Delayed sowing/harvest dates combined with strip deep rotary tillage improve annual grain yield and water use in a winter wheat-summer maize cropping system of the North China Plain

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Abstract: Optimizing sowing/harvest dates and tillage regimes offers potential to balance grain yield and water use in the winter wheat–summer maize cropping system of the North China Plain (NCP), but their interactive effects remain poorly quantified. A two-year field experiment (2022–2024) was conducted with two cropping systems (traditional sowing/harvest dates, CK; optimized delayed dates, OD) and three tillage practices (no-tillage, NT; rotary tillage, RT; strip deep rotary tillage, ST) during the maize season. Results showed that OD shifted 4.9–5.6% of precipitation from wheat to maize season, increasing soil water depletion in wheat and recharge in maize, thereby expanding soil water storage capacity. ST significantly reduced bulk density in the 0–40 cm layer and increased deep-layer (40–200 cm) soil water content by 5.1–20.8%, enhancing groundwater recharge and reducing annual net groundwater use compared with RT and NT. The integrated OD+ST practice increased summer maize yield, resulting in 7.5–8.2% higher annual grain yield than CK+NT. This combination also reduced soil evaporation at wheat anthesis and maize silking and increased annual water use efficiency (WUE). Principal component analysis showed that ST, especially when combined with OD, was associated with higher deep-layer soil water storage and higher crop transpiration at the sampled stages. These results indicate that, under the two-year field conditions, integrating delayed sowing/harvest dates with strip deep rotary tillage improved annual yield and WUE while reducing G_{use} in the winter wheat–summer maize system.

Keywords: winter wheat-summer maize; sowing/harvest date; tillage practice; water use efficiency; grain yield

1. Introduction

The North China Plain (NCP) is a major grain-producing region in China, where the winter wheat–summer maize cropping system accounts for approximately 75% of national wheat and 35% of maize production (National Bureau of Statistics of China, 2024). However, in this area, annual precipitation (500–800 mm) is far below crop water demand (870 mm), with only 20–30% falling in the wheat season (Fang et al., 2010; Ding et al., 2021). To maximize crop yields, over 300 mm of irrigation is typically required for wheat cultivation (Sun et al., 2010; Han et al., 2025), leading to severe groundwater overexploitation (Foster et al., 2004; Hu et al., 2005; Zhang et al., 2023a). While water-saving irrigation technologies can significantly enhance water use efficiency (WUE) (Yu et al., 2020; Li et al., 2025; Yang et al. 2025), at least 250 mm of irrigation is still required to maintain high yields, making substantial groundwater extraction inevitable (Meng et al., 2012; Qu et al., 2025). Therefore, new strategies are needed to reduce groundwater consumption without compromising yield in the NCP.

Adjusting sowing and harvest dates has been proposed as a strategy to better align crop water demand with precipitation patterns. A "double-delayed" strategy (wheat sowing and maize harvest delayed by 5–10 days) can substantially reduce water consumption during the wheat season while maintaining relatively high annual yields (Sun et al., 2007; Xu et al., 2018). When sowing was delayed by more than 20 days, winter wheat can still achieve acceptable yields (7.42 t ha^{-1}) with seasonal evapotranspiration significantly reduced, resulting in a water use efficiency of 1.84 kg m^{-3} under one-irrigation regime (Wang et al., 2016; Zhou et al., 2019; Zhang et al., 2023a). However, the impact of such adjustments on soil water dynamics, precipitation utilization, and groundwater consumption across the entire rotation system remains poorly quantified.

Tillage practices also play a critical role in regulating soil water dynamics, including infiltration, evaporation, and storage (Zhao et al., 2014; Wang et al., 2019). No-tillage increases surface bulk density, reducing evaporation but also limiting infiltration and root penetration (Kan et al., 2020). Rotary tillage improves porosity in the 0–15 cm layer but may increase evaporation losses and fails to disrupt the hard plow pan at approximately 15 cm depth, which impedes deep water infiltration (Wang et al., 2015; Kan et al., 2020). In contrast, strip deep rotary tillage, confined to a 15-cm-wide sowing belt with a maximum depth of 40 cm, has been shown to significantly reduce bulk density in the 0–40 cm layer, enhance deep-layer water infiltration, and reduce evaporation due to straw mulch retained in untilled inter-row areas (Han et al., 2022; Lv et al., 2026). This practice may therefore help capture more rainfall during the maize season and preserve it for the subsequent wheat season.

Despite these promising findings, few studies have systematically evaluated the combined effects of adjusting sowing/harvest dates and tillage regimes on the annual water balance, groundwater recharge, and crop performance in the winter wheat–summer maize system. We hypothesized that: (1) OD shifts seasonal precipitation from wheat to maize, reducing net groundwater use; (2) ST enhances deep soil water storage and groundwater recharge by alleviating subsoil compaction; (3) OD and ST synergistically improve annual yield and WUE via improved water partitioning (less evaporation, more transpiration). To test this hypothesis, a two-year field experiment was conducted with two cropping systems (traditional sowing/harvest dates, CK; optimized sowing/harvest dates, OD) and three tillage practices (no-tillage, NT; rotary tillage, RT; strip deep rotary tillage, ST) during the maize season. Our objectives were to evaluate how the interaction between sowing/harvest date and strip deep rotary tillage affects soil water distribution, crop yield, and WUE, and to provide a technical reference for water-saving crop management in the North China Plain.

2. Materials and methods

2.1. Experimental site

A two-year field experiment was conducted during the 2022–2023 and 2023–2024 growing seasons at the Xinxiang Experimental Station of Chinese Academy of Agricultural Sciences, Henan Province, China (35°18′N, 113°54′E). Xinxiang is a typical representative of the North China Plain (NCP), where intensive agriculture is practiced and over 80% of the arable land is under a winter wheat–summer maize cropping system. The region has a warm temperate continental monsoon climate, with an annual mean temperature of 12–14 °C, annual precipitation of 504.9–662.1 mm, and annual sunshine hours of 1928–2557 h. Daily precipitation, solar radiation, and mean temperature during the experimental period are shown in Fig. 1. The soil texture of the experimental field is sandy loam, with 12.8 $g\cdot kg^{-1}$ organic matter, 62.3 $mg\cdot kg^{-1}$ available nitrogen, 15.9 $mg\cdot kg^{-1}$ available phosphorus, and 112.1 $mg\cdot kg^{-1}$ available potassium in the 0–20 cm soil layer.

2.2. Experimental design and field management

The experiment was arranged in a randomized complete block design with a split-plot restriction. Three replications were used. Main plots (cropping systems, CK and OD) were randomly assigned within each block, and subplots (tillage practices, NT, RT, ST) were randomly assigned within each main plot. In CK, sowing and harvest dates followed local farmers' practices. In OD, wheat sowing was delayed by

15 days compared with CK, and the seeding rate was increased by 0.5 kg·ha^{-1} for every 2-day delay to maintain a comparable spike number at maturity. Maize harvest in OD was delayed by 25–30 days, as late as possible without affecting subsequent wheat sowing. The subplots consisted of three tillage practices applied during the maize season: no-tillage (NT), rotary tillage (RT), and strip deep rotary tillage (ST). NT involved direct seeding into standing stubble without prior soil disturbance. RT was performed to a depth of 0–15 cm using a rotary tiller (1GKN-250, Yungangxuangengjixie Co. Ltd., Lianyungang, Jiangsu, China). ST was conducted only in a 15-cm-wide sowing belt with a maximum depth of 40 cm using a specialized machine (2BMGF-4, Runfengyuan Agricultural Machinery Co., Ltd., Cangzhou, Hebei, China), while inter-row zones remained untilled and were covered with wheat straw. Each subplot measured 168 m^2 (4.8 m × 35 m).

The widely grown winter wheat cultivar Jimai 22 (JM22) and summer maize cultivar Denghai 605 (DH605) were selected. Wheat was sown at a density of 300 plants·m^{-2} with a row spacing of 20 cm. Basal fertilizers of 140 kg N·ha^{-1}, 120 kg P_2O_5·ha^{-1}, and 90 kg K_2O·ha^{-1} were applied before sowing, and an additional 120 kg N·ha^{-1} was top-dressed at jointing and anthesis stages, each accompanied by irrigation. Maize was planted at a density of 75,000 plants·ha^{-1} with a row spacing of 60 cm. Basal fertilizers of 150 kg N·ha^{-1}, 100 kg P_2O_5·ha^{-1}, and 80 kg K_2O·ha^{-1} were applied at sowing, and 100 kg N·ha^{-1} was side-dressed at the 10-leaf stage, combined with irrigation or rainfall. Irrigation in the wheat season under CK was applied at wintering, jointing, and anthesis stages, while under OD, irrigation was applied only at jointing and anthesis. Maize received irrigation during dry periods or at fertilizer application. Sowing/harvest dates, tillage regimes, and irrigation amounts for each treatment are summarized in Table 1. Weeds, pests, and diseases were effectively controlled during each growing season.

2.3. Sampling and measurements

2.3.1 Weather data

Daily meteorological data, including mean, maximum, and minimum air temperature, solar radiation, and precipitation during the winter wheat–summer maize growing seasons of 2022–2023 and 2023–2024, were obtained from the China Meteorological Administration.

2.3.2 Soil water content

Soil samples were collected at the sowing and harvest stages of winter wheat and summer maize. In each plot, five sampling points were selected following a diagonal pattern. Soil cores were taken from the 0–200 cm profile in 10-cm increments using a soil auger. Fresh soil samples were immediately placed into aluminum boxes, weighed, oven-dried at 105 °C to constant weight, and reweighed. Gravimetric soil water content ($g \cdot g^{-1}$) was calculated as the difference between fresh and dry soil weight divided by dry soil weight. Soil water storage (mm) in the 0–200 cm profile was calculated based on gravimetric water content and soil bulk density of each layer.

The change in soil water storage (ΔW, mm) in the 0–200 cm profile was calculated as:

$$\Delta W = \Sigma_i^n (\gamma_i \times H_i \times (\theta_{i2} - \theta_{i1})) \times 10 \quad [1]$$

where i is the soil layer number, n is the total number of soil layers (10-cm increments), γ_i is the bulk density of the i-th layer (g·cm^{-3}), H_i is the thickness of the i-th layer (cm), and θ_{i1} and θ_{i2} are the gravimetric soil water contents (%) at the beginning and end of the period in the i-th layer, respectively.

2.3.3 Soil water consumption and water balance components

Evapotranspiration (ET_a, mm) was calculated using the soil water balance method according to the following equation:

$$ET_a = I + P + W_g \pm \Delta W - D - R \quad [2]$$

where I is irrigation amount (mm), P is effective precipitation (mm), W_g is upward capillary rise from groundwater (mm), ΔW is the change in soil water storage in the 0–200 cm layer (mm), D is deep drainage below 200 cm (mm), and R is surface runoff (mm). In this study, surface runoff (R) was considered negligible due to the flat terrain and border ridges. Groundwater depth remained below 4 m throughout the study period, so capillary rise (W_g) was assumed to be zero. Water moving below 200 cm was regarded as deep drainage loss.

Deep drainage (D, mm) below 200 cm was estimated using the following equation:

$$D = W + P + I - \Delta ET_a - FWHC_m \quad [3]$$

where W is soil water storage in the 0–200 cm layer at sowing (mm), ΔET_a is the mean evapotranspiration during the corresponding growth period in treatments/years without drainage (mm), $FWHC_m$ is the maximum field water-holding capacity of the 0–200 cm soil profile (mm). In this study, deep drainage below 200 cm was used as calculated recharge and as an indicator of potential groundwater recharge.

Net groundwater use (G_{use}, mm) was calculated as:

$$G_{use} = I - D \quad [4]$$

where G_{use} is net groundwater use, I is irrigation amount, and D is calculated recharge below 200 cm.

Soil evaporation rate (mg h^{-1}) was measured at anthesis of winter wheat and at silking of summer maize. Soil evaporation rate was determined using micro-lysimeters according to the method described by Zhao et al. (2013). PVC tubes (130 mm height, 140 mm inner diameter, 5 mm wall thickness) were vertically inserted into the soil between rows until the upper rim was flush with the soil surface. The micro-lysimeters were carefully removed daily, sealed at the bottom with plastic bags, weighed, and immediately returned to their original position. Daily soil evaporation was calculated from the weight loss. Undisturbed soil cores inside the micro-lysimeters were replaced every 2-3 days and immediately after each irrigation or rainfall event.

Transpiration rate (T_r) of flag leaves for wheat and ear leaves for maize were determined at the anthesis of wheat and silking of maize using a portable gas exchange system (LI-6400, LI-COR Inc., Lincoln, NE, USA) under controlled conditions (1500-1800 μmol m^{-2} s^{-1} photosynthetically active radiation, 400 μmol mol^{-1} CO_2, and 30 ± 4 °C leaf temperature, and 50-60% relative humidity).

2.3.4 Grain yield and yield components

At wheat harvest, a 1- by 1-m area in each plot, with three replications, was harvested by hand to determine the grain yield. The grain yield was adjusted to a 13% moisture content. The 1,000-kernel weight was calculated as the average weight of three random samples of 500 kernels. The number of spikes was counted manually in two rows within 1.0 m, and the number of kernels per spike was counted manually to estimate a mean value based on 20 spikes.

At maize harvest, all ears from the four central rows of each plot (48 m^2) were collected, and the total ear number was counted to calculate the ear number per unit area. 20 ears were selected from each plot to determine kernel number per ear and 1000-kernel weight. A total of 100 kernels were measured five times from each plot, and the result was converted to 1 000-kernel weight. Maize yield was determined assuming 14% kernel water content.

2.3.5 Water use efficiency

Water use efficiency (kg m^{-3}) was calculated according to Eq. (5) (Hussain et al., 1995):

$$\text{Water use efficiency (WUE)} = Y / ET \qquad [5]$$

where Y is grain yield (kg ha^{-1}), and ET is the corresponding crop evapotranspiration (mm), which was calculated as in Eq. (2).

2.4. Statistical Analysis

Data preparation was performed using Microsoft Excel (Microsoft Corporation, 2019). After verifying the normality and homogeneity of variance, data on soil bulk density, soil water content, grain yield, and water use efficiency were analyzed using ANOVA. Means were compared using the Tukey's HSD test at the 0.05 and 0.01

probability level.

3. Results

3.1. Precipitation allocation and net groundwater use

The OD system significantly altered seasonal precipitation distribution. Compared with the traditional system (CK), the optimized system (OD) reduced wheat-season precipitation by 5.4%–7.6% but increased maize-season precipitation by 4.9%–5.6% across the two years (Table 2). Annual precipitation did not differ significantly between cropping systems.

G_{use} was significantly affected by cropping system, tillage regime, and their interaction (Table 2). During the wheat season, CK exhibited significantly higher irrigation amount, precipitation, groundwater recharge, and net G_{use} than OD. In contrast, during the maize season, the precipitation (except for 2022-2023) and groundwater recharge of OD showed significantly higher than those of CK, while OD reduced the net G_{use} compared with CK. Annually, both irrigation amount and net G_{use} were significantly lower under OD than under CK. Within each cropping system, ST consistently enhanced groundwater recharge compared with NT and RT, with annual increases of 19.1%-26.4% and 7.0%-13.9%, respectively. Consequently, annual net G_{use} under ST was 5.8%–8.6% lower than under NT and 2.7%–5.1% lower than under RT, although the difference between ST and NT was not always significant.

3.2. Soil bulk density and soil water content

Tillage regime significantly affected soil bulk density in the 0–60 cm layer (Fig. 2). Compared with NT, RT reduced bulk density by 7.4%–9.8% in the 0–20 cm layer, while ST reduced it by 7.7%–13.2% across the 0–40 cm layer. Notably, ST achieved significantly lower bulk density than RT in the 20–40 cm layer, indicating effective deep compaction alleviation.

Soil water content (SWC) in the 0–200 cm profile showed distinct vertical distribution patterns among tillage practices (Figs. 3, 4). At maize sowing, ST reduced SWC in the 0–40 cm layer by 13.1%–13.2% but increased SWC in the 40–200 cm layer by 8.8% compared with NT under both CK and OD. At maize maturity, ST increased average SWC in the 0–200 cm layer by 12.9%–16.8% relative to NT, with deep-layer (40–200 cm) SWC being 16.8%–17.3% higher under ST than under NT. Similar trends were observed at wheat sowing and maturity, indicating that ST promoted deep soil water storage and reduced surface water retention.

3.3. Soil evaporation and crop transpiration

Soil evaporation rate was significantly influenced by cropping system, tillage, and their interaction (Figs. 5, 6). At maize silking, OD decreased soil evaporation rate from the soil surface by 6.9%–7.4% across all tillage treatments compared with CK. Under both CK and OD, NT reduced evaporation rate in the 0–30 cm layer by 5.0%–22.3% relative to RT and ST. At wheat anthesis, OD decreased soil evaporation rate in the 0–30 cm layer by 7.4%–8.4% across tillage regimes, and NT consistently showed the lowest evaporation rates among tillage practices.

Crop transpiration rate (T_r) showed opposite trends between the two crops (Fig. 7). At maize silking, OD reduced Tr by 7.2%–11.0%, while ST still enhanced Tr by 4.3%–18.8% compared with NT and RT. At wheat anthesis, OD increased Tr by

6.0%–6.5% compared with CK, and ST increased Tr by 7.6%–12.3% relative to NT and RT. These results suggest that ST facilitates allocating more water to productive transpiration rather than soil evaporation.

3.4. Grain yield and water use efficiency

Cropping system, tillage regime, and their interaction significantly affected grain yield of both crops (Table 3). Compared with CK, OD significantly reduced wheat yield (by 2.3%–4.4%) due to decreased spike number, but significantly increased maize yield (by 4.2%–6.9%) primarily through higher 1000-kernel weight, resulting in comparable annual total yield between systems. Under both CK and OD, ST produced the highest grain yield for wheat, maize, and the annual total. Specifically, under OD, ST increased wheat, maize, and annual yield by 6.0%-6.9%, 6.6%-7.2%, and 6.3%-7.1%, respectively, compared with NT.

Water use efficiency (WUE) followed similar patterns (Table 4). OD reduced wheat-season ETa and increased WUE, while during maize season, OD enhanced both yield and WUE without increasing ETa. Annual WUE under OD was 5.7%–10.2% higher than under CK. Across both cropping systems, ST achieved the highest WUE for both crops and the annual rotation. Under OD, ST increased annual WUE by 4.3%-5.1% and 8.6%-10.5% compared with NT and RT, respectively.

The significant three-way interaction (Y×C×T) for maize yield (P < 0.05) and maize WUE (P < 0.05) indicated that the combined effect of cropping system and tillage on maize performance varied between years, primarily driven by differences in preseason precipitation. In the drier 2023–2024 wheat season, the advantage of ST under OD was more pronounced.

3.5. Principal component analysis

Principal component analysis (PCA) was conducted to differentiate the integrated effects of tillage regimes under different cropping systems (Fig. 8). Under CK, PC1 (45.9% variance) separated NT (negative side) from RT and ST (positive side). NT was closely associated with higher surface soil bulk density and SWC in the 0–40 cm layer, indicating restricted water infiltration. ST was positively correlated with deep-layer SWC and crop transpiration, suggesting improved water distribution and use efficiency. Under OD, PC1 (44.0%) and PC2 (36.3%) further distinguished treatments, with ST showing stronger alignment with deep soil water storage and transpiration, while RT was more associated with soil evaporation. These results indicate that ST, especially when combined with OD, enhances deep soil water replenishment and promotes water conversion into crop transpiration, thereby improving annual water balance and WUE.

4. Discussion

4.1. Optimizing sowing/harvest dates reallocates seasonal precipitation and reduces groundwater consumption

In the North China Plain (NCP), the mismatch between precipitation seasonality and crop water demand is the primary cause of excessive groundwater depletion in the winter wheat–summer maize cropping system (Sun et al., 2010; Han et al., 2025). Our results show that delaying wheat sowing by 15 days and maize harvest by 25–30 days (OD) shifted 4.9%–5.6% of precipitation from the wheat to the maize season without changing annual total precipitation (Table 2), allowed more precipitation to be captured by the summer maize season. More importantly, OD significantly reduced wheat-season irrigation by 8.2%–12.0% and annual net groundwater use by 8.2%–11.5% compared with CK, consistent with previous reports that delayed sowing reduces wheat water consumption (Xu et al., 2018; Zhang et al., 2023a).

Delayed sowing reduces pre-winter vegetative growth, thereby decreasing evapotranspiration during the low-precipitation winter–spring period (Sun et al., 2007; Zhou et al., 2019). This, in turn, preserves soil moisture for critical reproductive stages and allows more efficient use of spring rainfall. The slight reduction in wheat yield under OD was fully offset by increased maize yield, primarily through enhanced 1000-kernel weight due to extended grain filling under delayed harvest (Xu et al., 2018; Liu et al., 2019). This compensation is key to the viability of the double-delayed strategy, particularly under conditions of limited irrigation (Li et al., 2021; Zhao et al., 2025). Thus, aligning phenology with precipitation patterns offers a practical, low-cost water-saving approach without compromising annual productivity.

It should be noted that the OD system received less irrigation than CK by design, as delayed sowing reduces pre-winter water demand. Consequently, the observed water savings reflect the combined effect of sowing date adjustment and reduced irrigation, which cannot be fully disentangled in the current experimental design.

4.2. Strip deep rotary tillage enhances deep soil water storage and groundwater recharge

Tillage practices profoundly influence soil physical properties and water dynamics (Zhao et al., 2014; Wang et al., 2019). Our results demonstrated that strip deep rotary tillage (ST) significantly reduced soil bulk density in the 0–40 cm layer, particularly at 20–40 cm depth where conventional rotary tillage (RT) had little effect (Fig. 2). This deep loosening improved soil porosity and hydraulic conductivity, facilitating rapid infiltration of heavy rainfall events during the maize season (Yuan et al., 2025; Lv et al., 2026). Consequently, ST increased deep-layer (40–200 cm) soil water content at both maize and wheat sowing stages, indicating enhanced subsoil water storage available for the subsequent wheat crop.

Furthermore, ST disrupts the hard plow pan that commonly forms at 15–20 cm depth under long-term conventional tillage, thereby reducing resistance to vertical water flow (Wang et al., 2015; Kan et al., 2020). This allows more irrigation and rainfall to percolate below the root zone, recharging the aquifer. Compared to NT, which caused surface compaction and restricted infiltration, ST increased groundwater recharge by 19.1%-26.4% and reduced net groundwater use by 5.8%–8.6% annually (Table 2). Thus, ST serves as a key practice to convert more rainfall into usable soil water and groundwater, reducing reliance on irrigation. Recent studies confirm that strategic deep tillage improves deep soil water replenishment and enhances crop access to stored water, particularly in water-limited environments (Wickramarachchi et al., 2025; Yuan et al., 2025).

A limitation is that groundwater depth was not continuously monitored; our estimates of groundwater recharge and net use were inferred from soil water balance and deep drainage calculations. Direct measurements (e.g., using lysimeters or groundwater level loggers) are needed to validate these estimates.

4.3. Synergistic effects of OD and ST on water balance and crop water use

Although OD and ST each independently contributed to water savings, their combination produced synergistic benefits for the annual water balance. Under OD, the wheat season received less precipitation but had higher soil water storage at sowing (due to ST-enhanced deep storage), allowing wheat to rely more on stored deep soil water and less on irrigation. This was reflected in the significantly higher transpiration rate of wheat under ST (Fig. 7), indicating that wheat roots accessed deep soil water more effectively. Meanwhile, ST reduced soil evaporation during the maize season (Fig. 6), further conserving water for productive transpiration.

The OD+ST combination alters the partitioning of evapotranspiration components: OD reduces early-season wheat transpiration loss, while ST enhances infiltration and reduces unproductive evaporation through surface straw retention in untilled inter-rows (Wang et al., 2015; Sun et al., 2017). The PCA results (Fig. 8) clearly distinguished functional traits: under OD, ST was positively correlated with deep-layer soil water content (40–200 cm) and transpiration of both crops, whereas NT was associated with surface water retention and restricted infiltration. RT occupied an intermediate position but showed stronger links to soil evaporation, indicating less efficient water use. These findings suggest that OD creates a window for ST to fully express its benefits: delaying wheat sowing preserves deep-stored water for the wheat season, and delaying maize harvest allows maize to utilize late-season rainfall and stored soil water more effectively. This integrated strategy thus optimizes the temporal and spatial coupling of water supply and demand (Miao et al., 2024; Zhao et al., 2025).

4.4. Synergistic effects of OD and ST on annual yield and water use efficiency

The combination of delayed sowing/harvest dates (OD) and strip deep rotary tillage (ST) synergistically improved annual yield and WUE, though their contributions differed between crops. OD reduced wheat yields due to decreased spike number from delayed sowing (Xu et al., 2018; Zhou et al., 2019). However, ST partially offset this decline by improving kernel weight, likely through enhanced post-anthesis water supply from deep soil layers and increased transpiration. Moreover, OD increased maize yield through higher 1000-kernel weight from extended grain filling (Xu et al., 2018; Liu et al., 2019), and ST further amplified this benefit by improving deep soil water availability and reducing soil evaporation. The integrated OD+ST practice achieved 7.5%–8.2% higher annual yield than CK+NT.

Water use efficiency followed a similar pattern (Table 4). OD reduced wheat-season evapotranspiration while maintaining or slightly lowering yield, resulting in improved WUE for wheat. ST reduced unproductive soil evaporation and promoted transpiration, further increasing WUE for both crops. Under OD, ST improved annual WUE by 4.3%–5.1% and 8.6%–10.5% compared to NT and RT, respectively.

Importantly, the significant three-way interaction (Y×C×T) for maize yield and WUE ($P < 0.05$) indicates that the benefits of OD and ST were more pronounced in the drier 2023–2024 season. In that year, preseason precipitation was substantially lower, and the advantage of ST in capturing and storing limited rainfall for subsequent crop use was amplified. This suggests that the synergistic effect of delayed sowing and strip deep rotary tillage may be particularly valuable under water-limited conditions, highlighting the potential of this integrated strategy for climate resilience.

Although we observed increased 1000-kernel weight under OD+ST, we did not directly measure grain-filling dynamics, carbohydrate remobilization, or root system architecture. The physiological mechanisms underlying the observed yield improvements—particularly how ST enhances kernel weight under water-limited conditions—remain speculative and warrant further investigation.

4.5. Implications for sustainable water management and climate adaptation

We propose a conceptual model (Fig. 9) highlighting the potential function of integrated OD+ST strategy to enhance precipitation allocation, groundwater use, grain yield, and water use efficiency in a winter wheat–summer maize cropping system. By shifting seasonal precipitation allocation (OD) and enhancing groundwater recharge through alleviating subsoil compaction (ST), combining OD with ST shifted water use from irrigation toward stored soil water and effective rainfall, thereby reducing annual net groundwater consumption by 15.1%–16.6% compared with traditional practices. At the same time, annual grain yield was maintained or increased, and annual WUE was significantly improved. These outcomes align with the goals of water-saving and high-yield agriculture in water-limited regions.

Moreover, the double-delayed system (delayed wheat sowing and delayed maize harvest) enhances resilience against climate extremes. Under recent climate warming and increased frequency of extreme weather events in northern China (Bai et al., 2016; Hu et al., 2025; Zhou et al., 2025), delaying wheat sowing to mid-November helps avoid excessive pre-winter growth and spring frost risks (Sattar et al., 2023; Zhang et al., 2023b), and delaying maize harvest allows grain to reach lower moisture content, facilitating mechanical kernel harvesting and reducing post-harvest drying costs (Chai et al., 2017; Zhao et al., 2023).

4.6. Limitations and future research

This study provides strong evidence for the benefits of combining OD and ST, but several limitations should be acknowledged. First, the experiment was conducted at a single site with sandy loam soil; the effectiveness of ST may vary with soil texture and initial compaction status (Wickramarachchi et al., 2025). Second, the study duration captured only two contrasting precipitation patterns; long-term experiments are needed to assess inter-annual variability and system resilience. Third, we did not directly measure root system architecture or root water uptake dynamics, which would help mechanistically explain the observed differences in deep water utilization. Fourth, soil water content was measured only at key phenological stages (sowing and harvest), which may not capture rapid infiltration events or peak crop water use. Future research should integrate root phenotyping, isotopic water tracing, continuous soil moisture monitoring (e.g., time-domain reflectometry or capacitance sensors), and modeling approaches to quantify the water-saving potential of this system across different climatic scenarios and soil types (Yuan et al., 2025; Zhao et al., 2025).

5. Conclusions

Integrating delayed sowing/harvest dates (OD) with strip deep rotary tillage (ST) significantly improved the annual yield and water use of the winter wheat–summer maize cropping system. Delayed sowing/harvest dates reallocated seasonal precipitation, reducing irrigation demand and net groundwater use without compromising annual grain yield. Strip deep rotary tillage effectively reduced soil bulk density in the 0–40 cm layer, enhanced deep-layer (40–200 cm) soil water storage, and promoted groundwater recharge, as well as increased wheat and maize yield. The integrated OD+ST strategy achieved an 7.5%-8.2% increase in annual grain yield and 11.3%-16.9% increase in annual water use efficiency compared with the traditional CK+NT. These findings provide a practical and effective management strategy for balancing high crop yield with sustainable groundwater use in the North China Plain and other water-limited agricultural regions worldwide.

Author contributions statement

Xinyu Shen: investigation, validation, formal analysis, data curation, writing–original draft, visualization. **Jinxin Zhang:** formal analysis, data curation, writing–review and editing. **Junzhu Ge:** writing–review and editing, conceptualization, software, supervision. **Wenchao Zhen:** funding acquisition, methodology, resources, investigation, software. **Limin Gu:** writing–review and editing, formal analysis, software. **Zaisong Ding:** methodology, resources, investigation, software. **Xinbing Wang:** methodology, writing–review and editing, validation. **Congfeng Li:** writing–review and editing, software. **Ming Zhao:**

writing–review and editing, validation. **Baoyuan Zhou:** conceptualization, formal analysis, project administration, writing–review and editing, supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability statement

Data will be made available on request.

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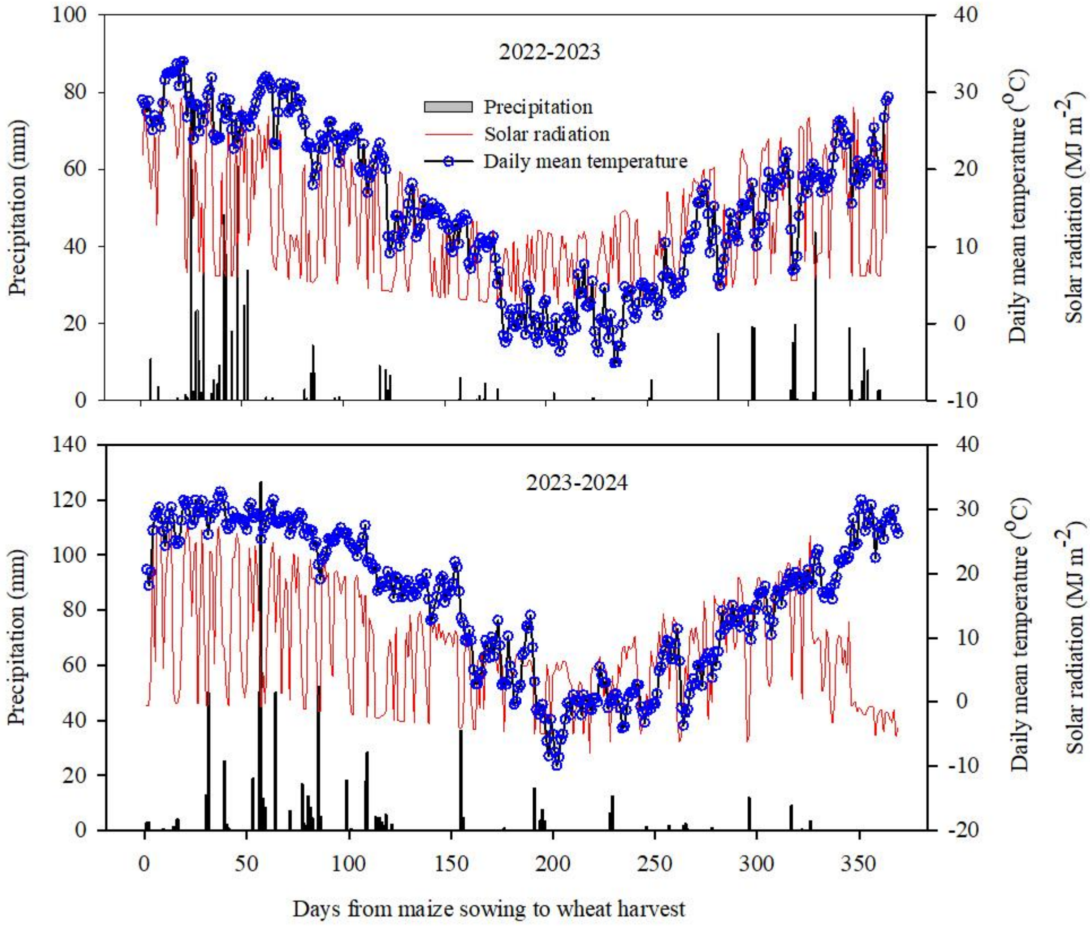
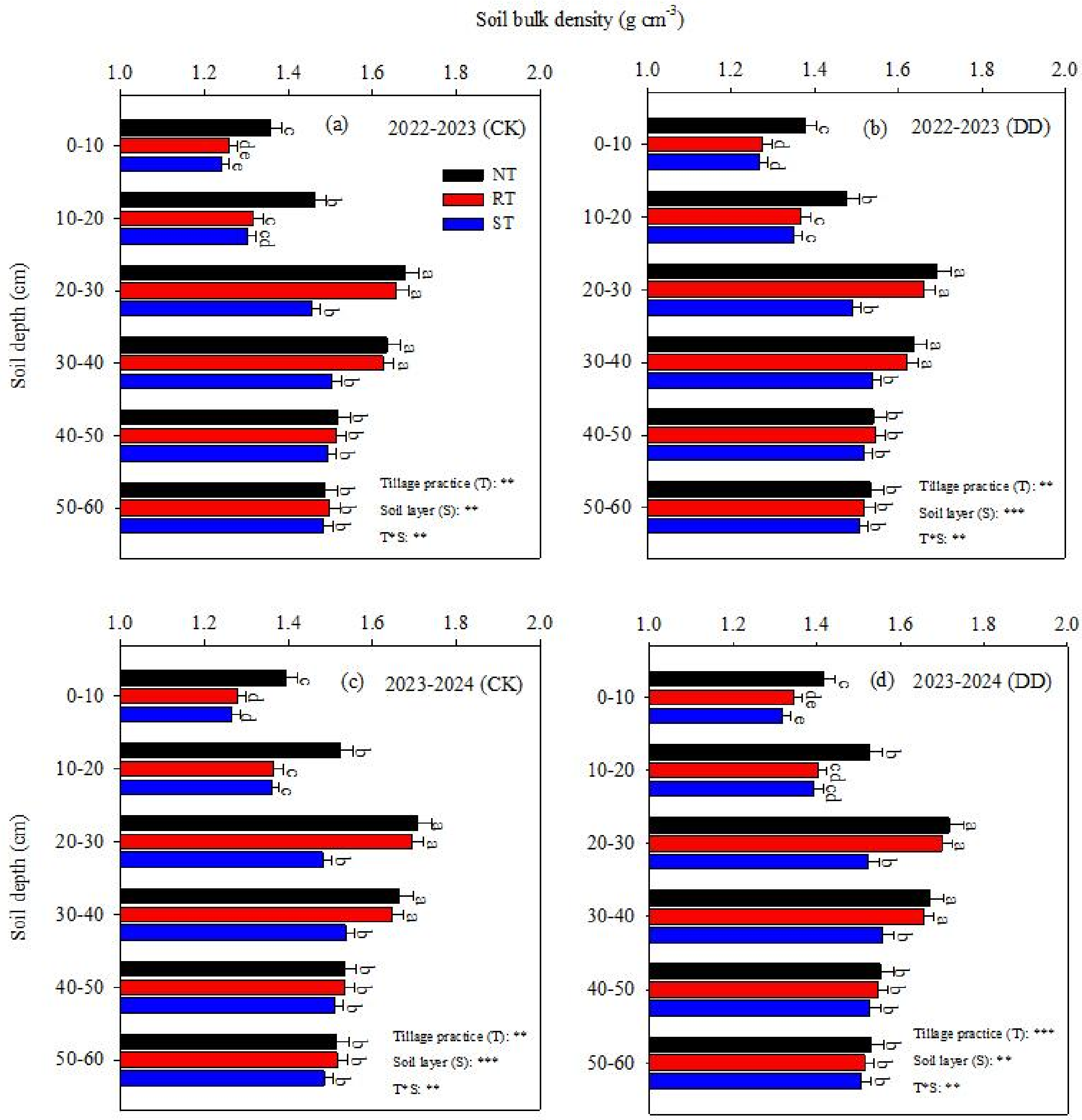
602 **Figures**



603

604 **Fig. 1 Daily precipitation, solar radiation, and mean temperature from wheat**
605 **sowing to maize harvest during 2022 to 2024 at Xinxiang County.**



606

607 **Fig. 2 Soil bulk density in the 0-60 cm layers after tillage conducted during the**

608 **summer maize growing season.** CK is the traditional winter wheat-summer maize

609 cropping system; OD is the optimized winter wheat-summer maize cropping system.

610 NT, no-tillage; RT, rotary tillage; ST, strip deep rotary tillage. Different lower-case

611 letters indicate significant differences at the 0.05 probability level.

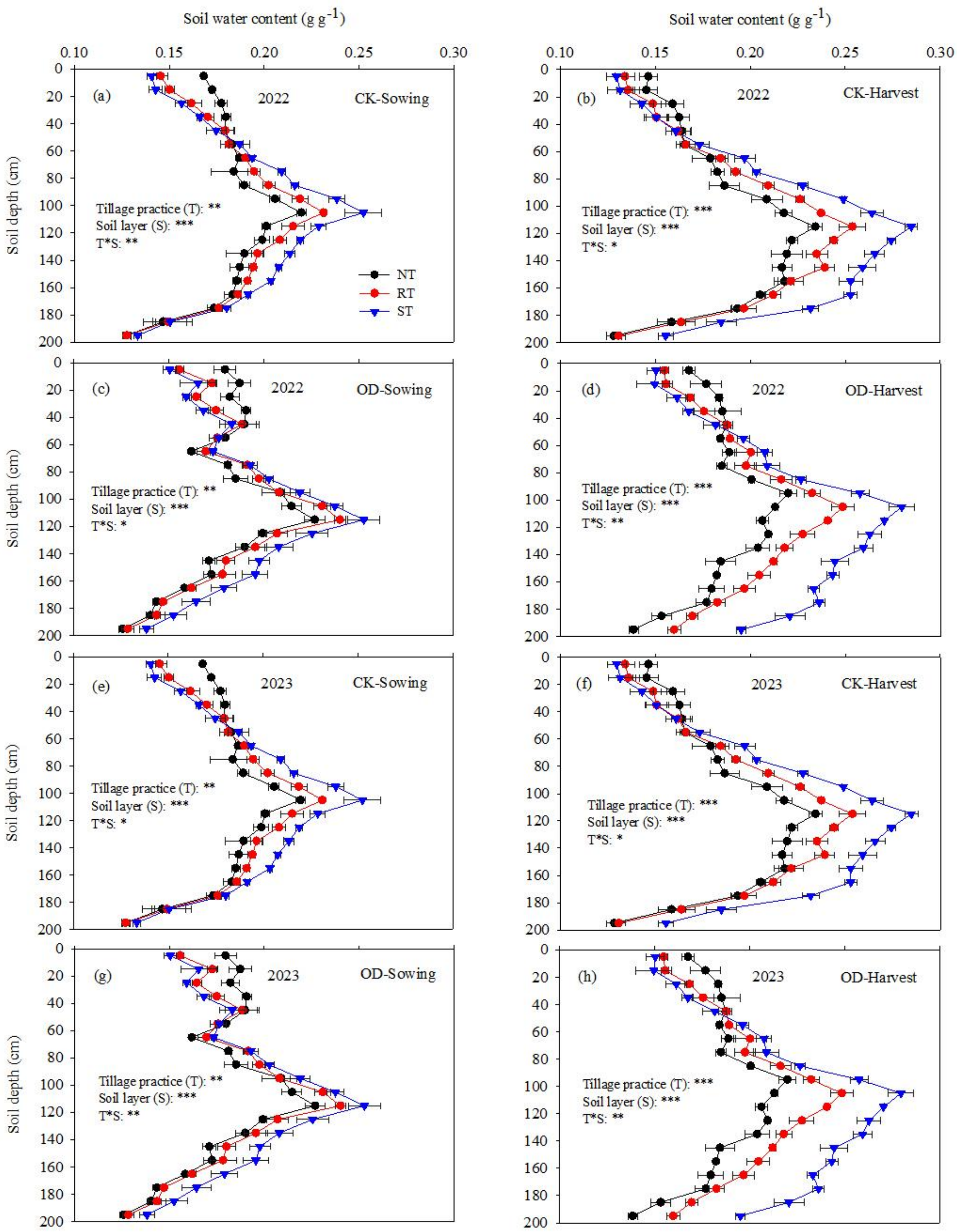


Fig. 3 Soil water content in the 0-200 cm layers during the winter wheat growing season. CK is the traditional winter wheat-summer maize cropping system; OD is the optimized winter wheat-summer maize cropping system. NT, no-tillage; RT, rotary tillage; ST, strip deep rotary tillage.

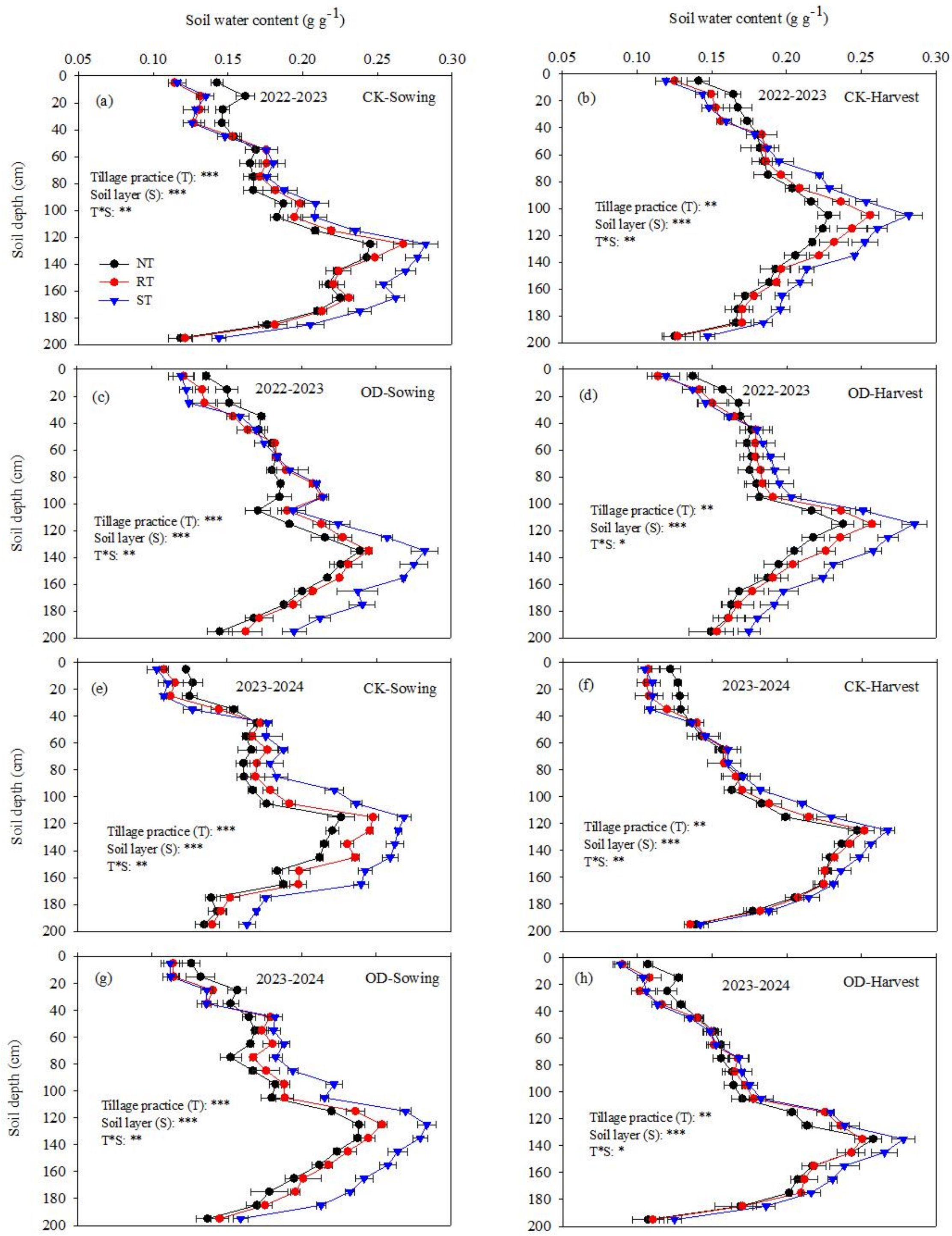


Fig. 4 Soil water content in the 0-200 cm layers during the summer maize growing season. CK is the traditional winter wheat-summer maize cropping system; OD is the optimized winter wheat-summer maize cropping system. NT, no-tillage; RT, rotary tillage; ST, strip deep rotary tillage.

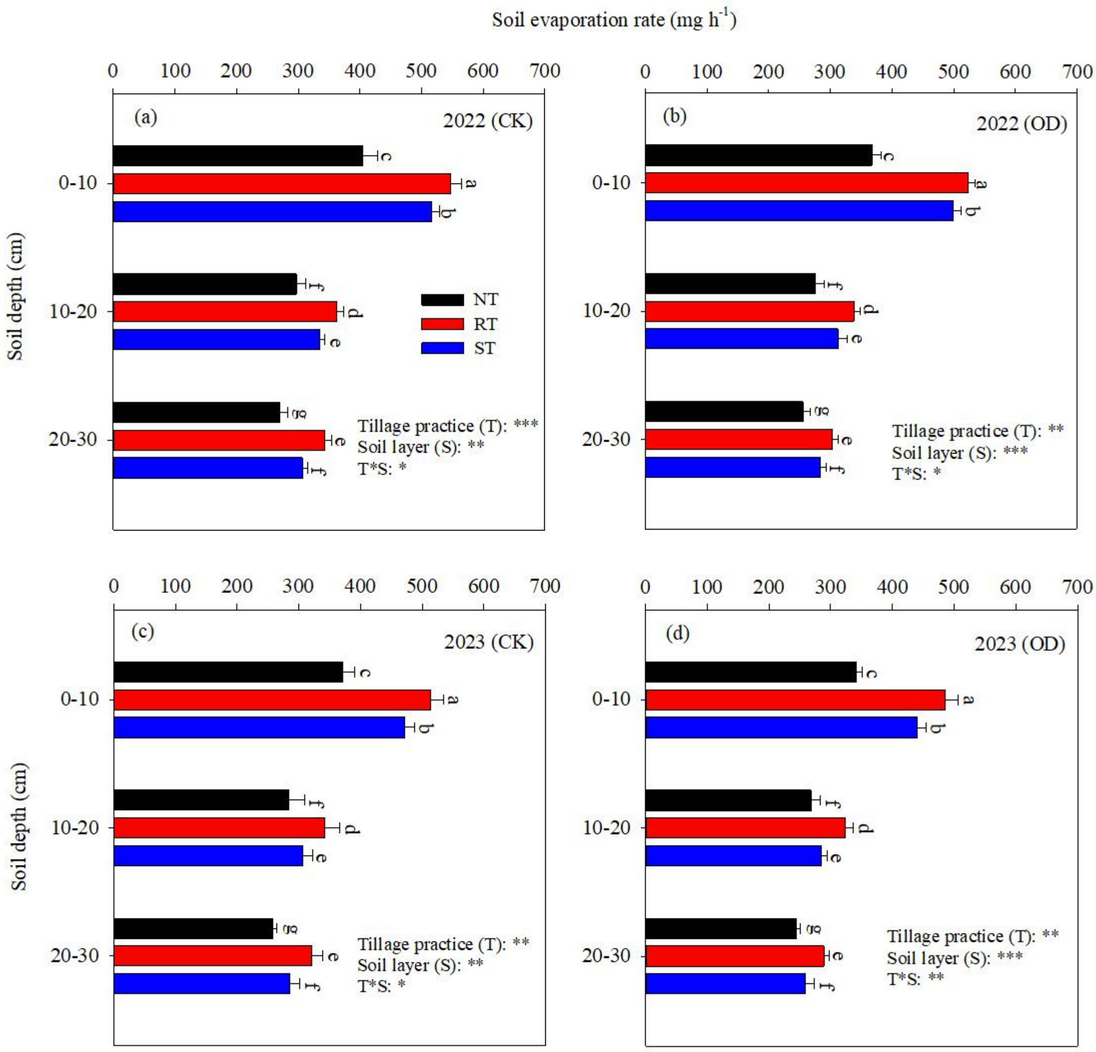


Fig. 5 Soil evaporation rate at the silking stage of summer maize. CK is the traditional winter wheat-summer maize cropping system; OD is the optimized winter wheat-summer maize cropping system. NT, no-tillage; RT, rotary tillage; ST, strip deep rotary tillage. Different lower-case letters indicate significant differences at the 0.05 probability level.

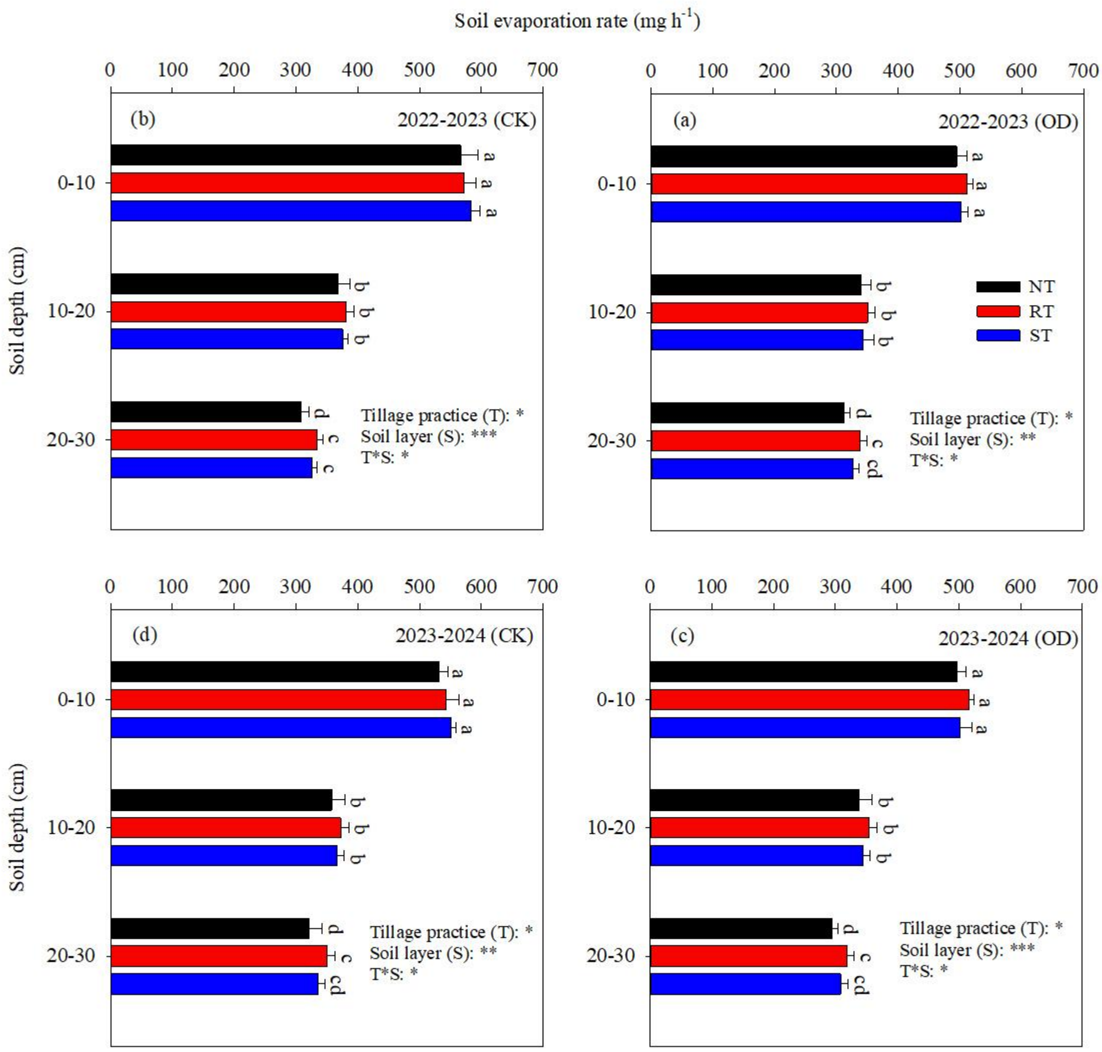


Fig. 6 Soil evaporation rate at the anthesis stage of winter wheat. CK is the traditional winter wheat-summer maize cropping system; OD is the optimized winter wheat-summer maize cropping system. NT, no-tillage; RT, rotary tillage; ST, strip deep rotary tillage. Different lower-case letters indicate significant differences at the 0.05 probability level.

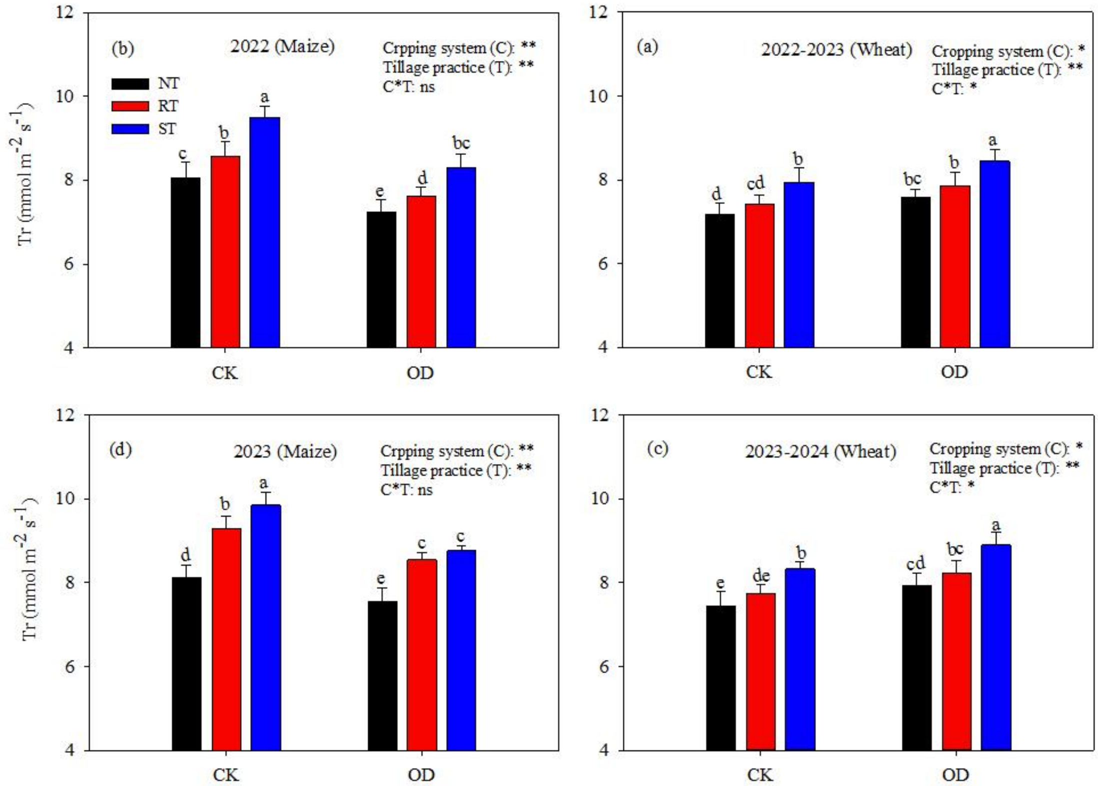


Fig. 7 Transpiration rate during flowering stage of wheat and maize. CK is the traditional winter wheat-summer maize cropping system; OD is the optimized winter wheat-summer maize cropping system. NT, no-tillage; RT, rotary tillage; ST, strip deep rotary tillage. Different lower-case letters indicate significant differences at the 0.05 probability level.

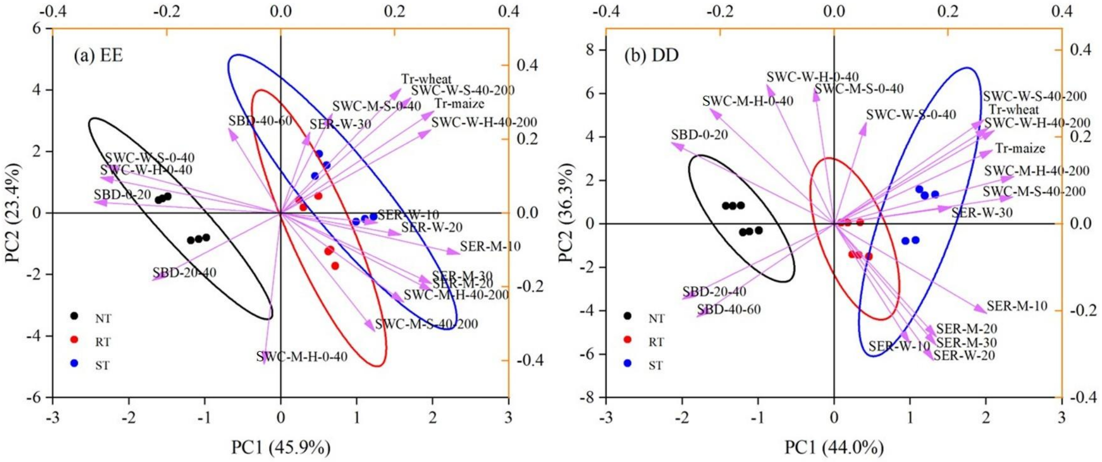


Fig. 8 Principal component analysis (PCA) of yield, soil water content, groundwater use among three tillage regimes under two cropping systems. PC1 represents the first axis, PC2 represents the second axis, and the The percentages indicate the proportions of variance explained by each axis. CK is the traditional winter wheat-summer maize cropping system; OD is the optimized winter wheat-summer maize cropping system. NT, no-tillage; RT, rotary tillage; ST, strip deep rotary tillage. SBD, SWC, Tr, and SER denote soil bulk density, soil water content, transpiration rate, and soil evaporation, respectively.

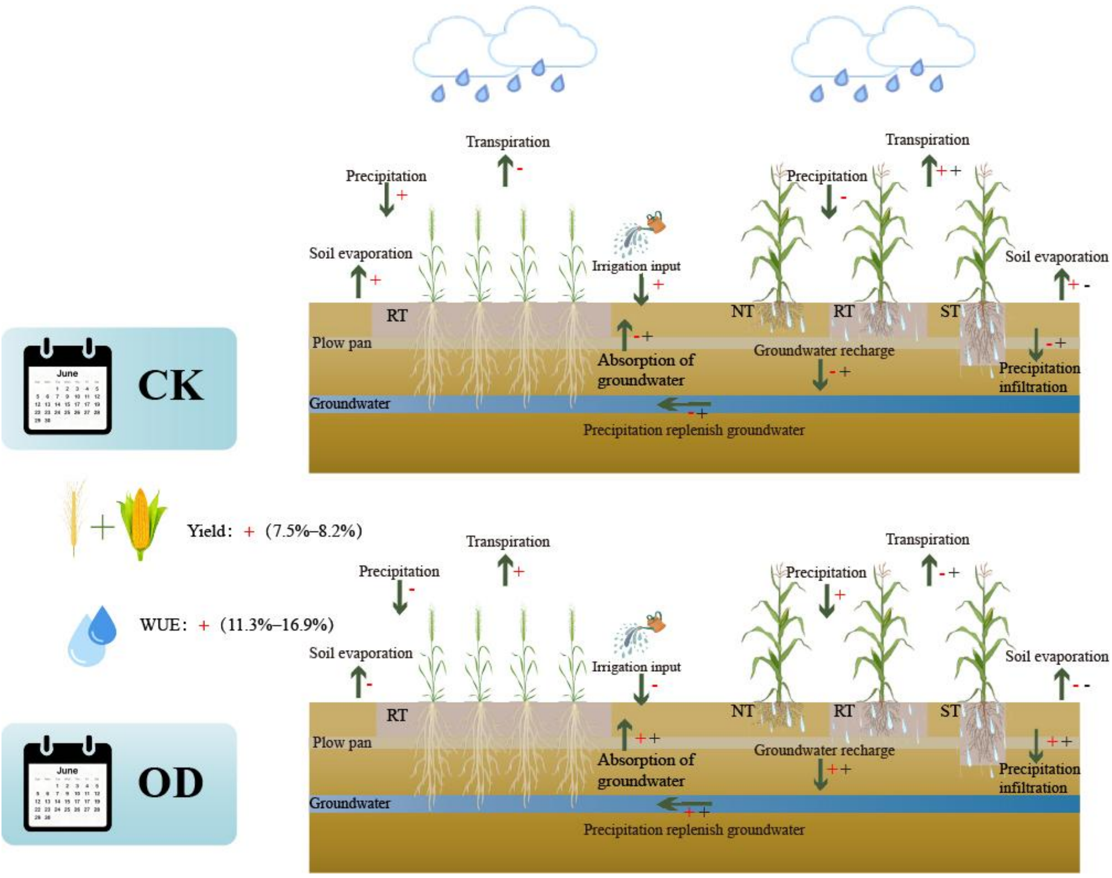


Fig. 9 Conceptual framework of the OD+ST strategy for enhancing precipitation allocation, groundwater use, grain yield, and water use efficiency in a winter wheat–summer maize cropping system. CK is the traditional winter wheat-summer maize cropping system; OD is the optimized winter wheat-summer maize cropping system. NT, no-tillage; RT, rotary tillage; ST, strip deep rotary tillage. Arrows indicate the direction of water fluxes. Positive ("+") and negative (" – ") signs denote relative increases and decreases in the respective variables ($P < 0.05$). Red symbols denote contrasts between cropping systems (CK and OD), whereas black symbols indicate contrasts among tillage practices within a given sowing/harvest regime.

Table 1 Scheme for different treatments

Year	Treatment	maize				wheat		
		Sowing date (YY/MM/DD)	Harvest date (YY/MM/DD)	Tillage practice	Irrigation rate（mm）	Sowing date (YY/MM/DD)	Harvest date (YY/MM/DD)	Irrigation rate（mm）
2022-2023	CK	2022/06/05	2022/09/30	NT/ RT /ST	70/100/70	2022/10/15	2023/06/02	180
	OD	2022/06/10	2022/10/25	NT/ RT /ST	50/80/50	2022/10/30	2023/06/08	150
2023-2024	CK	2023/06/03	2023/09/28	NT/ RT /ST	60/90/60	2023/10/15	2024/05/31	250
	OD	2023/06/08	2023/10/25	NT/ RT /ST	40/70/40	2023/10/30	2024/06/05	225

CK is the traditional winter wheat-summer maize cropping system; OD is the optimized winter wheat-summer maize cropping system.

Table 2 The net groundwater use in winter wheat–summer maize cropping system from 2022 to 2024

Year	Cropping system	Tillage practice	Maize season				Wheat season				Annual			
			Irrigation (mm)	Precipitation (mm)	Recharge (mm)	G_{use} (mm)	Irrigation (mm)	Precipitation (mm)	Recharge (mm)	G_{use} (mm)	Irrigation (mm)	Precipitation (mm)	Recharge (mm)	G_{use} (mm)
2022-2023	CK	NT	219a	486b	70d	148a	269a	105a	37c	232a	488a	591a	108d	380a
		RT	219a	486b	78c	141b	269a	105a	41b	228a	488a	591a	119c	369ab
		ST	219a	486b	85b	134c	269a	105a	45a	224a	488a	591a	129b	358bc
	OD	NT	209a	513a	75c	134c	247b	97b	34c	213b	457b	610a	110d	347cd
		RT	209a	513a	84b	125d	247b	97b	39b	209b	457b	610a	122c	334d
		ST	209a	513a	97a	112e	247b	97b	42a	206b	457b	610a	139a	317e
2023-2024	CK	NT	273a	363b	64d	209a	259a	260a	53c	207a	532a	623a	115d	417a
		RT	273a	363b	70c	203ab	259a	260a	58b	201a	532a	623a	128c	404ab
		ST	273a	363b	76b	197b	259a	260a	62a	197a	530a	623a	137b	393bc
	OD	NT	269a	381a	66d	203ab	228b	246b	47d	181b	497b	627a	114d	383cd
		RT	269a	381a	74b	195b	228b	246b	53c	175bc	497b	627a	127c	370d
		ST	269a	381a	86a	183c	228b	246b	57b	171c	497b	627a	143a	354e
Source of variation														
Year (Y)			**	**	**	**	**	**	**	**	**	**	**	**
Cropping system (C)			***	***	***	***	**	***	***	***	***	***	***	***
Tillage practice (T)			ns	ns	***	***	ns	***	***	ns	ns	ns	***	**
Y×C			**	**	**	**	**	**	**	**	**	**	**	**
Y×T			ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
C×T			**	**	**	**	ns	**	**	**	**	**	**	**
Y×C×T			ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns

CK is the traditional winter wheat-summer maize cropping system; OD is the optimized winter wheat-summer maize cropping system. NT, no-tillage; RT, rotary tillage; ST, strip deep rotary tillage. G_{use}, groundwater use. Different lower-case letters indicate significant differences at the 0.05 probability level. ns indicates not significant. *, **, and *** indicates significance levels at $P < 0.05$, $P < 0.01$, and $P < 0.001$.

Table 3 Grain yield and yield components of winter wheat and summer maize from 2022 to 2024

Year	Cropping system	Tillage practice	Maize				Wheat			
			Ear no. ($\times 10^4$ ha^{-1})	Kernel no. per ear	1000-kernel weight (g)	Grain yield (Mg ha^{-1})	Spikes no. ($\times 10^4$ ha^{-1})	Kernel no. per spike	1000-kernel weight (g)	Grain yield (Mg ha^{-1})
2022-2023	CK	NT	7.1a	491ab	356.1d	10.5cd	718.3a	30c	47.0bcd	9.1b
		RT	7.2a	478bc	348.9d	10.1d	716.7a	29c	47.8bc	9.3ab
		ST	7.3a	509a	374.8bc	11.2b	734.2a	32b	50.4a	9.6a
	OD	NT	7.0a	478bc	382.7b	11.1b	641.7b	32b	46.6cd	8.7c
		RT	7.1a	472c	361.8cd	10.8bc	642.5b	33a	45.5d	8.9bc
		ST	7.2a	497ab	407.6a	11.9a	652.5b	33a	48.3ab	9.3ab
2023-2024	CK	NT	7.3a	527b	307.7c	10.1c	655.6a	34c	38.6d	8.7bc
		RT	7.4a	507c	288.8d	9.6d	656.4a	37b	39.2cd	8.8ab
		ST	7.3a	542a	324.5b	10.7b	653.5a	38b	40.9bc	9.2a
	OD	NT	7.3a	523b	324.2b	10.6b	613.8b	37b	41.9ab	8.4c
		RT	7.4a	509c	305.1c	10.0cd	621.7b	38b	42.0ab	8.6bc
		ST	7.5a	545a	341.7a	11.3a	619.2b	40a	43.1a	8.9ab
Source of variation										
Year (Y)			*	**	**	**	**	**	**	**
Cropping system (C)			ns	***	***	***	**	**	ns	***
Tillage practice (T)			ns	***	***	***	ns	***	**	***
Y×C			*	**	**	**	**	**	**	**
Y×T			ns	ns	ns	ns	ns	*	ns	ns
C×T			*	**	**	**	*	**	**	**
Y×C×T			ns	ns	ns	ns	ns	*	ns	ns

CK is the traditional winter wheat-summer maize cropping system; OD is the optimized winter wheat-summer maize cropping system. NT, no-tillage; RT, rotary tillage; ST, strip deep rotary tillage. Different lower-case letters indicate significant differences at the 0.05 probability level. ns indicates not significant. *, **, and *** indicates significance levels at $P < 0.05$, $P < 0.01$, and $P < 0.001$.

Table 4 Evapotranspiration (ET) and water use efficiency (WUE) in winter wheat-summer maize cropping systems from 2022 to 2024

Year	Cropping system	Tillage practice	Maize season		Wheat season		Annual	
			ET (mm)	WUE (kg ha^{-1} mm^{-1})	ET (mm)	WUE (kg ha^{-1} mm^{-1})	ET (mm)	WUE (kg ha^{-1} mm^{-1})
2022-2023	CK	NT	558.1a	18.8c	448.7ab	20.3cd	1006.8ab	19.4cd
		RT	572.3a	17.6d	465.5a	20.0d	1037.7a	18.7d
		ST	568.2a	19.7b	458.3a	21.0bc	1026.5a	20.3bc
	OD	NT	552.9a	20.0b	409.2b	21.2b	962.2c	20.6b
		RT	571.0a	19.0bc	424.7b	21.0bc	995.7abc	19.8bc
		ST	566.5a	21.1a	417.2b	22.3a	983.7bc	21.6a
2023-2024	CK	NT	518.4abc	19.4c	499.6a	17.4cd	1018.0a	18.4d
		RT	539.6a	17.8d	518.9a	17.0d	1058.5a	17.4e
		ST	521.7ab	20.5b	514.4a	17.9c	1036.1a	19.2cd
	OD	NT	499.9d	21.3ab	442.5b	18.9b	942.4b	20.2b
		RT	515.5bcd	19.4bc	456.2b	18.8b	971.7b	19.1c
		ST	509.5cd	22.1a	444.5b	20.1a	953.0b	21.2a
Year (Y)			**	**	**	**	*	*
Cropping system (C)			*	*	**	**	**	**
Tillage practice (T)			***	***	***	***	***	***
Y×C			**	**	**	**	**	**
Y×T			*	*	ns	ns	ns	ns
C×T			**	**	**	**	**	**
Y×C×T			*	*	ns	ns	ns	ns

CK is the traditional winter wheat-summer maize cropping system; OD is the optimized winter wheat-summer maize cropping system. NT, no-tillage; RT, rotary tillage; ST, strip deep rotary tillage. Different lower-case letters indicate significant differences at the 0.05 probability level. ns indicates not significant. *, **, and *** indicates significance levels at $P < 0.05$, $P < 0.01$, and $P < 0.001$.