig. 1) were obtained from the automatic weather station (Yang Ling National Meteorological Observing Station).

### Experimental design

The dates for this study were between June 2019 and October 2020. Three tillage systems were evaluated: (i) conventional tillage (CT; a plowing depth of 20 cm), (ii) no tillage (NT; soil was left uncultivated before seeding), and (iii) reduced tillage (RT; zero tillage in the maize seasons and a plowing depth of 20 cm in the wheat seasons). The experimental plots were designed in randomized blocks. Each plot had three replicates, and they were 5 × 10 m, extending in a north–south direction and surrounded by protection rows, with 1.5 m spacing between plots. In the NT and RT experiments, stubble from the previous crop harvest was left and 4.0 t $ha^{-1}$ (a depth of approximately 3–5 cm) was chopped and spread on the soil surface prior to seedbed preparation. The experimental operation was sowing, fertilizing, returning the wheat straw to the field, and top dressing the remaining 2/3 of the N fertilizer. In the CT experiment, the straw from the previous winter wheat was baled, and no stubble remained on the soil surface.

Zheng dan 958 maize was sown by hand on June 12 2 019 and June 19 2 020. There was 60 cm spacing between rows, and three seeds per hole. After the corn had grown three true leaves, the seedlings were interrupted and thinned to a density of $7.5 \times 10^4$ plants $hm^{-2}$. Each plot was fertilized with nitrogen fertilizer (1/3 of 170 kg $ha^{-132}$), 75 kg $ha^{-1}$ $K_2O$ and 90 kg $ha^{-1}$ $P_2O_5$ as a base. Then, we top dressed the remaining 2/3 of nitrogen fertilizer on July 15 2 019, and July 22 2 020. Diseases and pests were controlled, and weeds were removed manually.

### Measurements and calculation

Data were measured at the jointing stage (V6), tasseling stage (VT), trumpet stage (V12), silking stage (R1), grain-forming stage (R2), milk-ripening stage (R3), and at maturity (R6).[33]

*Soil bulk density and soil porosity*

After maize harvest in 2020, the soil bulk density ($d$) was measured using the ring-cutting method for 0–10, 10–20, 20–40, and 40–60 cm soil depths. $d$ was calculated using Eqn (1).[16]

$$d = (W_1 - W_0) \times (1 - W) / R_V \tag{1}$$

where $d$ is soil bulk density (g $m^{-3}$), $W_0$ is the weight of cylinder (g), $W_1$ is the total weight of the cylinder and soil sample (g), $W$ is soil water content (%), $R_V$ is the volume of cutting ring ($cm^3$).

Soil porosity ($P_s$) was calculated with Eqn (2):[34]

$$P_s = \left(1 - \frac{d}{\rho}\right) \times 100\% \tag{2}$$

where $P_s$ is soil porosity (%), and $\rho$ is the density of soil solids, here assumed to be 2.63 g $cm^{-3}$.

*Soil water content and evapotranspiration*

The oven-drying method[35] was used to measure SWC at pre-sowing, V6, R1, R2, and R6. Soil water content was measured at 0–200 cm at the pre-sowing and harvest stages and 0–100 cm at all other stages at 10 and 20 cm intervals. Wet soil was taken with one soil auger (4.5 cm in diameter), one core per plot, loaded into aluminum boxes, dried at 105 °C for 30 min and 75 °C to a constant weight, and weighed. Evapotranspiration (ET) was calculated with Eqn (3):[36]

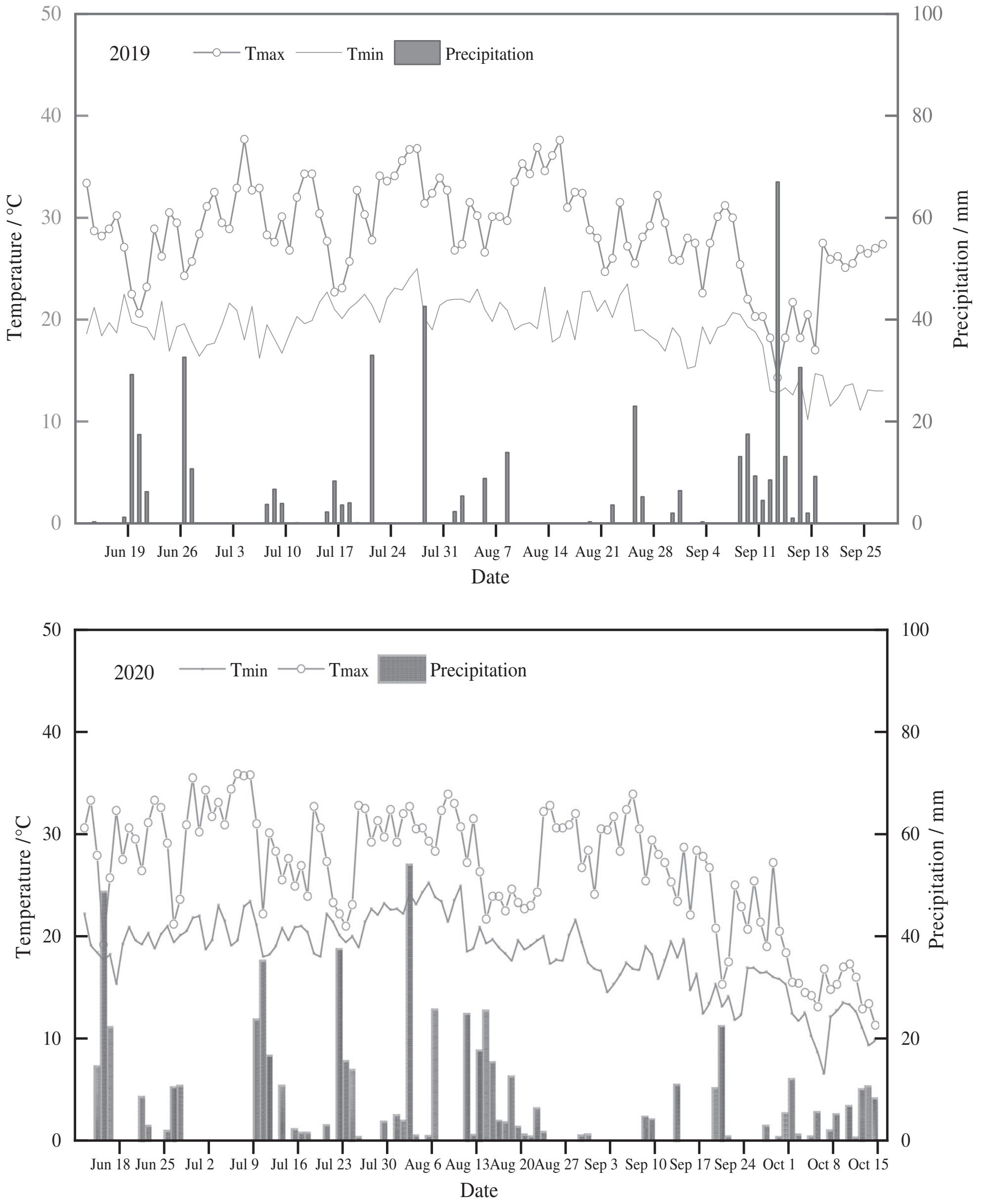

**Figure 1.** Meteorology from sowing to harvest in 2019 and 2020 included daily maximum and minimum air temperatures and precipitation for summer maize.

$$ET = P + I + \Delta W - SR - D \quad (3)$$

where *ET* is total evapotranspiration (mm), *P* is the precipitation during the growing season (mm), *I* is irrigation amount (mm), which equaled zero in this study because no irrigation was applied, $\Delta W$ is the difference between soil water storage in the 0–200 cm profile from sowing to harvest (mm). *SR* is runoff (mm), which was considered to be zero because each plot was surrounded by ridges to prevent runoff, *D* is the deep drainage into the lower 200 cm boundary (mm), which was assumed to be negligible in this study because no heavy rain or irrigation occurred during each maize-growing season.

### *Photosynthesis and crop growth*

The upper fourth of leaves or ear leaves (the similar growth and the same light direction) were used with photosynthetic instrument (LI-6800, Li-Cor, Inc., Lincoln, NE, USA) at R2 in 2019 and V6, VT, R2, and R6 in 2020. Three plants were randomly selected in each plot, and the mean of photosynthetic parameters of three plants was taken. Measurements at each plot were conducted from 10:00–11:00 using an open-air path at a photosynthetic photo-flux density of 1250 μ mol $m^{-2} \cdot s^{-1}$, natural illumination, and $CO_2$ concentration of 400 μ mol $mol^{-1}$. The net photosynthetic rate ($P_n$; μ mol $m^{-2} \cdot s^{-1}$), transpiration rate (*E*; mmol $m^{-2} \cdot s^{-1}$), intercellular $CO_2$ concentration ($C_i$; μ mol $mol^{-1}$), and stomatal conductance ($G_s$; mol $m^{-2} \cdot s^{-1}$) were included. Transpiration efficiency was calculated with Eqn (4):

$$T_a = \frac{P_n}{E} \quad (4)$$

where $T_a$ is the transpiration efficiency, $P_n$ is the net photosynthetic rate (μ mol $m^{-2}$ $s^{-1}$), and *E* is the transpiration rate (m mol $m^{-2}$ $s^{-1}$).

The chlorophyll content was measured at V6 and R2 in 2019 and V6, R1, R2, R3, and R6 in 2020, with three replicates. The leaf position for the chlorophyll content measurement was the same as the leaf position for the photosynthesis measurement. Leaf chlorophyll (a and b) was extracted using a 95% ethanol solution and then subjected to spectrophotometric absorbance at 649, 665 and 470 nm, and calculated by Li *et al*., (2016).[37]

Three representative plants were selected at V6, VT, R1, R2, and R6 in 2019 and 2020. The organs (stem, leaves, and ears) were divided and dried for 30 min at 105 °C, dried to a constant weight at 75 °C, and weighed.

The dry matter partitioning ratio ($DPR_i$) was calculated by Eqn (5):[38]

$$DPR_i = \frac{D_i}{DMA} \times 100\% \tag{5}$$

where $DPR_i$ is the dry matter partitioning ratio (lrb %); $DMA$ is the total above-ground dry matter accumulation (g), and $D_i$ is the dry weight of stems, leaves and ears (g).

### *Root growth*

A root sample from each plant was taken from each plot using soil monolith excavation[39] at physiological maturity in 2019 and 2020. Three plants from the inner lines of replicate plots were randomly selected, and root samples were collected by digging a layer every 10 cm to 60 cm depth, then the samples were bagged and returned to the laboratory. A 0.25 mm sieve and tap water were used to remove the soil. The clean root was scanned with the root scanner (Epson Perfection V800, California, USA). Root length (cm), root area ($cm^2$), and root volume ($cm^3$) were analyzed using the Win RHIZO software (Regents Instruments Inc., Quebec City, Canada). The root length density ($RLD$; cm $cm^{-3}$), root volume density ($RVD$; $10^3$ $cm^3$ $cm^{-3}$), and root area density ($RSD$; $cm^2$ $cm^{-3}$) were calculated as in Eqns (6)–(8):[40–42]

$$\mathrm{RLD} = \frac{L}{VT} \tag{6}$$

$$RSD = \frac{S}{VT} \tag{7}$$

$$RVD = \frac{V_0}{VT} \tag{8}$$

where $L$ is the total root length (cm), $S$ is the total root area ($cm^2$), $V_0$ is the total root volume ($cm^3$), and $VT$ is the actual volume ($25 \times 15 \times 60$ $cm^3$).

### *Grain filling*

In 2020, 18 representative plants were tagged before flowering in each plot, beginning 6 days after silking, three plants per treatment every 6 days, and 6 times in total. Kernels were peeled off from the apex of the ear, inferior kernels that did not develop normally were removed, and 100 kernels were counted, dried to a constant weight at 75 °C, and weighed. The grain-filling process is compatible with the growth equation:[43]

$$\mathrm{M} = \frac{A}{\left(1 + Be^{-Kt}\right)^{\frac{1}{N}}} \tag{9}$$

The grain filling rate was calculated as the derivative of Eqn (9):

$$\mathrm{V} = \frac{\mathrm{KM}\left[1 - \left(\frac{M}{A}\right)^N\right]}{N} \tag{10}$$

where $M$ is the weight of the grains (g); $t$ is the number of days after silking (d); $A$ is the final 100 kernel weight (mg). $B$, $K$, and $N$ are coefficients determined by the regression.

The secondary parameters of grain-filling characteristics were derived according to the method described by Qing-Sen Zhu.[4] The dry weight of 100 kernels at the maximum filling rate was calculated as follows:

$$M_{max} = \frac{A}{(1+N)^{1/N}} \tag{11}$$

The maximum grain-filling rate was calculated using the following formula:

$$V_{max} = KM_{max}\left[1 - (M_{\max}/A)^N/N\right] \tag{12}$$

The time to reach maximum filling rate was calculated as follows:

$$t_{max} = \ln(B/N)/K \tag{13}$$

The mean filling rate was calculated with the following formula:

$$V_{mean} = \frac{AK}{2(N+2)} \tag{14}$$

### *Grain yield*

Fresh grain from the nondestructive area of 2 m × 4 m in the middle of each replicate plot was sampled manually. At harvest, 15 ears of corn were selected randomly from each experiment plot and the 14% grain moisture content and the weight of 1000 kernels after threshing were measured. Yield composition included the number of ears per unit area, kernels per row, and kernel rows.

**Table 1.** Soil porosity and soil bulk density of three treatments after summer maize harvest in Oct.2020

| Soil depth (cm) | Treatment | Soil bulk density (g $cm^{-3}$) | Soil porosity (%) |
|---|---|---|---|
| 0–10 | CT | 1.46 ± 0.06b | 44.3 ± 2.5a |
| | NT | 1.62 ± 0.05a | 38.4 ± 2.3b |
| | RT | 1.47 ± 0.07b | 44.2 ± 2.3a |
| 10–20 | CT | 1.51 ± 0.08b | 42.8 ± 2.4a |
| | NT | 1.63 ± 0.04a | 38.0 ± 3.3b |
| | RT | 1.48 ± 0.07b | 43.6 ± 3.6a |
| 20–40 | CT | 1.58 ± 0.06b | 40.0 ± 2.3a |
| | NT | 1.59 ± 0.08b | 39.7 ± 2.4a |
| | RT | 1.62 ± 0.07a | 38.4 ± 3.0b |
| 40–60 | CT | 1.58 ± 0.09a | 39.8 ± 2.2b |
| | NT | 1.58 ± 0.08a | 39.8 ± 2.5b |
| | RT | 1.50 ± 0.06b | 41.8 ± 2.6a |

Different lowercase letters represent significant difference at 5% probability.
NT, no tillage; RT, reduced tillage; CT, conventional tillage.

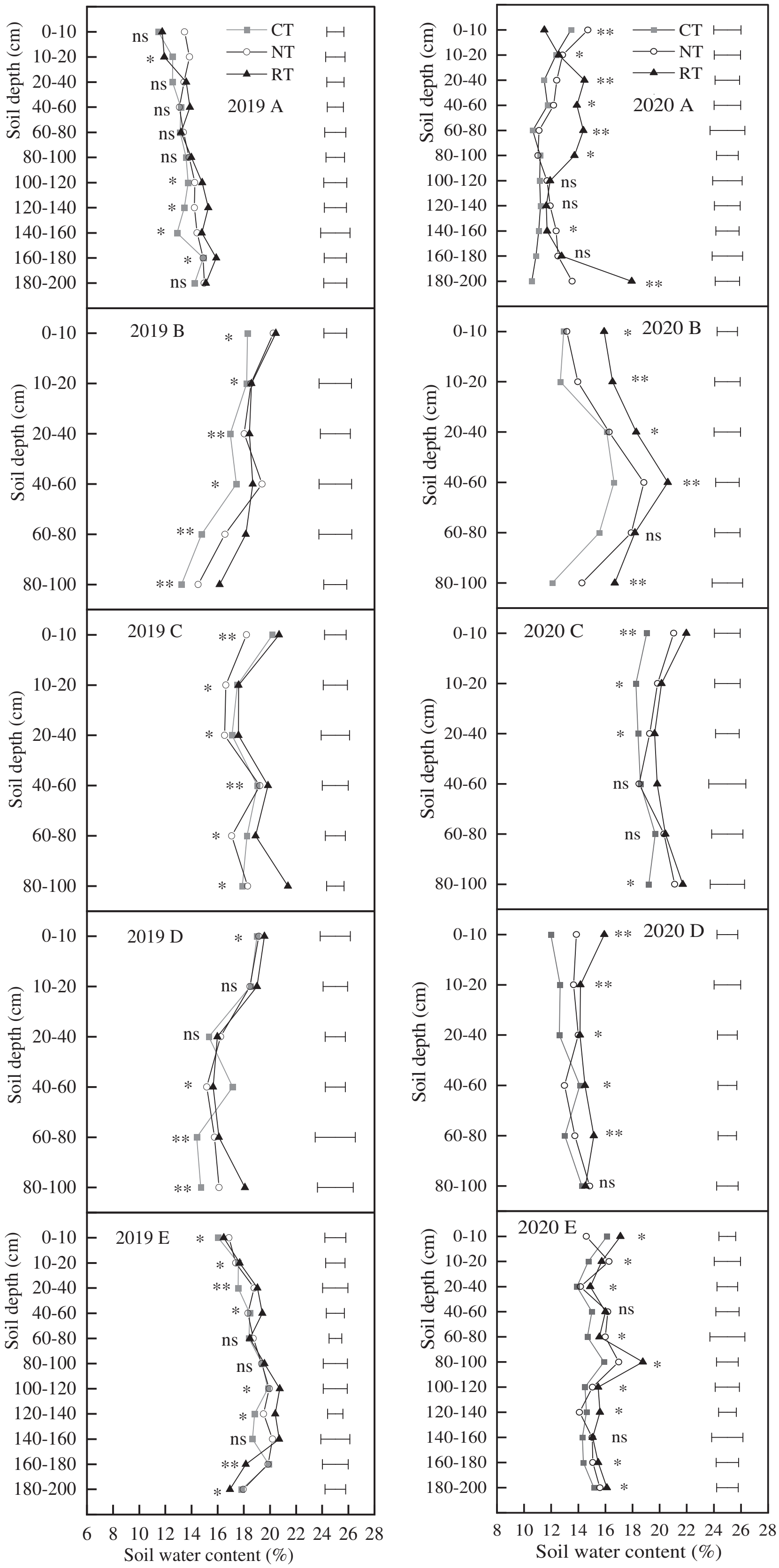

**Figure 2.** Soil water content in 2019 and 2020. NT, no tillage; RT, reduced tillage; CT, conventional tillage. A, B, C, and D represent pre-sowing stage, jointing stage, silking stage, grain filling stage, and physiological maturity, respectively. * and **, significant at $P \leq 0.05$ and $P \leq 0.01$. ns, not significant at $P \leq 0.05$. Bars indicate the standard error of means.

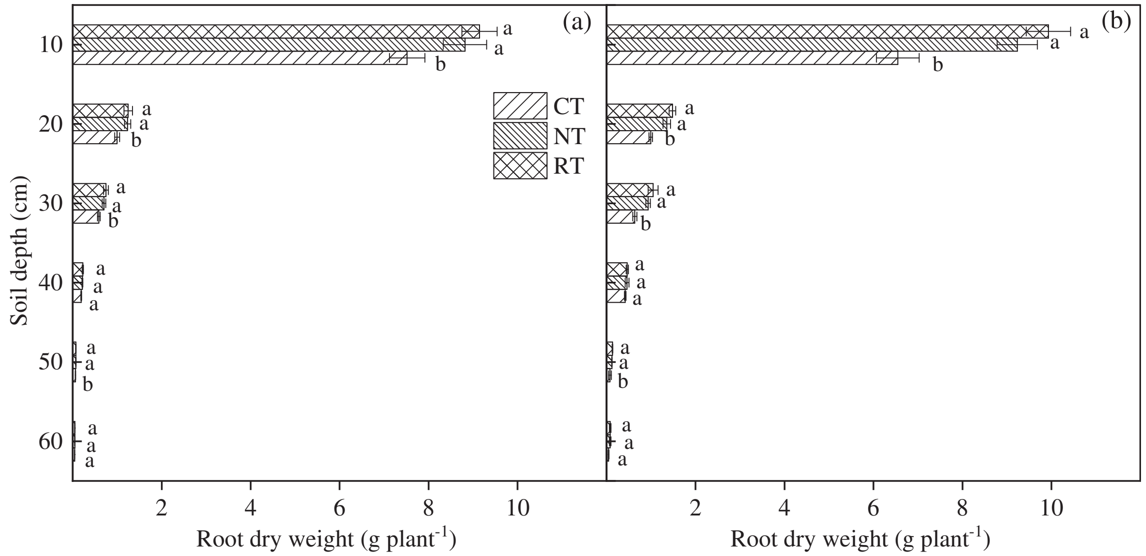

**Figure 3.** Root dry weight at maturity (a) in 2019 and (b) in 2020. NT, no tillage; RT, reduced tillage; CT, conventional tillage. Different lowercase letters represent significant differences at 5% probability. Bars indicate the standard errors.

**Table 2.** Root morphology included root length density (RLD), root area density (RSD), root volume density (RVD) of three treatments in 2019 and 2020

| Treatment | Physiological maturity of 2019 | | | Physiological maturity of 2020 | | |
|---|---|---|---|---|---|---|
| | RLD (cm cm$^{-3}$) | RSD (cm$^2$ cm$^{-3}$) | RVD (10$^3$ cm$^3$ cm$^{-3}$) | RLD (cm cm$^{-3}$) | RSD (cm$^2$ cm$^{-3}$) | RVD (10$^3$ cm$^3$ cm$^{-3}$) |
| CT | 0.22b | 0.05b | 1.12b | 0.24b | 0.06b | 1.18b |
| NT | 0.26ab | 0.07a | 1.30a | 0.30a | 0.07a | 1.40a |
| RT | 0.27a | 0.07a | 1.34a | 0.29a | 0.07a | 1.38a |
| LSD (0.05, %) | 1.81 | 0.50 | 9.32 | 9.05 | 0.30 | 12.60 |

Lowercase letters represent significant difference at 5% probability. LSD, least significant differences.
NT, no tillage; RT, reduced tillage; CT, conventional tillage.

**Table 3.** Chlorophyll a or b content of leaf at the jointing stage (V6) and grain filling stage (R2) in 2019 and during the whole growing season (the jointing stage V6, tasseling stage VT, grain filling stage R2, milk ripening stage R3 and physiological maturity stage R6) in 2020

| Chlorophyll a or b (mg L$^{-1}$) | Treatment | 2019 | | 2020 | | | | |
|---|---|---|---|---|---|---|---|---|
| | | V6 | R2 | V6 | VT | R2 | R3 | R6 |
| a | CT | 7.46b | 10.91c | 7.50b | 12.03c | 11.88b | 10.05b | 10.54b |
| | NT | 8.32a | 11.51b | 8.72a | 12.53a | 13.35a | 11.60a | 11.93a |
| | RT | 8.60a | 12.43a | 8.23ab | 12.12b | 12.11b | 11.54a | 11.39a |
| | LSD (0.05) | 0.40 | 0.18 | 0.31 | 0.03 | 0.05 | 0.31 | 0.22 |
| b | CT | 1.93b | 3.51a | 1.60 b | 3.45 a | 3.57 a | 2.72b | 2.70b |
| | NT | 2.36a | 3.60a | 2.96 a | 3.45a | 3.82 a | 3.65a | 2.87a |
| | RT | 2.47a | 3.68a | 2.69ab | 3.46a | 3.88 a | 3.64 a | 2.85a |
| | LSD (0.05) | 0.17 | 0.14 | 0.47 | 0.03 | 0.26 | 0.12 | 0.03 |

Different lowercase letters represent significant difference at 5% probability. LSD, least significant differences.
NT, no tillage; RT, reduced tillage; CT, conventional tillage.

## Statistical analysis

The ANOVA was conducted using SPSS 23.0, and significance was set at $P \leq 0.05$. Origin 2020 software was used for graphing and simulation. Treatment means were compared by computing least significant differences (LSDs) to identify significant differences at the 0.05 probability level. Pearson correlations were used to assess the extent and significance of linear correlations between the dependent variables evaluated in the study.

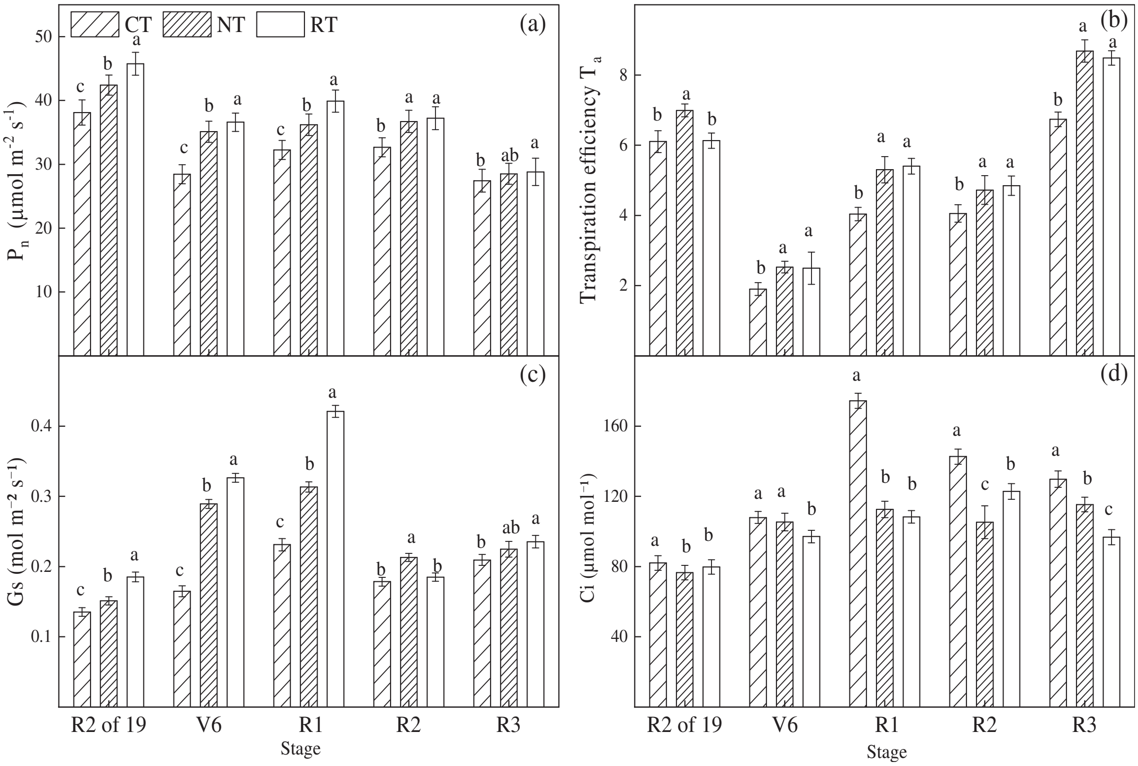

**Figure 4.** $P_n$ (a), $T_a$ (b), $G_s$ (c), $C_i$ (d) in three treatments at grain filling stage in 2019 (R2 of 2019) and the jointing stage (V6), silking stage (R1), grain filling stage (R2) and milk ripening stage (R3) in 2020. NT, no tillage; RT, reduced tillage; CT, conventional tillage. Different lowercase letters represent significant difference at 5% probability. Bars indicate the standard errors.

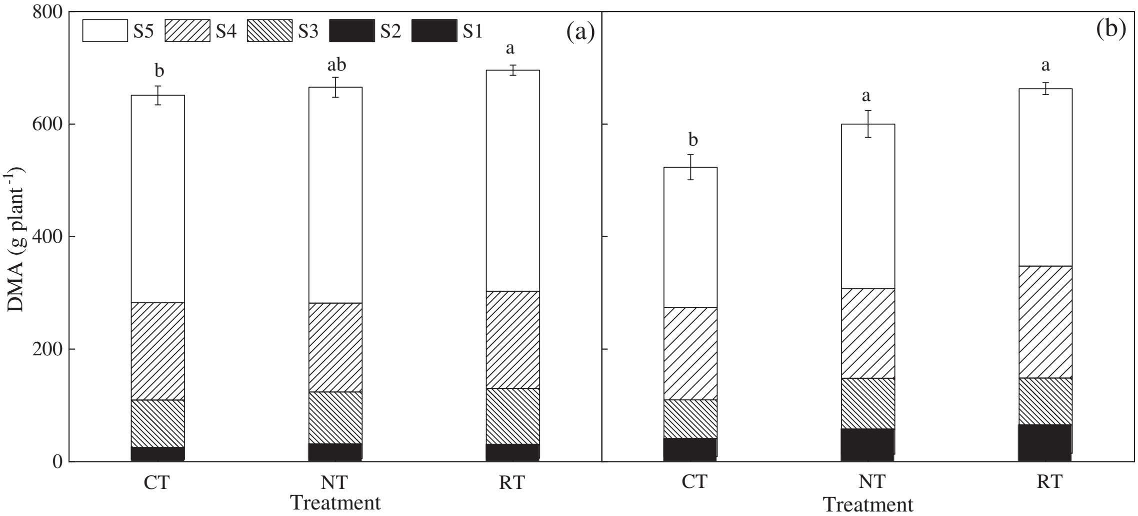

**Figure 5.** Above-ground dry matter accumulation (DMA) in three treatments at the jointing stage V6 (S1), tasseling stage VT (S2), silking stage R1 (S3), grain filling stage R2 (S4) and maturity R6 (S5) in 2019 (a) and 2020 (b). NT, no tillage; RT, reduced tillage; CT, conventional tillage. Different lowercase letters represent significant difference at 5% probability. Bars indicate the standard errors.

# RESULTS

## Meteorology

Similar trends in the daily maximum ($T_{max}$) and minimum ($T_{min}$) air temperature are shown in Fig. 1 for the 2019 and 2020 maize-growing seasons. During the two maize-growing seasons, precipitation (P) was 511 mm in 2019 and 507 mm in 2020.

## Soil bulk density and soil water content

At 0–20 cm depth, soil bulk density was increased and soil porosity was reduced in the NT experiment (Table 1) compared to CT and RT, whereas the difference was not significant between CT and RT with respect to soil porosity.

Conservational tillage practices (RT and NT) retained more SWC at 0–60 cm for almost all measured growth stages (with the

**Table 4.** Above-ground dry matter allocation rate of summer maize at grain filling stage and evapotranspiration (ET) of maize in 2019 and 2020 as affected by year and tillage system

| Year | Treatment | ET (mm) | Dry matter partitioning ratio (%) | | |
|---|---|---|---|---|---|
| | | | Stem | Leaf | Ear |
| 2019 | CT | 344e | 41.2b | 20.5a | 38.3c |
| | NT | 355e | 38.1d | 18.5b | 43.4ab |
| | RT | 362d | 38.3 cd | 17.6bc | 44.1a |
| 2020 | CT | 401c | 42.0a | 19.9a | 38.1c |
| | NT | 414bc | 39.1c | 18.4b | 42.4b |
| | RT | 421a | 38.8 cd | 17.0c | 44.1a |
| ANOVA (*P*-value) | Year (Y) | 50.2** | 86.6** | 35.8** | 179.6** |
| | Tillage (T) | 36.14* | 15.30* | 2.55 | 2.38 |
| | Y × T | 11.02* | 0.36 | 0.42 | 1.28 |
| | LSD (0.05) | 2.42 | 0.33 | 0.30 | 0.30 |

Note: Different lowercase letters represent significant difference at 5% probability. LSD, least significant differences. NT, no tillage; RT, reduced tillage; CT, conventional tillage. CV, coefficient of variation. * and ** are significant at 5% and 1%, respectively.

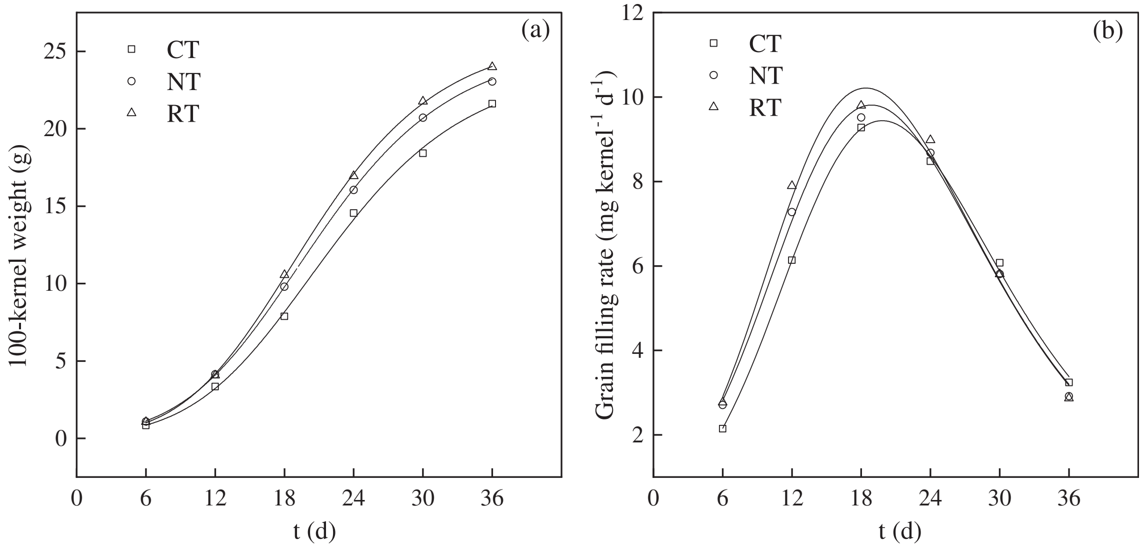

**Figure 6.** Richards fitting curves of summer maize grain filling of three treatments in 2020. The final 100-kernel weight (a), inferior kernel grain filling rate (b) as affected by tillage practices. NT, no tillage; RT, reduced tillage; CT, conventional tillage.

exception of R1 in 2019) over both study years (Fig. 2). In 2019, compared to CT, RT and NT increased SWC at the V6 and R6 stages. However, CT had a higher SWC than NT at R1. The SWC of RT was significantly higher than CT and NT in most layers. In 2020, compared with CT, RT increased SWC by 22%, 11%, 14% at the V6, R1, R2, respectively; NT increased SWC by 7%, 8%, 6% at the V6, R1, R2, respectively. The NT and CT experiments from V6 to R6 in 2019 showed no significant difference in soil water content at 60–200 cm soil depth; however, in 2020, the difference was significant at this depth, and the order was RT > NT > CT.

### Root growth

Root dry weight decreased rapidly with increased soil depth, and was affected significantly by three tillage practices in the 0–30 cm depth in 2019 and 2020 (Fig. 3). The root dry weight was RT > NT > CT at maturity in both study years. At maturity in 2020, NT and RT increased by 20% and 28%, respectively, in comparison with CT.

Tillage practices had significant effects on root morphology (Table 2). For example, in comparison with NT and RT, *RLD*, *RSD*, and *RVD* were significantly lower in CT at maturity in 2019 and 2020, while the difference was not significant between NT and RT. Compared with CT, the *RLD* of RT was increased by 23% in 2019 and 18% at maturity in 2020; the RLD of NT was increased by18% in 2019 and 20% at maturity in 2020.

### Photosynthesis and crop growth

As the maize grew, the chlorophyll content tended to increase initially and then decrease (Table 3). At V6 and R2 in 2019, NT and RT had significantly higher chlorophyll content in comparison with CT, and the difference was not significant between NT and RT. Averaged across the V6, VT, R2, R3, and R6 stages of summer maize in 2020, NT produced the most leaf chlorophyll a, followed by RT and CT. Compared with CT, Chlorophyll a in NT increased by 16% and 15% at V6 and R3, respectively; Chlorophyll a in RT increased by 10% and 15% at V6 and R3, respectively, while the

**Table 5.** Simulated (A), Weight at maximum grain filling rate ($M_{max}$), maximum grain filling rate ($V_{max}$), time reaching a maximum grain filling rate $t_{max}$ and mean grain filling rate ($V_{mean}$) in three treatments in 2020

| Treatment | A (mg kernel$^{-1}$) | $R^2$ | $M_{max}$ (mg kernel$^{-1}$) | $V_{max}$ (mg kernel$^{-1}$ d$^{-1}$) | $t_{max}$ (d) | $V_{mean}$ (mg kernel$^{-1}$ d$^{-1}$) |
|---|---|---|---|---|---|---|
| CT | 240.6c | 0.994 | 103.3b | 10.15c | 20.14a | 6.9c |
| NT | 252.1b | 0.995 | 110.2a | 10.99b | 19.15b | 7.4b |
| RT | 262.0a | 0.996 | 111.9a | 11.60a | 18.90b | 7.8a |
| LSD (0.05) | 25.60 | — | 12.10 | 0.15 | 0.26 | 0.11 |

Lowercase letters represent significant difference at 5% probability. LSD, least significant differences.
NT, no tillage; RT, reduced tillage; CT, conventional tillage.

**Table 6.** Grain yield in three treatments in 2019 and 2020 as affected by year and tillage system

| Year | Treatment | The number of ear ($10^4$ ha$^{-1}$) | Number of kernels per ear | 1000- kernel weight (g) | Grain yield (t ha$^{-1}$) |
|---|---|---|---|---|---|
| 2019 | CT | 6.43 a | 466.3 d | 323.7 d | 9.64 c |
|  | NT | 6.33 a | 479.6 d | 333.4 c | 9.80 c |
|  | RT | 6.40 a | 506.3 c | 349.9 b | 10.51 b |
| 2020 | CT | 6.48 a | 515.7 c | 321.2 d | 9.34 d |
|  | NT | 6.30 a | 544.3 b | 341.9 a | 10.60 b |
|  | RT | 6.31 a | 552.3 a | 346.7 a | 10.90 a |
| ANOVA (F–value) | Tillage practice (T) | 0.2 | 11.4 ** | 24.6 ** | 78.6 ** |
|  | Year (Y) | 0.4 | 66.2 ** | 7.5 ** | 34.0 ** |
|  | T × Y | 0.11 | 0.77 | 5.24 * | 27.01 ** |

Different lowercase letters represent significant difference at 5% probability. NT, no tillage; RT, reduced tillage; CT, conventional tillage. CV, coefficient of variation. * and ** are significant at 5% and 1%, respectively.

**Table 7.** Pearson's correlation coefficient among evapotranspiration (ET), soil water content (SWC) in the 0–60 cm soil depth, total root dry matter accumulation (RDMA) at maturity, net photosynthetic rate ($P_n$), intercellular $CO_2$ concentration ($C_i$), total above-ground dry matter accumulation (DMA), 100–kernel weight at final grain filling (M), grain yield (Y) across tillage practices

|  | ET | SWC | RDMA | $P_n$ | DMA | M | Y |
|---|---|---|---|---|---|---|---|
| SWC | 0.53 * |  |  |  |  |  |  |
| RW | 0.74 * | 0.70 * |  |  |  |  |  |
| $P_n$ | 0.88 ** | 0.82 ** | 0.78 * |  |  |  |  |
| DMA | 0.75 ** | 0.91 ** | 0.86 ** | 0.88 ** |  |  |  |
| F | 0.82 ** | 0.73 * | 0.70 * | 0.86 ** | 0.69 * |  |  |
| Y | 0.63 ** | 0.89 ** | 0.74 ** | 0.75 * | 0.83 ** | 0.90 * |  |
| $C_i$ | −0.73 ** | −0.54 * | −0.64 * | −0.70 * | −0.76 * | −0.75 * | −0.80 ** |

Correlation coefficients for * and ** are significant at 5% and 1%, respectively.

difference between NT and RT was not significant in the late grain filling stage. Differences in chlorophyll b were significant in the late stage of grain filling; NT and RT showed increases of 35 and 34%, respectively, in comparison with CT, and the difference between NT and RT was not significant.

$P_n$, $T_a$, $G_s$, and $C_i$ were significantly affected by tillage practices in both study years (Fig. 4). RT had the highest $P_n$ and CT had the lowest at all growth stages in 2019 and 2020. In comparison with CT, transpiration efficiency was higher in RT and NT, and peak $T_a$ in NT and RT was 12% and 24% higher, compared to CT at R1, respectively. The $G_s$ of RT and NT increased by 55% and 35%, respectively, compared with CT. Conversely, $C_i$ showed the opposite result; CT was higher than NT and RT at all stages.

Above-ground dry matter (DMA) was significantly impacted by tillage practices in both study years (Fig. 5). Reduced tillage significantly increased DMA in comparison with CT in 2019 ($P < 0.05$), whereas NT showed no difference. In 2020, DMA was 18% higher in NT and 46% higher in RT in comparison with CT. During all stages, DMA was the highest in RT, followed by NT and CT, and the differences between NT and RT were not significant.

Table 4 shows that the evapotranspiration (ET) of RT was significantly higher than that of CT. The difference between NT and CT was not significant in 2019. In 2020, the ET of RT and NT was significantly higher than that of CT. The above-ground dry matter allocation rate of summer maize at the grain filling stage was similar in 2019 and 2020; dry matter was more in the ear than in the stem and leaf, and the ear dry matter partitioning ratios at grain filling stage were consistent over the two study years, indicating that the study results were valid and consistent.

### Grain filling

Figure 6 shows that the grain filling process was impacted by tillage practices. Growth curves of 100 kernel weight under different treatments showed slow initial growth, which accelerated during the middle stages and slowed again as the ear approached maturity. The 100 kernel weight of NT and RT was higher than that of CT throughout the growing season, and the difference was most apparent 24 days after silking, with relative increases of 12% and 15%, respectively.

The grain-filling parameters $t_{max}$ of CT were greater than those of NT and RT (Table 5), indicating that NT and RT reached the $V_{max}$ earlier. Both the maximum and mean grain filling rate were highest in RT, followed by NT and CT, and $V_{max}$ in RT and NT increased significantly by 10% and 7%, respectively, compared to CT. When grain filling was at an end, the 100 kernel weight of RT and NT increased significantly, by 11% and 5%, respectively, in comparison with CT.

### Grain yield

Grain yield and yield composition were significantly affected by the three tillage practices in both study years (Table 6). In 2019, RT had a significantly increased yield by 9% in comparison with CT, whereas the differences between NT and CT were not significant. In 2020, both RT and NT had significantly higher kernels, and thousand grain weight, and yield increased by 17% and 14%, respectively, in comparison with CT. There was a significant positive correlation between ET, grain yield, and SWC in the 0–60 cm depth (Table 7).

## DISCUSSION

Soil water content is an important indicator of the summer maize inferior kernel filling rate.[1] In the study, SWC was significantly higher, in comparison with CT, in NT and RT, indicating that RT and NT can increase the SWC. This is consistent with the results of Helgason *et al*., (2009),[44] Sainju *et al*., (2012)[45] and Unger *et al*., (1997)[46] in different areas. Straw/stubble mulching has been shown to be an effective agricultural practice that can be used to conserve water by suppressing soil evaporation, especially during the early crop growth stage when the crop canopy is small.[47,48] Limiting the amount of tillage also disturbs the soil less, leading to a relatively dense surface layer that inhibits soil-water evaporation,[47] resulting in higher SWC in NT and RT. Without mulching, higher soil porosity and more disturbance increased soil water evaporation loss;[16] the SWC under conventional tillage was therefore lower.

Roots are an integral plant organ responsible for the acquisition of water and nutrients. The amount of water taken up by roots depends on soil water supply, root morphology, and root physiological features.[8] No tillage and RT significantly improved root morphology, increased *RLD*, *RSD*, and *RVD*, and increased root dry weight at depths of 0–30 cm. This was consistent with Du *et al*. (2021).[49] This is because NT and RT increased soil water availability by increasing the soil water content. On the other hand, straw mulch on the soil surface formed a physical barrier that could block the solar radiation and prevent exchange between the soil and atmosphere, which would decrease the soil temperature when the air temperature was higher and increase the soil temperature when the air temperature was lower.[50] Crop straw return and limiting the amount of tillage (disturbs the soil less) had positive effects on soil microbial biomass by enhancing SOC and nutrient availability.[51] These facilitated the provision of more nutrients to the root system, promoted root growth, and ultimately increased root dry matter accumulation.

Higher soil water uptake by roots contributes to water transfer to the leaves, which in turn maintains effective photosynthesis.[52] In this study, NT and RT significantly increased the net photosynthetic rate of summer maize leaves. Furthermore, soil water uptake by the root system helped the leaf stomata to open and absorb more $CO_2$.[53] Compared with CT, the stomatal conductance of leaves in both the NT and RT experiments was significantly higher, and the intercellular $CO_2$ concentration was significantly lower. This indicates that NT and RT had enhanced leaf stomatal conductance by improving root water transfer to the leaves, which improved $CO_2$ utilization and increased the net photosynthetic rate.[53] Higher transpiration efficiency reflected the higher light energy radiation efficiency[54] in the NT and RT experiments, which was favorable for improving photosynthetic capacity. The transpiration rate of CT was higher than both NT and RT; however, the transpiration efficiency was the lowest. This was associated with the lower SWC and net photosynthetic rate. Furthermore, the NT and RT experiments displayed significantly increased chlorophyll content compared with CT, which was mainly due to the increased uptake and conversion of light energy and organic matter under NT and RT.[55] The higher photosynthesis resulted from the increased SWC and the improved root growth (Table 7). The improvement in photosynthesis was attributed to the increased SWC,[1] which agrees with our study. Moreover, the chlorophyll content of NT and RT remained higher than that of CT at maturity, indicating that NT and RT delayed leaf senescence and prolonged photosynthesis,[56] contributing to above-ground dry matter accumulation.

Kernel weight depends on DMA and the kernel distribution ratio.[38] Above-ground dry matter accumulation was significantly increased in the NT and RT experiments in comparison with CT, indicating that stronger photosynthesis provided more assimilates for grain filling. The dry matter partitioning ratio in the ear was higher in comparison with that in the stem and leaf at the grain filling stage in both 2 years. This indicates that the distribution of plant dry matter to the stem and leaves was reduced but ear was increased under NT and RT at the grain-filling stage, which contributed to grain filling.[38] The ear dry matter partitioning ratio was in highest under RT, followed by NT and CT, indicating that the ear dry matter partitioning ratio was closely related to grain filling. The ear dry matter partitioning ratio in 2019 was similar to that in 2020 (Table 4). This indicates that grain filling was similar in both years of the study.

Grain filling is a significant physiological process for starch synthesis and accumulation,[57] where photosynthetic assimilates are transported from stems, sheaths, and leaves to the grains in the sucrose forming, which then undergoes a series of enzymatic reactions to form starch.[58–60] An adequate availability of assimilates is therefore a major driving factor for high inferior kernel filling rates.[61] No tillage and RT had significantly increased inferior kernel filling rates 20 days after silking in 2020. In terms of grain filling characteristics, NT and RT significantly increased the *A*, $M_{max}$, $V_{max}$ and $V_{mean}$ of the inferior kernel, while $t_{max}$ was less than CT. This was because under NT and RT, the $V_{max}$ was reached earlier, and an adequate supply of assimilates increased the $V_{max}$

and $V_{mean}$, which in turn increased the A. $V_{max}$ and $V_{mean}$ were significantly positively correlated with grain quality,[27] and our study shows that the higher $V_{max}$ and $V_{mean}$ observed in the NT and RT experiments were also accompanied by an increase in grain yield.

Yield depends on the number of ears, the number of grains, and grain weight.[62] In comparison with CT, the number of ears was small under NT and RT; however, the 1000 kernel weight and yield were significantly higher. This indicates that the higher inferior kernel grain filling rate increased the overall grain weight, and ultimately increased the weight of 1000 kernel and summer maize yield. Additionally, yield can indirectly reflect inferior kernel grain filling of two study years (Table 7).

## CONCLUSIONS

Reduced tillage and no tillage increased the soil water content, which in turn had a positive effect on summer maize root growth, leaf chlorophyll, and photosynthesis, leading to increased biomass. Increased assimilates promoted inferior kernel grain filling and resulted in a higher grain yield compared with conventional tillage practices. Considering the higher benefits of increased yield and enhanced soil water storage, reduced tillage would be an optimal tillage strategy for sustainable agriculture on the semi-arid Loess Plateau.

## ACKNOWLEDGEMENTS

This research was supported by the National Natural Science Fund of China (52079112 and 51679205).

## REFERENCES

1 Lamptey S, Li L, Xie J and Coulter JA, Tillage system affects soil water and photosynthesis of plastic-mulched maize on the semiarid loess plateau of China. *Soil Till Res* **196**:104479 (2020).

2 Chen T, Xu Y, Wang J, Wang Z, Yang J and Zhang J, Polyamines and ethylene interact in rice grains in response to soil drying during grain filling. *J Exp Bot* **64**:2523–2538 (2013).

3 Borrás L and Gambín BL, Trait dissection of maize kernel weight: towards integrating hierarchical scales using a plant growth approach. *Field Crop Res* **118**:1–12 (2010).

4 Xu Y, Qian X, Li Y, Wang Z and Yang J, Effect of alternate irrigation in partitioned roots on the. Kernel-filling and its related physiological characteristics in maize. *Acta Agron Sin* **42**:230–242 (2016).

5 Nagato K, Differences in grain weight of spikelets located at different positions within a rice panicle. *Jpn J Crop Sci* **13**:156–169 (1941).

6 SHEN L-x, Huang Y-K and Ting L, Top-grain filling characteristics at an early stage of maize.(Zea mays L.) with different nitrogen use efficiencies. *J Integrat Agric* **16**:626–639 (2017).

7 Wang Z, Liang H, Gao J, Yu X, Sun J, Su Z *et al.*, Relationship of sink. Activity with endogenous hormones and polyamine contents in inferior kernels of maize. *Acta Agron Sin* **43**:1196–1204 (2017).

8 Wang Z, Gao J and Ma B, Concurrent improvement in maize yield and nitrogen use efficiency with integrated agronomic management strategies. *Agron J* **106**:1243–1250 (2014).

9 Xu T, Lyu T, Zhao J, Wang R, Chen C, Liu Y *et al.*, Photosynthetic characteristics, dry matter accumulation and translocation, grain filling parameter of three main maize varieties in production. *Acta Agron Sin* **44**:414–422 (2018).

10 Yao S, Kang Y, Lü G, Liu M, Yang W and Li D, Analysis on grain filling characteristics of winter wheat under sprinkler irrigation and surface irrigation conditions. *Trans Chinese Soc Agric Eng* **27**:13–17 (2011).

11 Paponov I, Bondarenko Y, Neumann G and Engels C, Effect of nitrogen supply on individual kernel weight and partitioning in kernels of maize during lag phase and grain filling. *Plant Nutr* **92**:122 (2006).

12 Jia Q, Sun L, Mou H, Ali S, Liu D, Zhang Y *et al.*, Effects of planting patterns and sowing densities on grain-filling, radiation use efficiency and yield of maize (Zea mays L.) in semi-arid regions. *Agric Water Manag* **201**:287–298 (2018).

13 Gao L, Becker E, Liang G, Houssou AA, Wu H, Wu X *et al.*, Effect of different tillage systems on aggregate structure and inner distribution of organic carbon. *Geoderma* **288**:97–104 (2017).

14 Wang Z, Li T, Li Y, Zhao D, Han J, Liu Y *et al.*, Relationship between the microbial community and catabolic diversity in response to conservation tillage. *Soil Till Res* **196**:104431 (2020).

15 Yang H, Wu G, Mo P, Chen S, Wang S, Xiao Y *et al.*, The combined effects of maize straw mulch and no-tillage on grain yield and water and nitrogen use efficiency of dry-land winter wheat (Triticum aestivum L.). *Soil Till Res* **197**:104485 (2020).

16 Zhai L, Wang Z, Song S, Zhang L, Zhang Z and Jia X, Tillage practices affects the grain filling of inferior kernel of summer maize by regulating soil water content and photosynthetic capacity. *Agric Water Manag* **245**:106600 (2021).

17 Gong H, Li J, Ma J, Li F, Ouyang Z and Gu C, Effects of tillage practices and microbial agent applications on dry matter accumulation, yield and the soil microbial index of winter wheat in North China. *Soil Till Res* **184**:235–242 (2018).

18 Wang C, Zhao J, Feng Y, Shang M, Bo X, Gao Z *et al.*, Optimizing tillage method. And irrigation schedule for greenhouse gas mitigation, yield improvement, and water conservation in wheat-maize cropping systems. *Agric Water Manage* **248** (2021).

19 McHugh OV, Steenhuis TS, Abebe B and Fernandes ECM, Performance of in situ rainwater conservation tillage techniques on dry spell mitigation and erosion control in the drought-prone north Wello zone of the Ethiopian highlands. *Soil Till Res* **97**:19–36 (2007).

20 Kassam A, Friedrich T and Derpsch R, Global spread of conservation agriculture. *Int J Environ Stud* **76**:29–51 (2019).

21 Gozubuyuk Z, Sahin U, Adiguzel MC, Ozturk I and Celik A, The influence of different tillage practices on water content of soil and crop yield in vetch–winter wheat rotation compared to fallow–winter wheat rotation in a high altitude and cool climate. *Agric Water Manag* **160**:84–97 (2015).

22 Luo L, Yu Z, Wang D, Zhang Y and Shi Y, Effects of planting density and soil moisture on flag leaf photosynthetic characteristics and dry matter accumulation and distribution in wheat. *Acta Agron Sin* **37**:1049–1059 (2011).

23 Zhang KK, Zhou SM, Zhang M, Shi SS and Yin J, Effects of reduced nitrogen application and supplemental irrigation on photosynthetic characteristics and grain yield in high-yield populations of winter wheat. *J Appl Ecol* **27**:863–872 (2016) (in Chinese).

24 Li Y, Yang L, Wang H, Xu R, Chang S, Hou F *et al.*, Nutrient and planting modes strategies improves water use efficiency, grain-filling and hormonal changes of maize in semi-arid regions of China. *Agric Water Manag* **223**:105723 (2019).

25 He J, Shi Y, Zhao J and Yu Z, Strip rotary tillage with subsoiling increases winter wheat yield by alleviating leaf senescence and increasing grain filling. *Crop J* **8**:327–340 (2020).

26 Yang J, Zhang J, Wang Z and Zhu Q, Hormones in the grains in relation to sink strength and postanthesis development of spikelets in rice. *Plant Growth Regul* **41**:185–195 (2003).

27 Fang H, Gu XB, Jiang TC, Yang JY, Li YN, Huang P *et al.*, An optimized model for simulating grain-filling of maize and regulating nitrogen application rates under different film mulching and nitrogen fertilizer regimes on the loess plateau, China. *Soil Till Res* **199**:11 (2020).

28 Xiaoli C, Pute W, Xining Z, Xiaolong R and Zhikuan J, Rainfall harvesting and mulches.Combination for corn production in the subhumid areas prone to drought of China. *J Agron Crop Sci* **198**:304–313 (2012).

29 Liu XE, Li XG, Hai L, Wang YP and Li FM, How efficient is film fully-mulched ridge–furrow cropping to conserve rainfall in soil at a rainfed site? *Field Crop Res* **169**:107–115 (2014).

30 Ali G, Wang ZK, Li XR, Jin NX, Chu HY and Jing LJ, Deep soil water deficit and recovery in.Alfalfa fields of the loess plateau of China. *Field Crop Res* **260**:107990 (2021). https://doi.org/10.1016/j.fcr.2020.107990

31 Camarotto C, Dal Ferro N, Piccoli I, Polese R, Furlan L, Chiarini F *et al.*, Conservation agriculture and cover crop practices to regulate water, carbon and nitrogen cycles in the low-lying venetian plain. *Catena* **167**:236–249 (2018).

32 Yang X, Lu Y, Ding Y, Yin X, Raza S and Tong Y, Optimising nitrogen fertilisation: a key to improving nitrogen-use efficiency and minimising nitrate leaching losses in an intensive wheat/maize rotation (2008–2014). *Field Crop Res* **206**:1–10 (2017).

33 Abendroth L, Elmore, R., Boyer, M., Marlay, S., *Corn growth and development*.Iowa State Univ. Extension Publication #PMR-1009 (2011).

34 Botta G, Jorajuria D, Balbuena R, Ressia M, Ferrero C, Rosatto H *et al.*, Deep tillage and traffic effects on subsoil compaction and sunflower (Helianthus annus L.) yields. *Soil Till Res* **91**:164–172 (2006).

35 Jia D, Dai X and He M, Polymerization of glutenin during grain development and quality expression in winter wheat in response to irrigation levels. *Crop Sci* **52**:1816–1827 (2012).

36 Wang D, Yu Z and White PJ, The effect of supplemental irrigation after jointing on leaf senescence and grain filling in wheat. *Field Crop Res* **151**:35–44 (2013).

37 Li Y, Niu W, Lü W, Gu J, Zou X, Wang J *et al.*, Aerated irrigation improving photosynthesis characteristics and dry matter accumulation of greenhouse tomato. *Trans Chinese Soc Agricl Eng* **32**:125–132 (2016).

38 Cai Q, Sun Z, Zheng J, Wang W, Bai W, Feng L *et al.*, Dry matter accumulation, allocation, yield and productivity of maizesoybean intercropping systems in the semi-arid region of Western Liaoning Province. *Sci Agric Sin* **54**:909–920 (2021) (in Chinese).

39 Thidar M, Gong D, Mei X, Gao L, Li H, Hao W *et al.*, Mulching improved soil water, root distribution and yield of maize in the loess plateau of Northwest China. *Agric Water Manag* **241**:106340 (2020).

40 Mosaddeghi M, Mahboubi A and Safadoust A, Short-term effects of tillage and manure on some. Soil physical properties and maize root growth in a sandy loam soil in western Iran. *Soil Till Res* **104**:173–179 (2009).

41 Li Q, Dong B, Qiao Y, Liu M and Zhang J, Root growth, available soil water, and water-use efficiency of winter wheat under different irrigation regimes applied at different growth stages in North China. *Agric Water Manag* **97**:1676–1682 (2010).

42 Qin R, Stamp P and Richner W, Impact of tillage on maize rooting in a Cambisol and Luvisol in Switzerland. *Soil Till Res* **85**:50–61 (2006).

43 Richards F, A flexible growth function for empirical use. *J Exp Bot* **10**: 290–301 (1959) (in Chinese).

44 Helgason BL, Walley FL and Germida JJ, Fungal and bacterial abundance in long-term no-till and intensive-till soils of the northern Great Plains. *Soil Sci Soc Am J* **73**:120–127 (2009).

45 Sainju UM, Caesar-TonThat T, Lenssen AW and Barsotti JL, Dryland soil greenhouse gas emissions affected by cropping sequence and nitrogen fertilization. *Soil Sci Soc Am J* **76**:1741–1757 (2012).

46 Unger PW, Schomberg HH, Dao TH and Jones OR, Tillage and crop residue management practices for sustainable dryland farming systems (1997).

47 Gajda A, Przewloka B and Gawryjolek K, Changes in soil quality associated with tillage system applied. *Int Agrophys* **27**:133–141 (2013).

48 Lampurlanés J, Angás P and Cantero-Martınez C, Root growth, soil water content and yield of. Barley under different tillage systems on two soils in semiarid conditions. *Field Crop Res* **69**:27–40 (2001).

49 Du K, Li F, Qiao Y, Leng P, Li Z, Ge J *et al.*, Influence of no-tillage and precipitation pulse on continuous soil respiration of summer maize affected by soil water in the North China plain. *Sci Total Environ* **766**:144384 (2021).

50 Gu X, Li Y and Du Y, Effects of ridge-furrow film mulching and nitrogen fertilization on growth, seed yield and water productivity of winter oilseed rape (Brassica napus L.) in northwestern China. *Agric Water Manag* **200**:60–70 (2018).

51 Guo Z, Liu H, Wan S and Hua K, Enhanced yields and soil quality in a wheat-maize rotation using buried straw mulch. *J Sci Food Agr* **97**: 3333–3341 (2017). https://doi.org/10.1002/jsfa.8183.

52 Zegada-Lizarazu W and Iijima M, Deep root water uptake ability and water use efficiency of pearl millet in comparison to other millet species. *Plant Prod Sci* **8**:454–460 (2005).

53 Chaves MM, Flexas J and Pinheiro C, Photosynthesis under drought and salt stress: regulation mechanisms from whole plant to cell. *Ann Bot* **103**:551–560 (2009).

54 Kang J, Zhao W and Zhu X, Silicon improves photosynthesis and strengthens enzyme activities in the C3 succulent xerophyte Zygophyllum xanthoxylum under drought stress. *J Plant Physiol* **199**:76–86 (2016).

55 Yang H, Yang X, Zhang Y, Heskel MA, Lu X, Munger JW *et al.*, Chlorophyll fluorescence tracks seasonal variations of photosynthesis from leaf to canopy in a temperate forest. *Global Change Biol* **23**:2874–2886 (2017).

56 Chang S, Chang T, Song Q, Zhu X-G and Deng Q, Photosynthetic and agronomic traits of an elite hybrid rice Y-Liang-you 900 with a record-high yield. *Field Crop Res* **187**:49–57 (2016).

57 Huang Y, Grain development and yield formation of maize. Forest by products in China (2002) (in Chinese).

58 Wang Z, *Plant Physiology*. China Agriculture Press, Beijing (2000) (in Chinese).

59 Nakamura Y, Yuki K, Park S-Y and Ohya T, Carbohydrate metabolism in the developing endosperm of rice grains. *Plant Cell Physiol* **30**:833–839 (1989).

60 Nakamura Y and Yuki K, Changes in enzyme activities associated with carbohydrate metabolism during the development of rice endosperm. *Plant Sci* **82**:15–20 (1992).

61 Xu Y, Gu D, Qing H, Zhang H, Wang Z and Yang J, Changes in carbohydrate accumulation and activities of enzymes involved in starch synthesis in maize kernels at different positions on an ear during grain filling. *Acta Agron Sin* **41**:297–307 (2015).

62 Lv X, Han J, Liao Y and Liu Y, Effect of phosphorus and potassium foliage application post-anthesis on grain filling and hormonal changes of wheat. *Field Crop Res* **214**:83–93 (2017).