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Research article

Diverse tillage practices with straw mulched management strategies to improve water use efficiency and maize productivity under a dryland farming system

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ABSTRACT

Straw mulching incorporation has a wide range of environmental benefits that make it an effective practice for sustainable agro-ecosystem in the semi-arid regions. There is an urgent need to improve the ^{13}C-photosynthates distribution, water use efficiency (WUE) and maize canopy characteristics under the diverse tillage practices with straw mulched management strategies for sustainable intensification of maize production. The field study consists of three diverse tillage systems (RT: rotary tillage; CT, conventional tillage; MT, minimum tillage) with three straws mulching (NS: no straw mulch; SS: straw mulch on the soil surface; SI: straw incorporated into the soil) were assessed under the ridge-furrow rainfall harvesting system. Our results showed that the rotary tillage with straw incorporated into the soil significantly reduces the ET rate (11 %), and leaf rolling index; as a result considerably improves LAI, LEI, ^{13}C-photosynthates distribution, N accumulation, and above ground biomass under various growth stages. The RT_{SI} treatment significantly improved soil water storage, soil organic carbon (52 %, SOC), soil C storage (39 %, SCS), and NPK nutrients uptake (70 %, 62 %, and 69 %) of maize than observed for the rest of all other treatments, respectively. The RT_{SI} treatment improves soil water balance, grain yield (53 %), biomass yield (37 %), WUE_g (51 %), WUE_b (35 %), nutrients uptake, and mitigating soil water depletion than the MT_{NS} treatment. Although RT_{SS} can achieve optimal soil water storage in the short term, RT_{SI} has a great potential in improving soil carbon stability, canopy characteristics, soil water storage, and WUE, contributing to sustainable and intensive corn production in agricultural ecosystems in semi-arid regions.

1. Introduction

With global warming, larger regions of the world may face soil degradation and water scarcity issues [1], which might be one of the most important factors of limiting maize production in semi-arid regions. Scarce farmland accounts for over 70 % of China total arable

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land, mainly concentrated in arid and semi-arid regions [2]. Inadequate and unstable precipitation is the key resource of water for maize productivity in the dry-land farming system [3]. Effective use of rainfall and maximizing water efficiency are the main goals for promoting sustainable and intensive corn productivity in this area, which have a significant impact on a local and regional scale [4]. To mitigate the impact of these constraints, the study explored different types of water saving strategy and practices to improve the efficiency of limited precipitation use [5,6].

The covered ditch system is an on-site water collection technology and also an off-season water collection and storage strategy. Due to the increase in soil water storage, also crop yields have been considerably increased [6]. In this system, alternate ridges and trenches are constructed to collect runoff [7], and plastic films reduce evaporation and water erosion. The practice of adding rice straw can provide favorable soil conditions [8,9]. Persistent rice straw in the field not only reduces air pollution when burning rice straw, however, also improves soil nutrients status [10,11]. Compared to traditional farming methods such as applying fertilizer only to the soil, rice straw can improve crop yield and soil water contents [12]. In order to prevent crop residues from being burned, it is recommended to use them as surface coatings and return them to the soil to increase soil organic matter (SOM) and physical ownership of the soil [13,14], thereby improving the soil organic carbon (SOC) and water retention capacity (WHC) of the soil [15]. Grass cover reduces the direct impact of solar radiation on the Earth; it can prevent water loss caused by evaporation [16,17]. Crop residues also increase carbon storage [18,19]. There is an urgent need to adopt management practices to improve carbon stability through effective water resource management in order to achieve the long-term sustainability of rainwater-irrigated ecosystems [20]. In addition, carbon stability is an important indicator of soil fertility, integrated water resource management, and crop productivity. Improving carbon stability through higher SOC is a prerequisite for sustainable agricultural ecosystems [21].

Agricultural practices have a significant impact on soil water balance [22,23], as well as on rainwater use and food productivity [24,25]. Traditional tillage (TT) using crop residues has the advantage of a 5.8 % yield, 12.6 % water use efficiency, and 25.9 % increase in net profit [26]. Likewise, minimum tillage (MT) and crop residues can supplement the water available to crops in the soil profile [27,28]. Peng et al. [29] study that rotation tillage improved WUE and corn yield due to improved SWS and crop absorption capacity. RT improves water permeability and storage, improves soil water resistance, and improves crop drought resistance [30].

Crop residues an important natural resource that can improve soil fertility status and maize production [31,32]. Teixeira et al. [33] study that rice straws can enhance soil nutrients status by accelerates the release of nutrients from rice straws. Rice straw contains organic substances and is rich in nutrients. Maintaining rice straw has become the simplest method to improve soil fertility [34,35]. In situations of water scarcity, optimal utilization of rainfall is an essential means to develop water productivity, and enhance maize yields [36]. In arid regions, although straw mulching can reduce evaporation, its ability to increase yield may be limited by precipitation [37–39]. In severe drought years, water imbalances or water shortages often occur in the soil, which can lead to a sharp decline in crop yields, even for cover crops [40,41]. In order to determine strategies for optimizing crop productivity and water use, it is important to understand the response of plants to rice straw supply under limited water resources [42,43].

The unpredictability between this research works makes it essential to further investigate how diverse tillage systems and straw mulch management strategies affect these soil water balance, maize canopy characteristics, nutrient uptake, and water use efficiency under ridge and furrow systems in rain-fed ecosystems. We hypothesized that straw mulch management strategies could mitigate the ET rate, leaf rolling index and improve soil water balance and grain yield with environmental friendly and sustainable. Thus, the aims of this research were (1) to evaluate diverse tillage systems with straw mulch effects on soil water balance and soil nutrients status; (2) to study tillage systems with straw mulch effects on ^{13}C-photosynthates distribution, maize yield, and WUE for sustainable water use in maize production; (3) to investigate canopy characteristics of maize under in semi-arid regions.

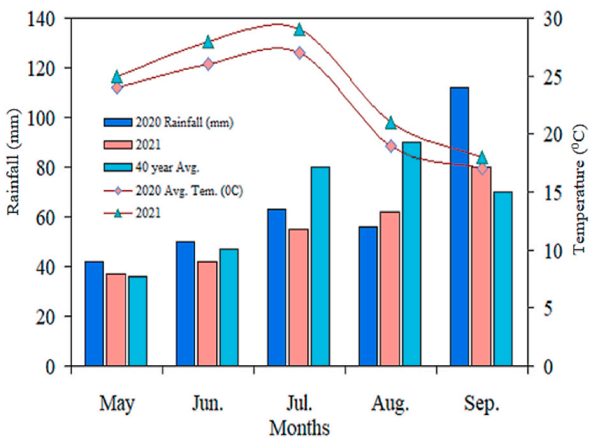

Fig. 1. Monthly rainfall and temperature distribution during the maize-growing seasons.

2. Materials and methods

2.1. Location description

This field study was conducted in Qingyang City from 2020 to 2021, located at longitude of 107°63′E, latitude of 35°75′N and an elevation of 1178 m asl. The annual average temperature is 11.4 °C, the total sunshine hours are 2550 h yr^{-1}, and the annual average precipitation are 397 mm yr^{-1}. More than 59 % of the precipitation occurs from July to September. The rainfall from May to September 2020 is 284 mm, and that in 2021 is 318 mm. Monthly precipitation distribution and temperature in a two-year field study of maize, as well as a 40-year monthly average (1980–2020) (Fig. 1). The chemical properties of the 0–20 cm soil layer are shown in Table 1.

2.2. Field management

The field study used a randomize complete block design with four replicates, each with a block area of 200 m2 (40 × 5 m). Field studies included nine treatments in which consists of three farming methods; RT: rotary tillage, CT: conventional tillage, MT: less tillage. Rotary tillage includes rotary tillage with a depth of 15 cm, traditional tillage includes a plow with a depth of 25 cm, and minimum tillage includes shallow tillage with a depth of 15 cm. There are three straws covering strategies, NS: no straw covering; SS: Straw mulch on the soil surface; SI: Straw added to the soil. The amount of wheat straw returned to the experimental field was 3900 kg ha^{-1}, which was mechanically cut to a length of 5 cm. Basel fertilizer should be applied to all plots before planting corn during each growing season. The width of ridges and ditches is 60 cm, and the height of ridges is 15 cm. During sowing (40 % of total nitrogen), jointing (30 %), and flowering (30 %), total nitrogen should be continuously supplied to the ditch. It is recommended NPK was applying at the rate of 180, 90, and 30 kg ha^{-1} days before sowing. The planting amount of Dafeng 30 corn variety is 75000 ha per plant, and the planting time is June 5, 2020 and June 3, 2021, respectively, with a row spacing of 60 cm. A large space of 0.8 m is left between adjacent plots to prevent the loss of water and nutrients. Irrigation water is not available, but weeds are removed by hand.

2.3. Sampling

2.3.1. Soil moisture

Before sowing corn, soil moisture was measured at a depth of 0–200 cm using a soil auger method with a diameter of 54 mm at 20, 40, 60, 80, 100, and 120 DAP at intervals of 20–200 cm. Soil water storage (SWS) was calculated by Ref. [44]:

$$SWS = C \times \rho \times H \times 10 \tag{1}$$

where C is the soil water content (%), ρ is the soil bulk density (g cm^{-3}), and H is the soil depth (cm).

The evapotranspiration (ET) rate was determined by using the following equation [45]:

$$ET = (P + I + C) - (D + R - \Delta W) \tag{2}$$

where P is the precipitation; I is the irrigation; C is the upward flow into the root zone; D is the downward drainage out of the root zone; R is the surface runoff.

The soil available water (SAW) is calculated as follows:

$$SAW = SWS - PWPw \tag{3}$$

Where PWPw is the soil water content corresponding to the percentage of permanent wilt (mm) [46]. The change in soil water balance is calculated as follows:

$$\Delta SWB = R' - ET' \tag{4}$$

Where R′ and ET' is the rainfall and evapotranspiration in a given period (mm); ΔSWB is the change in soil water storage capacity within a given period of time (mm) (Wang ET al., 2018).

2.3.2. Nitrogen accumulation

During the 20, 40, 50, 70, 90, and 120 DAPs in 2020 and 2021, six maize plants were randomly selected for sampling. After drying at 105 °C, weigh different plant parts (leaves, stems, sheaths, corn cobs, and grains) for 30 min, then 70 until a constant weight is reached, and then use the Kjeldahl method for digestion, distillation, and titration for N analysis to determine total aboveground

Table 1
The chemical properties of experimental site of the soil layers (0–20 cm).

Year	pH	SOM (g kg^{-1})	TN (g kg^{-1})	TP (g kg^{-1})	TK (g kg^{-1})	AP (mg kg^{-1})	AK (mg kg^{-1})
2020	8.24	14.34	1.14	1.07	18.02	21.05	159.03
2021	8.08	14.29	1.11	1.03	17.90	20.93	160.15

SOM: soil organic matter; TN: total nitrogen; TP: total phosphorus; TK: total potassium; AP: available phosphorus; AK: available potassium.

absorption.

2.3.3. *Leaf area index (LAI), leaf rolling index (LEI) and leaf erection index (LRI)*

The LAI was calculated by using the following formula:

$$LAI = LA/GA \tag{5}$$

where LA is the leaf area per plant (m^2) and GA is the ground (m^2).

Calculate LEI, and LRI by measuring the natural length (Ln, cm), maximum leaf length (Lm, cm), natural leaf width (Wn, cm), and maximum leaf width (Wm, cm) of corn leaves using the following equations [47]:

$$LEI = \frac{Ln}{Lm} \times 100 \tag{6}$$

$$LRI = \frac{Wm - Wn}{Wm} \times 100 \tag{7}$$

2.3.4. ^{13}C-photosynthates distribution

During the mature stage, the biomass of all leaves with 5 replicates was measured $\delta^{13}C$. Use the Isoprime 100 instrument (Isoprime

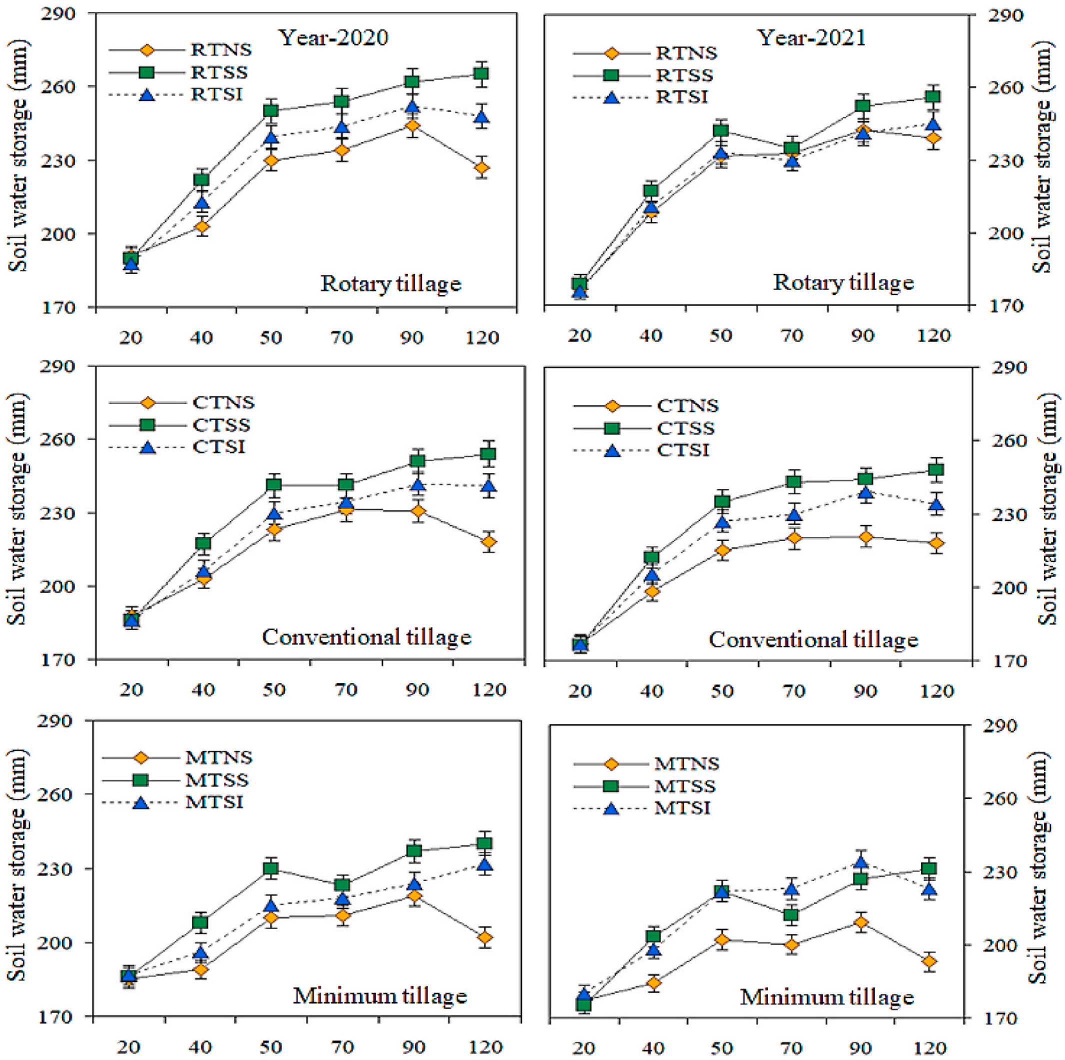

Fig. 2. Effects of different tillage practices with straw mulching management strategies on soil water storage at the depth of 0–200 cm soil layers at different days after planting (DAP) of maize during 2020–2021. Note: RT: rotary tillage; CT: conventional tillage; MT: minimum tillage; $_{NS}$: no straw mulch; $_{SS}$: straw mulch on soil surface; $_{SI}$: straw incorporated into the soil. Vertical bars represent the (means ± SR) (n = 3).

100 %, Cheadle, UK) to prepare fine powder from dry leaf samples for ^{13}C analysis.

2.3.5. Estimation of SOC and SCS storage

The SOC stocks were estimated from the change in top soil SOC (Mg C ha^{-1}) [48]:

$$SOC\ (Mg\ C\ ha^{-1}) = \rho b \times d \times SOC \times 10 \tag{8}$$

where, ρb, bulk density; d, soil profile depth; and 10 is a product of unit conversion factor.

The soil C storage (SCS) was calculated below [49]:

$$SCS\ (t\ ha^{-1}) = SOC \times BD \times d \times 0.1 \tag{9}$$

where BD denotes the soil bulk density, d denotes the soil layer thickness, and 0.1 is the conversion factor.

$$WUE_b = BY/ET \tag{10}$$

$$WUE_g = GY/ET \tag{11}$$

WUE_b is water use efficiency of biomass, and WUE_g is water use efficiency of grain.

2.3.6. Maize yields and nutrients uptake

At the end of each growing season, all plants, except for the boundary row of each field, are harvested manually during the harvest phase to determine grain and biomass yields. Select 10 plants from each plot, cut them from the ground, dry them in an oven, and screen them using a 0.5 mm sieve. After wet digestion of the sample in H_2SO_4–H_2O_2, total N and P were determined using an automatic continuous flow analyzer. Total potassium was determined by a flame photometer (6400A, China).

2.4. Statistical analysis

Analysis of variance was performed using SPSS 13.0 (SPSS Inc., Chicago, IL, USA). Data from each sampling event were analyzed separately. Means among treatments were compared based on the least significant difference test (LSD 0.05). Significance level was set at $P < 0.05$. Figures are made by using a sigma plot and excel sheet.

Table 2
Components of soil water balance in the 0–200 cm depth as affected by tillage practices with straw mulching during 2020–2021 maize growing seasons.

Year	Treatments	SAWph (mm)	SAWs (mm)	SAWh (mm)	Growing period (mm)		ΔSWBy (mm)
					ΔSWSg	ET	
2020	RT_{NS}	179	191a	227e	36e	315e	48d
	RT_{SS}	179	190a	265a	75a	346c	86a
	RT_{SI}	179	188a	248b	60c	334d	69b
	CT_{NS}	179	188a	218e	30f	321d	39e
	CT_{SS}	179	186a	254b	68b	369b	75b
	CT_{SI}	179	187a	241c	55c	352c	62c
	MT_{NS}	179	185b	202f	17g	331d	23f
	MT_{SS}	179	186a	240c	54c	389a	61c
	MT_{SI}	179	187a	232d	45d	367b	53c
2021	RT_{NS}	227	177a	239c	62c	349e	12a
	RT_{SS}	265	179a	256a	77a	386c	-9c
	RT_{SI}	248	176a	245b	69b	378c	-3b
	CT_{NS}	218	177a	218e	41d	373d	0b
	CT_{SS}	254	176a	248b	72a	411a	-6c
	CT_{SI}	241	177a	234c	57c	396c	-7c
	MT_{NS}	202	177a	193f	16e	383c	-9c
	MT_{SS}	240	175b	231d	56c	427a	-9c
	MT_{SI}	232	180a	223d	43d	401b	-9c

[a]RT: rotary tillage; CT: conventional tillage; MT: minimum tillage; $_{NS}$: no straw mulch; $_{SS}$: straw mulch on soil surface; $_{SI}$: straw incorporated into the soil.
[b]SAWph: soil available water at previous harvest; SAWs: soil available water at sowing; SAWh: soil available water at harvest; ΔSWSg: change in soil water storage during the growing season; ETg: evapotranspiration during the growing season; ΔSWBy: annual soil water balance.
[c]Within a column for a given year, means followed by different letters are significantly different ($P \leq 0.05$).

3. Results

3.1. Soil water storage (SWS) and soil water balance

The amount of soil water storage varies depending on farming methods and growing season (Fig. 2). During the sowing period, the SWS between different treatments were not significant. Due to different rainfall events and their distribution, SWS has changed under different farming systems and different straw mulching strategies. Corn water consumption increases as plants grow, but RT tillage with straw mulching on the soil surface can reduce drought, ensuring successful plant growth. Compared with all other treatments, the SWS of RT_{SS} treatment at different growth stages of maize was significantly higher. From 40 to 90 days after planting (DAP), there was a significant improvement in the SWS trend for each treatment compared to 40 DAP. At 70 DAP, the two-year average data showed that SWS under RT_{SI} treatment was significantly superior to RT_{NS} treatment. Among various tillage methods, straw mulching has the largest SWS on the soil surface compared to NS and SI mulching strategies, but at different growth stages, with the exception of 20 DAP, the difference is significant. From 90 to 120 DAP, the SWS changes between different treatments are significantly. Straw mulching on the soil surface under different tillage methods significantly increased SWS at different growth stages of maize.

Evapotranspiration varies in different growth seasons but is significantly affected by tillage practices under straw mulching strategies (Table 2). The ET in 2020 is significantly greater than that in 2021. ΔSWBg is significantly affected by different farming systems, and there are differences between different growing seasons. 2020 ΔSWBg is greater than 2021. During the growing season, all tillage practices severely deplete soil water. The annual soil water balance varies with different tillage methods and growing seasons (Table 2). ΔSWBy and ΔSWBg is not parallel, 2020 ΔSWBy is greater than 2021. In 2020, all treatments resulted in water replenishment $\Delta SWBy>0$. Based on the average value is 2020, RT_{SS}, CT_{SS}, and MT_{SS} processed ΔSWBy was 86, 75, and 61 mm, while the average for 2021 was - 9, - 6, and - 9 mm, respectively.

3.2. Distribution of ^{13}C-photosynthates in different organs and nutrients uptake

Straw mulching strategies under different tillage systems have changed the distribution of ^{13}C photosynthetic patterns among different plant organs (Table 3). At physiological maturity, the concentration of ^{13}C in maize stems is higher, followed by grains and other leaves. During physiological maturation, the average data showed that under RT_{SI} treatment, the photosynthetic distribution of ^{13}C in grains was higher, while under MT_{NS} treatment, it was the lowest. Compared with RT_{SI} treatment, the distribution of ^{13}C photosynthesis in grains under RT_{NS} treatment and RT_{SS} treatment decreased by 24.3 % and 12.0 %, respectively. In addition, under different tillage systems, non-straw mulching significantly reduced the photosynthetic distribution pattern of ^{13}C in other leaves and stems, while SS and SI treatments under different tillage systems significantly improved the distribution of ^{13}C in ear bracts and stem, respectively.

Different tillage systems using straw mulching strategies have a significant impact on N, P, and K uptake (Table 4). During the period 2020–2021, RT_{SI} processing significantly increased the N, P, and K of all treatments. During the two growing seasons, the average N, P, and K uptake of RT_{SI} treatment was significantly higher than that of RT_{NS} treatment by 43.0 %, 37.4 %, and 45.3 %, respectively. Under different tillage methods, straw returning significantly improved the absorption of N, P, and K by the soil compared to not covering straw or covering straw on the soil surface. However, during the period 2020–2021, there was no significant difference

Table 3
Effects of different treatments[a] on ^{13}C-photosynthates distribution in different organs (%) at physiological maturity of maize during 2020–2021.

Year	Treatments	^{13}C-photosynthates distribution in different maize organs (%)					
		Stem	Other leaves	Cob	Ear bracts	Tassel	Grain
2020	RT_{NS}	39.13e	13.66b	5.32b	7.47c	2.27b	29.95c
	RT_{SS}	43.53c	14.21a	5.85b	8.09b	2.66b	34.53b
	RT_{SI}	49.12a	14.36a	6.63a	9.24a	3.11a	40.50a
	CT_{NS}	37.94f	13.62b	5.07b	6.93d	2.21b	29.02c
	CT_{SS}	40.32d	14.14a	5.53b	7.94c	2.44b	31.89c
	CT_{SI}	46.32b	14.21a	6.24a	9.02a	2.71b	34.76b
	MT_{NS}	36.93f	13.10b	4.64c	6.85d	1.87c	25.36d
	MT_{SS}	40.73d	14.06a	5.46b	7.51c	2.29b	30.06c
	MT_{SI}	45.92b	14.14a	5.99b	8.09b	2.66b	34.76b
2021	RT_{NS}	51.99b	23.04c	7.61c	11.81b	1.82b	38.72e
	RT_{SS}	52.93b	25.84b	8.22b	12.87a	1.93b	43.49c
	RT_{SI}	55.46a	28.63a	9.46a	13.93a	2.13a	50.25a
	CT_{NS}	51.05b	22.54c	7.10c	11.47b	1.72b	37.43e
	CT_{SS}	52.15b	24.44b	8.07b	12.51a	1.87b	40.64d
	CT_{SI}	54.36a	27.23a	8.54b	13.40a	2.05a	47.05a
	MT_{NS}	50.40c	19.88d	5.97d	9.73c	1.68b	33.94f
	MT_{SS}	51.67b	24.12b	7.25c	12.34a	1.89b	40.46d
	MT_{SI}	53.26a	25.20b	8.54b	13.20a	2.03a	43.84c

[b]Values are given as means, and different lowercase letters indicate significant differences at $P \leq 0.05$ levels in the same line (LSD test) (n = 3).

[a] RT: rotary tillage; CT: conventional tillage; MT: minimum tillage; $_{NS}$: no straw mulch; $_{SS}$: straw mulch on soil surface; $_{SI}$: straw incorporated into the soil.

Table 4
Effects of different treatments[a] on soil organic carbon (SOC), soil C storage (SCS) and nutrients uptake of maize at maturity stage of maize during 2020–2021.

Years	Treatments	SOC (g kg^{-1})	SCS (t ha^{-1})	Nitrogen uptake (kg ha^{-1})	Phosphorus uptake (kg ha^{-1})	Potassium uptake (kg ha^{-1})
2020	RT_{NS}	9.68e	28.11d	48.62e	23.26e	58.11d
	RT_{SS}	11.85c	34.99b	74.42c	26.71d	90.07b
	RT_{SI}	16.90a	41.78a	87.12a	37.61a	108.10a
	CT_{NS}	9.22e	26.21e	38.02f	19.81f	48.05e
	CT_{SS}	11.80c	30.45c	56.17d	25.41d	68.12c
	CT_{SI}	14.40b	35.33b	84.47a	34.71b	103.22a
	MT_{NS}	8.37f	25.45e	25.22g	13.81g	32.17f
	MT_{SS}	10.95d	28.22d	59.22d	25.71d	70.15c
	MT_{SI}	13.55b	32.11c	81.82b	31.81c	98.08b
2021	RT_{NS}	10.53e	29.32e	52.77e	25.36e	62.02e
	RT_{SS}	15.70c	37.01b	76.62c	36.01b	95.07c
	RT_{SI}	18.20a	43.22a	90.62a	40.11a	111.57a
	CT_{NS}	9.40e	27.29f	42.62f	21.81f	51.97f
	CT_{SS}	14.85c	33.88c	62.92d	28.91c	73.87d
	CT_{SI}	17.35a	38.32b	88.07a	39.61a	107.02a
	MT_{NS}	8.55f	26.76f	28.32g	15.41f	36.17g
	MT_{SS}	12.70d	31.29d	59.47d	27.76c	72.07d
	MT_{SI}	16.05b	35.11c	85.52b	39.11a	102.47b

[b]Values are given as means, and different lowercase letters indicate significant differences at $P \leq 0.05$ levels in the same line (LSD test) (n = 3).
[a] RT: rotary tillage; CT: conventional tillage; MT: minimum tillage; $_{NS}$: no straw mulch; $_{SS}$: straw mulch on soil surface; $_{SI}$: straw incorporated into the soil.

between RT_{SI} and CT_{SI} treatments. Compared with CT_{NS} treatment, the average N, P, and K uptake of CT_{SI} treatment increased significantly by 53.3 %, 44.0 %, and 52.4 %, respectively.

3.3. Nitrogen accumulation, SOC and SCS storages

During the period 2020–2021, different tillage systems and three straws mulching strategies have a significant impact on the dynamic change of N accumulation (Fig. 3). Nitrogen accumulation in all treatments increased slowly at the early stage of growth (20–50 DAP) and rapidly at the middle stage of growth (50–90 DAP), In the late stage (90–120 DAP), nitrogen accumulation under RT tillage systems was significantly higher than that under CT and MT tillage systems during the period 2020–2021, regardless of straw mulching strategies. The nitrogen accumulation yield under straw-returning conditions was significantly higher than that under no straw mulching and straw mulching conditions, but there were no significant differences during the 20–50 DAP period.

Soil parameters such as SOC and SCS storage were recorded during the study (Table 4). Different tillage systems using straw mulching strategies have significant effects on soil organic carbon and SCS storage. During the period 2020–2021, RT_{SI} processing significantly increased SOC and SCS reserves compared to all other processing. During the two growing seasons, the average SOC and SCS storage of RT_{SI} treatment was significantly higher than 42.4 % and 32.4 % of RT_{NS} treatment, respectively. Under different tillage methods, compared to not covering straw or covering straw on the soil surface, the storage of SOC and SCS after adding straw to the soil significantly increased. However, during the period 2020–2021, significant differences were recorded between RT_{SI}, CT_{SI}, and MT_{SI} treatments. Compared to CT_{NS} treatment, the average storage of SOC and SCS in CT_{SI} treatment increased significantly by 41.4 % and 27.4 %, respectively, while compared to MT_{NS} treatment, the average storage of SOC and SCS in MT_{SI} treatment increased significantly by 42.8 % and 22.3 %, respectively.

3.4. Leaf area index (LAI), leaf rolling index (LRI) and leaf erection index (LEI)

The LAI of maize is significantly affected by different tillage systems and straw mulching strategies at different growth stages (Fig. 4). In LAI, significant differences begin at the jointing stage, reach a peak at the tassel stage, and then slowly decrease in the filling and ripening stages. Under different tillage systems, straw mulching strategies have a major impact on LAI. However, the differences between different tillage systems and straw mulching strategies are significant at all growth stages except the trefoil stage. In addition, RT_{SI} treatment increased LAI at all growth stages, with the exception of the trefoil stage, MT treatment decreased LAI (regardless of straw mulching strategy), followed by RT and CT tillage methods, indicating that insufficient rainfall during the filling stage can lead to premature leaf senescence and a decrease in LAI. Over an average period of 2 years, RT and CT tillage methods reduced the LRI and increased the LEI (Figs. 5 and 6). The mean LRI in the early growth stage (3-L, JS, and TS) was higher than that in the late growth stage (GFS and MS). Compared to NS treatments, SS and SI treatments reduced the LRI at each growth stage, and significant reductions were observed at the grain filling and ripening stages under different tillage methods. During the 3-leaf period of each year, the LRI of RT_{SI} was lower as compared to CTSI and MT_{SI}. For LEI, the order of RT_{SI}, RT_{SI}, and MT_{SI} processing is RT_{SI} > RT_{SI} > MT_{SI} processing. Changes in LEI generally follow a consistent trend every year.

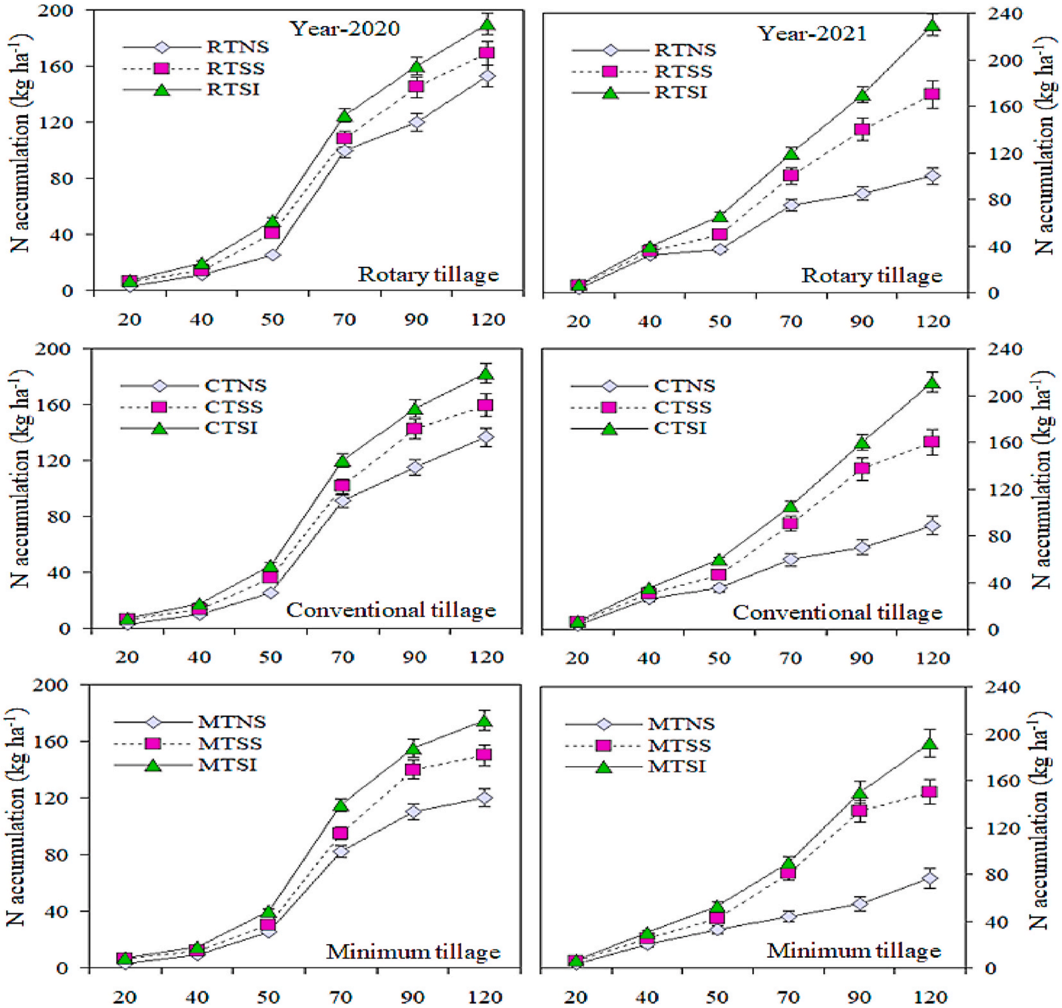

Fig. 3. Effects of different tillage practices with straw mulching management strategies on aboveground N production at different days after planting (DAP) of maize during 2020–2021. Note: RT: rotary tillage; CT: conventional tillage; MT: minimum tillage; $_{NS}$: no straw mulch; $_{SS}$: straw mulch on soil surface; $_{SI}$: straw incorporated into the soil. Vertical bars represent the (means ± SR) (n = 3).

3.5. *Maize production, water use efficiency (WUE_g) and WUE_b*

Compared with RT_{NS} treatment, RT_{SI} treatment significantly increased corn yield by 43.0 %, while CT_{SI} treatment significantly increased corn yield by 42.3 % compared to CT_{NS} treatment, with an average research time within two years (Table 5). The average of two-year data indicated that compared to RT_{NS} treatment, the grain yield of RT_{SI} treatment significantly increased (4.6 t ha^{-1}), while the grain productivity of CT_{SI} treatment significantly increased (4.2 t ha^{-1}). The average grain yield and biomass yield of RT_{SI} treatment were significantly higher than those of RT_{NS} treatment, increasing by 43.0 % and 22.5 %, respectively. Compared with CT_{NS} treatment, the average grain yield and biomass yield of CT_{SI} were significantly improved by 42.3 % and 24.9 %, when compared with MT_{NS} treatment. RT_{SI} treatment significantly increased the seasonal ET rate compared to RT_{NS} treatment (9.3 %), while CT_{SI} significantly increased the seasonal ET rate compared to CT_{NS} treatment (10.9 %). Under MT_{SI} treatment, the seasonal ET rate was significantly higher as compared with MT_{NS} treatment (12.4 %). The two-year average data showed that compared to RT_{NS} treatment, RT_{SI} treatment resulted in a significant enhance in WUE_g and WUE_b (11.0 and 8.0 kg mm^{-1} ha^{-1}), while CT_{SI} treatment resulted in a significant improve in WUE_g and WUE_b (8.9 and 7.3 kg mm^{-1} ha^{-1}).

4. Discussion

Due to water scarcity, corn production in rain irrigated areas may be limited due to poor photosynthesis [50,51]. Straw mulching in trench belts can effectively accumulate a small amount of rainwater, promote precipitation infiltration and reduce evaporation, thereby increasing soil moisture content [52,53]. Corn water consumption increases as plants grow, but RT tillage with straw mulching on the soil surface can reduce drought, ensuring successful plant growth. Compared with all other treatments, the SWS of RTSS

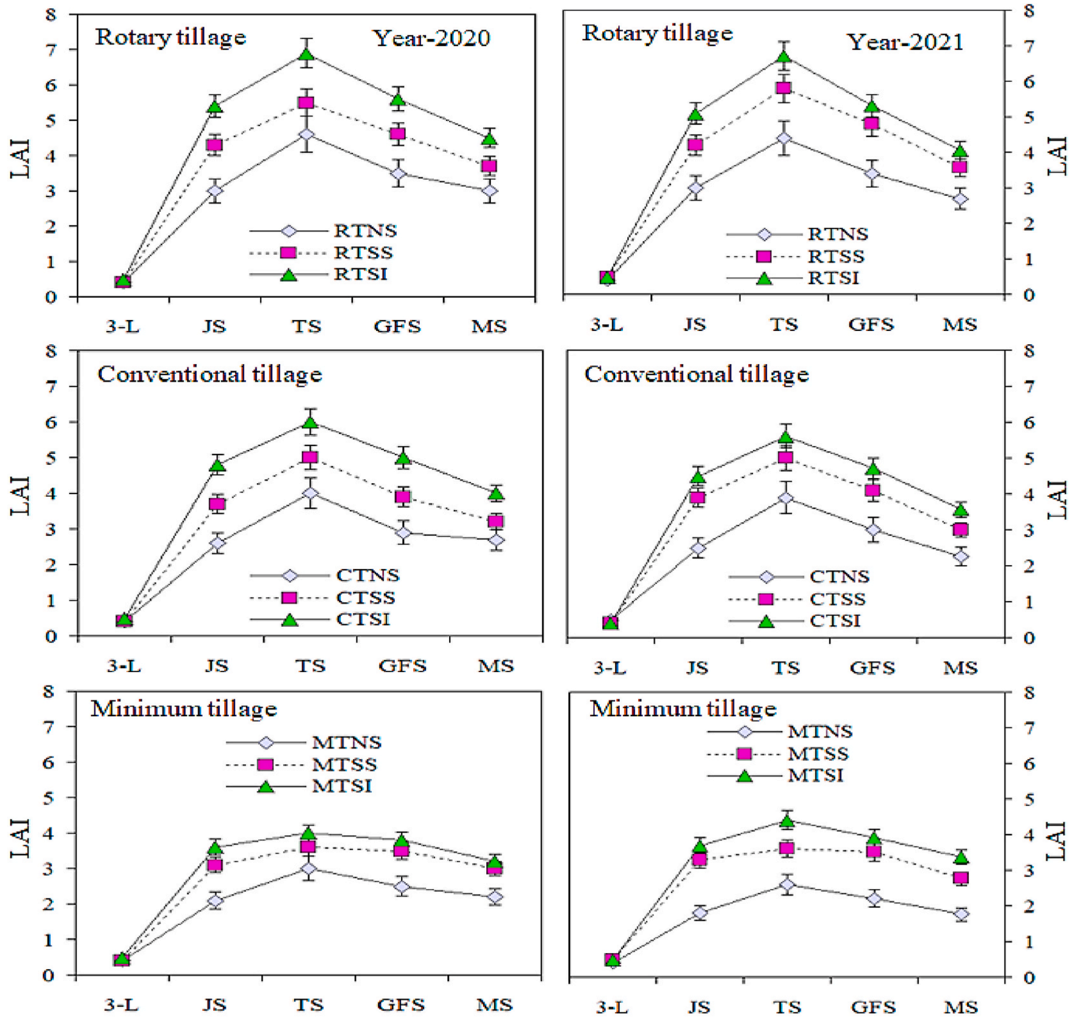

Fig. 4. Effects of different tillage practices with straw mulching management strategies on leaf area index (LAI) at different growth stages of maize during 2020–2021. Note: RT: rotary tillage; CT: conventional tillage; MT: minimum tillage; $_{NS}$: no straw mulch; $_{SS}$: straw mulch on soil surface; $_{SI}$: straw incorporated into the soil. 3-L: three leaf stage; JS: jointing stage; TS: tasseling stage; GFS: grain filling stage; MS: maturity stage. Vertical bars represent the (means ± SR) (n = 3).

treatment at different growth stages of maize was significantly higher. Straw mulching on the soil surface under different tillage methods significantly increased SWS at different growth stages of maize. Traditional tillage and RT significantly improved soil water content, but decreased saturated hydraulic conductivity, consistent with previous research results [54,55]. RT did not enhance the available soil moisture at harvest or sowing time [56], which is attributed to increase in soil water stable aggregates [57,58]. The soil water balance varies with different tillage methods and growing seasons. Based on the average value in 2020, RT_{SS}, CT_{SS}, and MT_{SS} processed ΔSWBy is 86, 75, and 61 mm, respectively, while the average value for 2021 is - 9, - 6, and - 9 mm. As well, some study has found that the SWS under RT is higher than that of CT and MT tillage system [59,60], and RT increases the SWS at harvest stage [44] (Ma et al., 2015).

$\Delta^{13}C$ can tell us that this is the ecological impact on the photosynthetic capacity of maize leaves [61,62]. Farquhar et al. [18], also pointed out that it is mainly the impact of water stress that changes $\Delta^{13}C$ concentration. The higher the photosynthetic capacity of corn crops, the higher $\Delta^{13}C$ value is [63,64]. During physiological maturation, the average data showed that under RT_{SI} treatment, the photosynthetic distribution of ^{13}C in grains was higher, while under MT_{NS} treatment, it was the lowest. In addition, SS and SI treatments under different tillage systems significantly enhanced the photosynthetic distribution of ^{13}C in the ear bracts and stem. Buchmann et al. [65] $\Delta^{13}C$ is much higher. Water-deficient soils limit nitrogen mineralization and nutrient transport to roots, thereby reducing the response of crop yields to nitrogen input [66,67]. Under RT tillage systems, regardless of straw mulching strategies, nitrogen accumulation was significantly higher than under CT and MT tillage systems during the period 2020–2021. The nitrogen accumulation yield under the condition of returning straw to the field was significantly higher than that under the conditions of no straw mulch and straw mulch, but there were no significant differences during the 20–50 DAP period. RT with straw mulch increases

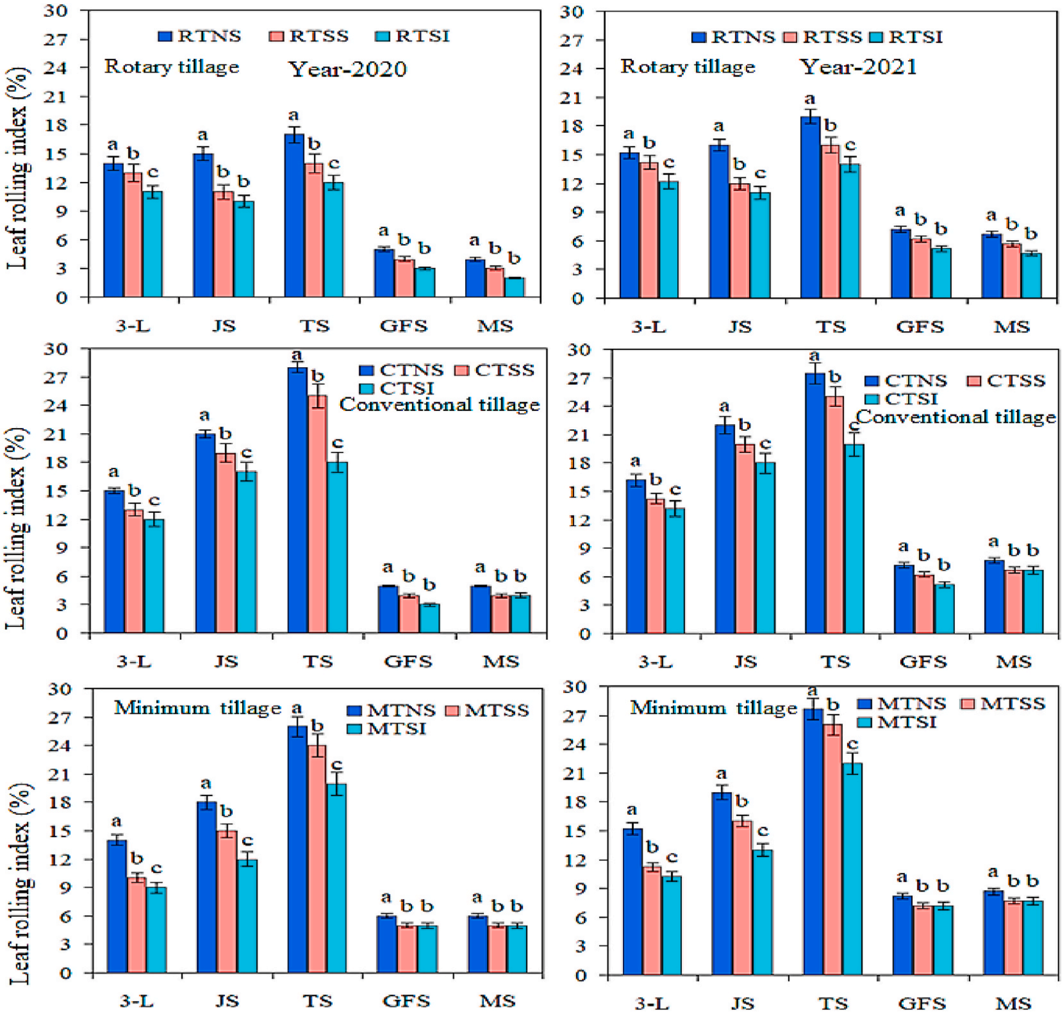

Fig. 5. Effects of different tillage practices with straw mulching management strategies on leaf rolling index (%) at different growth stages of maize during 2020–2021. Note: RT: rotary tillage; CT: conventional tillage; MT: minimum tillage; $_{NS}$: no straw mulch; $_{SS}$: straw mulch on soil surface; $_{SI}$: straw incorporated into the soil. 3-L: three leaf stage; JS: jointing stage; TS: tasseling stage; GFS: grain filling stage; MS: maturity stage. Vertical bars represent the (means ± SR) (n = 3).

SOC and other environmental benefits and is widely recommended as an alternative to intensive farming [68,69]. In our previous studies, it has been found that there is a significant positive correlation between SOC and the amount of straw mulch added [70,71]. The combination of RT and CT with straw mulch layered SOC [72,73], significantly increased total SOC. During the two growing seasons, the average SOC and SCS reserves under RT_{SI} treatment were significantly higher than 42.4 % and 32.4 % under RT_{NS} treatment. Under different tillage methods, compared with soil surfaces without or covered with straw, the SOC and SCS reserves of straw entering the soil were significantly increased. Straw mulching increased carbon input during crop growth period, while, further increasing carbon stability, and ultimately increasing the concentration of SOC in the soil [74,75].

The enhance in biomass have attributed to the growth of leaves and plants [44]. Ali et al. [1] pointed out that the enhance in biomass and yield caused by straw addition is related to the improvement of LAI and leaf growth. RT_{SI} increased LAI at all growth stages, except in the trefoil stage, where MT treatment decreased LAI (regardless of straw mulching strategy), followed by RT and CT tillage methods, indicating that insufficient rainfall during the filling stage can lead to premature leaf senescence and decreased LAI. Li et al. [35] pointed out that the maximum LAI occurs during the filling stage, and then gradually decreases due to leaf through senescence. The average LRI at the early growth stage was higher than that at the late growth stage. Compared to NS treatments, SS and SI treatments reduced the LRI, and significantly reductions were observed at the ripening stages under different tillage methods. For LEI, the order of RT_{SI}, RT_{SI}, and MT_{SI} processing is $RT_{SI} > CT_{SI} > MT_{SI}$ processing. Changes in LEI generally follow a consistent trend every year. The LRI and LEI can be used as sensitive indicators of soil moisture at [39,42].

Plastic mulch can regulate soil moisture to achieve the highest yield [32,35]. Our research results also showed that the average grain yield and biomass yield of RT_{SI} were significantly maximum than those of RT_{NS} treatment. RT_{SI} significantly increased the seasonal ET rate compared to RT_{NS} treatment (9.3 %), while CT_{SI} treatment significantly increased the seasonal ET rate compared to

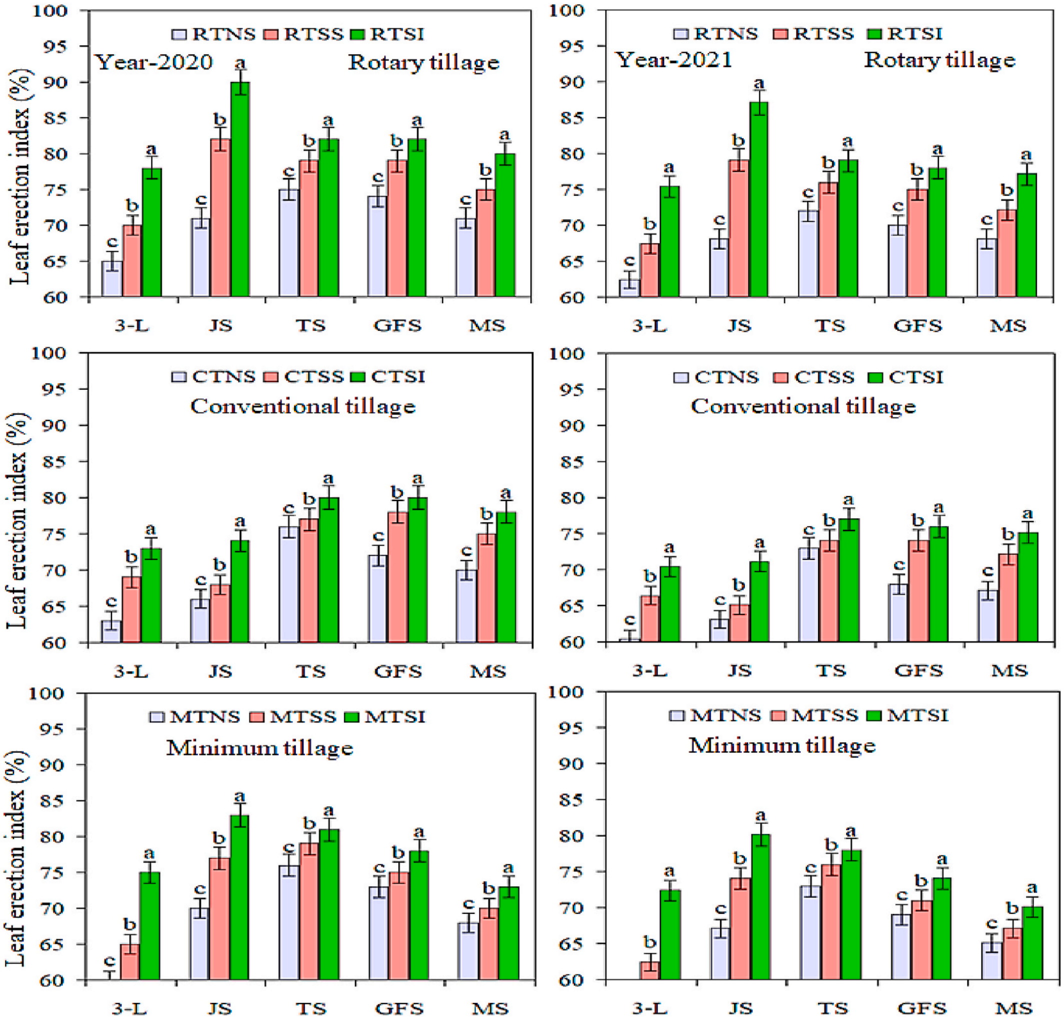

Fig. 6. Effects of different tillage practices with straw mulching management strategies on leaf erection index (%) at different growth stages of maize during 2020–2021. Note: RT: rotary tillage; CT: conventional tillage; MT: minimum tillage; $_{NS}$: no straw mulch; $_{SS}$: straw mulch on soil surface; $_{SI}$: straw incorporated into the soil. 3-L: three leaf stage; JS: jointing stage; TS: tasseling stage; GFS: grain filling stage; MS: maturity stage. Vertical bars represent the (means ± SR) (n = 3).

CT_{NS} treatment (10.9 %). Congreves et al. [11] also study that straw can improve corn production. Similar to our research results, Zhu et al. [75] pointed out that mulching can minimize the loss of evaporated water, protect soil water storage, and improve WUE [44,55]. The two-year average data showed that compared to RT_{NS} treatment, RT_{SI} treatment significantly increased WUE_g and WUE_b, while CT_{SI} treatment significantly increased compared to CT_{NS} treatment. RT farming systems have enhanced WUE and production, which can be attributed to improvements in soil fertility [21,37], leading to increased biomass and ultimately increased WUE [28]. Gong et al. [19] reported that the positive impact of SI treatment on WUE and maize productivity of the RT tillage system was greater in a dry year.

5. Conclusions

Diverse tillage systems with straw mulched management strategies cannot only increase the sustainable intensification of maize production, water and nutrients productivity of maize, but also reduce the ET rate and reducing soil water depletion under the RF system. Our results showed that under the rotary tillage with straw incorporated into the soil significantly reduces the ET rate, leaf rolling index; as a result significantly improve LAI, LRI, LEI, ^{13}C-photosynthates distribution, N accumulation and aboveground biomass under various growth stages. The RT_{SI} treatment significantly improved soil water storage, SOC, SCS and NPK nutrients uptake of maize than observed in the rest of all other treatments. The RT_{SI} treatment improved soil water balance, grain yield (53 %), biomass yield (37 %), WUE_g (51 %), WUE_b (35 %), nutrients uptake and mitigating soil water depletion than that of MT_{NS} treatment. Thereby, rotary is optimal tillage practice with straw incorporated into the soil for sustainable intensification of maize production and

Table 5
Effects of different treatments[a] on grain yield (t ha^{-1}), biomass yield (t ha^{-1}), evapotranspiration (ET, mm), and water use efficiency (WUE, kg ha^{-1} mm^{-1}) of maize during 2020–2021.

Years	Treatments	Grain yield (t ha^{-1})	Biomass yield (t ha^{-1})	ET (mm)	WUEg (kg mm^{-1} ha^{-1})	WUEb (kg mm^{-1} ha^{-1})
2020	RT_{NS}	5.9f	15.7f	315e	18.7d	49.8c
	RT_{SS}	9.7b	17.8d	334d	29.1a	53.4b
	RT_{SI}	10.9a	20.6a	346c	31.5a	59.5a
	CT_{NS}	5.6f	14.3g	321d	17.4e	44.5e
	CT_{SS}	7.1d	16.9e	352c	20.2d	48.0c
	CT_{SI}	9.9b	19.2b	369b	26.8b	52.0b
	MT_{NS}	5.2g	13.4h	331d	15.7f	40.4f
	MT_{SS}	6.7e	16.4e	367b	18.3d	44.7e
	MT_{SI}	9.2c	18.3c	389a	23.7c	47.0d
2021	RT_{NS}	6.3e	15.0d	349e	18.0d	43.0c
	RT_{SS}	9.4b	17.2b	378c	24.9b	45.5b
	RT_{SI}	10.5a	19.0a	386c	27.2a	49.3a
	CT_{NS}	5.7f	13.1e	373d	15.3e	35.1f
	CT_{SS}	8.6c	16.0c	396c	22.0b	40.4d
	CT_{SI}	9.7b	17.3b	411a	23.6b	42.1d
	MT_{NS}	4.9g	11.6f	383c	12.8f	30.3g
	MT_{SS}	7.6d	15.8d	401b	19.2d	39.4e
	MT_{SI}	9.1b	17.1b	427a	21.3c	40.1d

[b]Values are given as means, and different lowercase letters indicate significant differences at $P \leq 0.05$ levels in the same line (LSD test) ($n = 3$).
[a] RT: rotary tillage; CT: conventional tillage; MT: minimum tillage; $_{NS}$: no straw mulch; $_{SS}$: straw mulch on soil surface; $_{SI}$: straw incorporated into the soil.

soil water changes in semi-arid regions.

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CRediT authorship contribution statement

Mingxi Li: Writing – review & editing, Resources, Formal analysis, Data curation. **Shahzad Ali:** Writing – original draft, Supervision, Software, Methodology, Investigation, Conceptualization. **Shaik Althaf Hussain:** Writing – review & editing, Software, Resources, Project administration, Funding acquisition. **Aqil Khan:** Writing – review & editing, Formal analysis. **Yan Chen:** Writing – original draft, Methodology, Funding acquisition, Data curation, Conceptualization.

Declaration of competing interest

No conflict of interest exists in the submission of this manuscript.

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