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Diversified crop rotations improve crop water use and subsequent cereal crop yield through soil moisture compensation

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ABSTRACT

The water-intensive conventional winter wheat–summer maize (WM) double cropping system in the North China Plain (NCP) has significantly decreased the groundwater table. To address this issue, we undertook a two-year field experiment to explore the potential and mechanisms of water-saving and yield increase of five newly designed diversified crop rotations incorporating spring crops (sweet potato, soybean, peanut, spring maize, and millet) into cereal crops compared with the conventional WM (as control). The results revealed that the five diversified crop rotations significantly decreased annual actual crop evapotranspiration by 7–12% and net groundwater use by 21–31% compared to the conventional WM. Sweet potato and peanut-based rotations significantly enhanced annual average equivalent yields up to 32% and economic benefit (+50%, +7%) while improving water productivity by 24–68% compared to WM. Shallow-rooted crops (sweet potato, soybean, peanut, and millet), when used as the preceding crop, improved soil water storage in the 0–180 cm soil layer at the start of the succeeding wheat planting season by 3–9% compared to the conventional WM. These shallow-rooted crops mainly concentrated their root systems in the 0–120 cm soil water, particularly the top 80 cm, complementing the deeper root systems of wheat, which extended down to 180 cm. Consequently, this optimal soil water use regime in diversified crop rotations increased the leaf area index and aboveground biomass of the succeeding wheat and maize crops, increasing total grain yields by 4–11%. Thus, introducing shallowed-root annual crops as preceding crops to the current WM rotation is beneficial for decreasing irrigation inputs, enhancing overall crop productivity, and mitigating groundwater table decline in the NCP.

1. Introduction

Producing more food with limited freshwater resources in the face of climate change and evolving environmental conditions is a formidable challenge (Clark et al., 2019). While agricultural intensification has significantly increased crop productivity, it has also resulted in simplified production systems in recent decades (Hufnagel et al., 2020). Unfortunately, this intensification has caused environmental issues, including excessive groundwater extraction (Kang and Eltahir, 2018), the release of climate-affecting greenhouse gases (Bowles et al., 2018), and a loss of biodiversity (Buhk et al., 2017). Crop diversification has emerged as a strategy to increase crop production (Jarecki et al., 2018; Garbelini et al., 2022; Wang et al., 2023a), reduce groundwater overextraction (Yang et al., 2015a, 2021), and enhance agroecosystem services and resilience (Li et al., 2019; Liu et al., 2022).

The North China Plain (NCP), the heartland of modern China, has contributed about 23% of national total grain production over the past four decades (National Bureau of Statistics of China, 2022a)—including half of the nation's wheat, 35% of its maize, and substantial amounts of peanut and soybean (Yang et al., 2021). The typical cropping system in

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the NCP is winter wheat (*Triticum aestivum* L.) and summer maize (*Zea mays* L.) double cropping (WM), which consumes 700–1000 mm of water per year (Yang et al., 2019). About 70% of the water requirement for winter wheat comes from irrigation (Wang et al., 2023b), resulting in an annual decline in the groundwater table of nearly 1 m (Yang et al., 2021). This decline has led to environmental droughts (Zhao et al., 2022), land subsidence (Su et al., 2021), and the intrusion of seawater into groundwater aquifers (Jiang et al., 2020). Thus, there is a pressing need to introduce new crops into the dominant cereal cropping system in the NCP to develop diversified crop rotations and reduce irrigation demands.

Prior research has indicated that diversified crop rotations can increase crop yields (Jarecki et al., 2018; Garbelini et al., 2022) and water productivity (WP) (Lenssen et al., 2010, 2014; Schlegel et al., 2017, 2019). For instance, in Kansas State, USA, from 1996 to 2015, crop rotations incorporating sorghum after wheat yielded greater soil water storage, crop yield, biomass, and WP than continuous sorghum cropping (Schlegel et al., 2017). A six-year field study in the semiarid northern Great Plains of the USA demonstrated that alternate-year rotations with durum wheat, canola, and pea, along with improved cultural practices, enhanced soil water content, crop grain yields, and WP (Sainju et al., 2020). In Spain, a diverse crop rotation (canola-pea-wheat) increased wheat yield by 1.79 t ha^{-1} compared to a cereal rotation (barley–-wheat), as well as improved WP (Nascimento et al., 2023). In southwestern Finland from 2005 to 2017, spring wheat yields in a diversified rotation (spring wheat–turnip rape–barley–pea) improved by 13–30% under various tillage practices compared with monoculture (Jalli et al., 2021). Furthermore, a long-term trail in Brazil from 2009 to 2017 found that all diversified crop rotations invovling soybean, wheat, maize, and various cover crops produced higher 8-year cumulative profits and gross margins than the continuous maize–soybean rotation (Garbelini et al., 2022). Jarecki et al. (2018) predicted that diversified rotations would mitigate crop water stress and result in higher yields under future climate scenarios from 2016 to 2100 compared to simpler rotations.

In the NCP, rotations incorporating crops like potato, cotton, and spring maize use less groundwater (Gao et al., 2022) while increasing system productivity (Gikonyo et al., 2022) and WP (Liu et al., 2008). For instance, integrating forage crops into a fallow–peanut system enhanced system productivity by 85%, net income by US$ 1016 ha^{-1}, and WP by 30% (You et al., 2022). Including shallow-rooted crops in conventional cereal cropping systems enhanced WP at an economic scale, decreased groundwater depletion, and mitigated groundwater table decline (Yang et al., 2015a,b, 2017). Wang et al. (2020) demonstrated that potato and peanut-based crop rotations improved the subsequent wheat crop's productivity. Sun et al. (2019) reported that involving spring maize in the WM rotation with critical irrigation management could mitigate groundwater overexploitation compared to the conventional WM system. Hence, it is worthwhile exploring optimized diversified crop rotations for the NCP that can balance groundwater use, food production, and farmer profitability.

While previous studies have highlighted the benefits of diversified crop rotations for food production and profitability, further exploration of the mechanism underlying the rotation effect on soil water use and yield in crop sequences is needed. This study, based on a two-year field experiment of six diversified WM-based rotations with completed rotation cycles, aimed to (1) quantify water consumption ($ET_{c\ act}$) and net groundwater use in each rotation, (2) assess differences in system productivity (yield and profitability) with various aspects of water productivity, (3) investigate the 'lag effect' in diversified crop rotations, where the preceding crop diversification impacts the grain yield and WP of succeeding cereal crops, (4) examine the temporal and spatial complementarity of soil moisture by combining shallow and deep-rooted crops in diversified crop rotations. The findings from this study will provide a reference for developing diversified crop rotations in the NCP and other similar water-stressed agricultural regions, striking a balance between food production and groundwater use.

2. Materials and methods

2.1. Study area

The field experiment was conducted from October 2018 to October 2020 at the Quzhou experimental station (37°51′46″N, 115°0′59″E) in Hebei province within the NCP (Fig. 1a). This region experiences a typical warm, temperate, semi-humid, and continental monsoon climate. Over the past 60 years, it has received an average annual precipitation of 495 mm (Fig. 1b) with more than 60% occurring in July and August (Fig. 1c). The annual average temperature is 13.1°C (Fig. 1c) and there is 201 frost-free days per year. The total potential evaporation is around 1835 mm per year (Liang et al., 2016). The soil at the experimental site is sandy loam from 0–20 cm, with pH 7.8, 1.31 g·m^{-3} bulk density, 14.12 g kg^{-1} organic matter, 1.25 g kg^{-1} total nitrogen (N), 24.1 mg kg^{-1} inorganic N, 11.6 mg kg^{-1} available P, and 138 mg kg^{-1} available K. Table S1 provides detailed soil properties for the 0–200 cm soil profile.

2.2. Field experimental design

The experiment had a completely randomized design with three replicates. Each plot measured 6 m × 7 m. The treatments included six different crop rotations (Fig. 2): (1) Winter wheat–summer maize rotation (WM, as the control), (2) Sweet potato (*Pomoea batatas* L.)→winter wheat–summer maize (Sweet potato→WM), (3) Soybean (*Glycine max* L.)→winter wheat–summer maize (Soybean→WM), (4) Peanut (*Arachis hypogaea* L.)→winter wheat–summer maize (Peanut→WM), (5) Spring maize (*Zea mays* L.)→winter wheat–summer maize (Spring maize→WM), and (6) Millet (*Panicum miliaceum* L.)→winter wheat–summer maize (Millet→WM). The cropping index (CI), which represent the harvest frequency within a rotation cycle, was 2 for WM and 1.5 for the other diversified rotations. The symbol "→" indicates crops rotated over two years. N, P, and K fertilizers were applied following local farming practices. Irrigation for spring crops and subsequent wheat and maize was applied at critical crop growth stages following regional farmers practices with broad irrigation. Table 1 provides detailed information on crop sowing and harvest dates, fertilizer inputs, and irrigation times and amounts.

2.3. Data collection and measurements

Daily weather data, including precipitation and temperature, were recorded at a meteorological station near the field experiment site. Volumetric soil water contents (VSWC) from 0–180 cm were measured from October, 2018 to October, 2020 (sowing to harvest) every 16–20 days during spring crop growing seasons and at wheat sowing, jointing, anthesis, and harvest, and maize sowing, large trumpet, tasseling, and harvest. The VSWC were collected with a neutron probe from 20 to 180 cm with an interval depth of 20 cm. The top 20 cm of VSWC were measured gravimetrically by oven-drying soil cores to avoid inaccurate measurements of the neutron probe near the soil surface. Leaf area index (LAI) and aboveground biomass (AGB) were measured for winter wheat (at jointing, anthesis and maturity) and summer maize (at big trumpet, tasseling, and maturity). Crop grain yields were harvested at full maturity from the whole plot area, and the harvested grains were threshed and air-dried to standard moisture content (wheat: 14%, maize: 14%, and millet: 13%) (Dai et al., 2016; Ngoune Tandzi and Mutengwa, 2019; Zhang et al., 2020). Yield components, including spike numbers, kernel per spike, grain number, and thousand-grain weight, were recorded for winter wheat and summer maize. Moisture contents was determined and converted to the standard moisture content (10%) for peanuts (with shells) (Mondal et al., 2020) and 13.5% for soybean after removing pods (Vitantonio-Mazzini et al., 2021) to calculate unit area yields. Valid sweet potato tubers, with a diameter ≥1.0 cm and distinct swelling areas, were weighed to determine yield per sampling

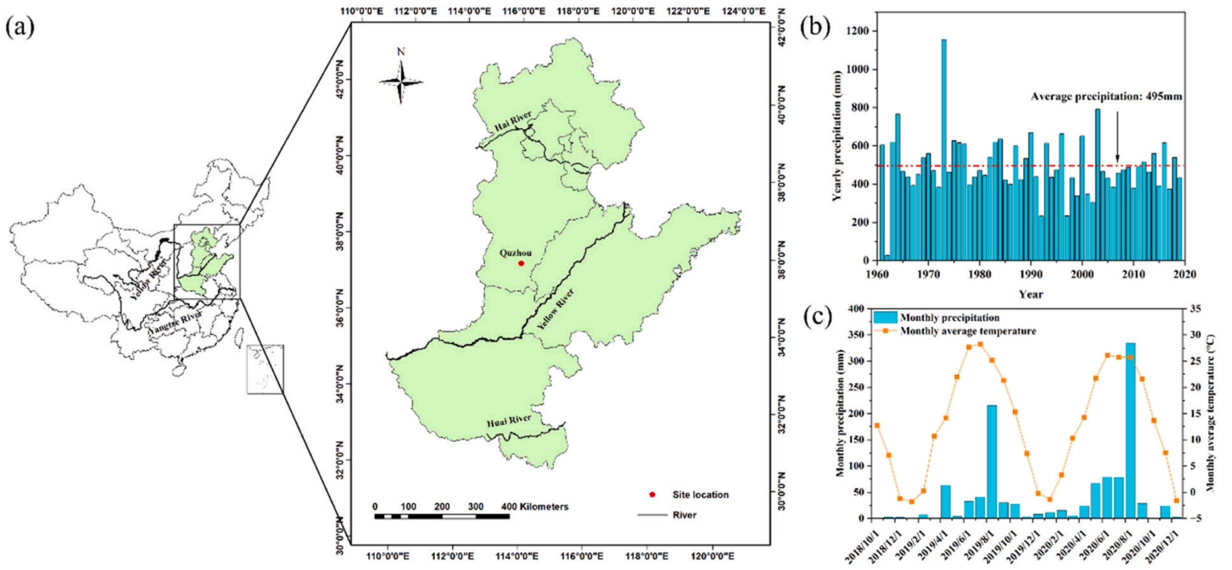

Fig. 1. Location of Quzhou experiment station in North China Plain (a), annual precipitation from 1960 to 2020 (b), and monthly precipitation and average temperature from 2018 to 2020 during the field experiment period (c).

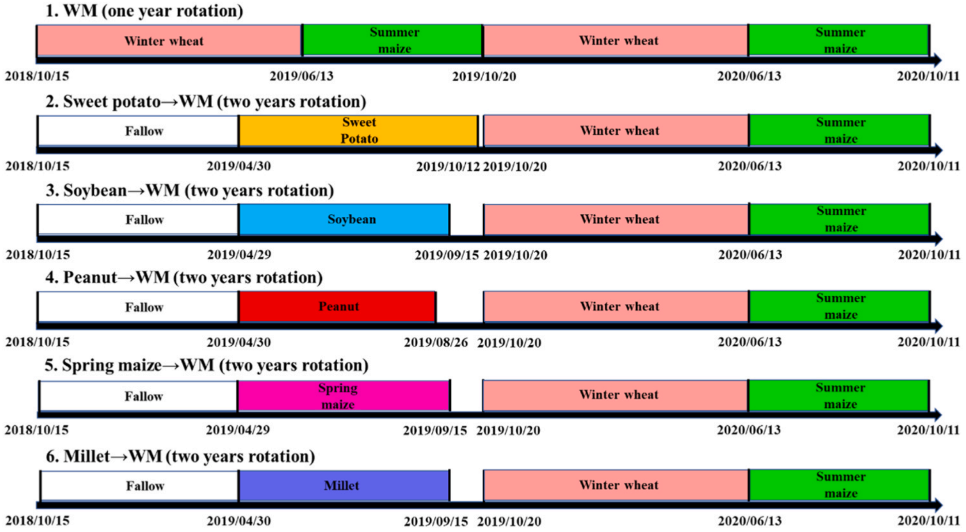

Fig. 2. Crop rotation design and crop sequences with sowing and harvest time.

Table 1

Irrigation and fertilizer times and amounts for each crop.

Crops	Cultivars	Sowing date	Harvest date	Total irrigation (mm)	Irrigation time	Irrigation amount/ time (mm)	N (kg·ha^{-1})		P_2O_5 (kg·ha^{-1})	K_2O (kg·ha^{-1})
							Basal	Top-dressing	Basal	Basal
Winter wheat	Luyuan 502	15, Oct.	13, Jun.	150	Jointing, anthesis	75	96	144	135	105
Summer maize	Woyu 3	13, Jun.	11, Oct.	75	Sowing	75	67.5	157.5	120	150
Sweet potato	Jishu 7	30, Apr.	12, Oct.	120	Tuber swelling	120	112.5	0	112.5	112.5
Soybean	Jidou 12	29, Apr.	15, Sep.	90	Branching, flowering, pod filling	30	112.5	0	112.5	112.5
Peanut	Jihua 11	29, Apr.	26, Aug.	120	Late flowering, late podding	60	112.5	0	112.5	112.5
Spring maize	Woyu 3	29, Apr.	15, Sep.	135	Sowing, jointing, large trumpet	45	67.5	157.5	120	150
Millet	Jigu 17	30, Apr.	15, Sep.	90	Sowing, milking	45	112.5	0	112.5	112.5

Note: Irrigation of winter wheat for all rotations was adjusted to three times (75 mm each), at overwintering, jointing, and anthesis, respectively.

point, with fresh masses converted into common units of measurement (t ha^{-1}) (Tedesco et al., 2021).

2.4. Evaluation calculations

2.4.1. Equivalent yield, economic benefit, and relative water productivities

Due to different kinds of crop species with different product outputs, the equivalent yield (EY) (Wang et al., 2023a) of each crop was calculated using the 2019 winter wheat price as the baseline. Economic benefit (EB) was calculated by multiplying crop yield by its corresponding product price (P) in Chinese Yuan and subtracting crop production costs (Peng et al., 2023). The China National Consumer Price Index (CPI) from 2019 was used as a baseline to eliminate inflation influence. Crop prices were obtained from the China Yearbook of Agricultural Price Survey (National Bureau of Statistics of China, 2022b), while the CPI value was sourced from the China Statistical Yearbook (National Bureau of Statistics of China, 2022a) (Table S2). Water productivity of each rotation was calculated in equivalent yield scaled (WP_{EY}) and economic benefit scaled (WP_{EB}), as follows:

$$EY_i = Y_i \times \frac{P_i}{P_{wheat}} \tag{1}$$

$$EB_i = Y_i \times P_i \times \frac{CPI_i}{CPI_{2019}} - C \tag{2}$$

$$WP_{EY} = \frac{EY_i}{ET_{cact}} \tag{3}$$

$$WP_{EB} = \frac{EB_i}{ET_{cact}} \tag{4}$$

where EY_i is the equivalent yield of the i th crop (kg·ha^{-1}), Y_i is the crop yield of the i th crop (kg·ha^{-1}), P_i is the price of the i th crop (Yuan·kg^{-1}) and P_{wheat} is the price of winter wheat (Yuan·kg^{-1}) in 2019; EB_i is the economic benefit of the i th crop (Yuan·ha^{-1}), and C is the crop production cost including top-dressing fertilization and irrigation costs etc. (Yuan·ha^{-1}); WP_{EY} is the equivalent yield water productivity (kg·m^{-3}), $ET_{c\ act}$ is the actual crop evapotranspiration during the growing season (mm), and WP_{EB} is the economic benefit water productivity (Yuan·m^{-3}). Each indicator for one crop rotation is summed across the crops within one crop rotation cycle.

2.4.2. Water consumption and Net water use

Actual crop evapotranspiration ($ET_{c\ act}$) for a growing season or cropping year was calculated using the soil water balance equation (Zhang et al., 2008):

$$ET_{cact} = P + I + \Delta SWS - DP - W_g - R \tag{5}$$

where $ET_{c\ act}$ is actual crop evapotranspiration (mm), P is precipitation (mm), I is irrigation (mm), ΔSWS is change in soil water storage (0–180 cm) from crop sowing to harvest, equal to the SWS of sowing minus harvest, DP is deep percolation (mm), W_g is capillary rise, and R is runoff (ignored due to the flat plain). Capillary rise was negligible as the groundwater table is >20 m below the soil surface.

Deep percolation was estimated using the recharge coefficient (α) multiplied by the irrigation amount and effective rainfall (Meng et al., 2017).

$$DP = \alpha \times (P + I) \tag{6}$$

where α depends on soil texture, irrigation amount, and effective rainfall, ranging from 0.1 for clay soil to 0.3 for sandy soil, as determined by monitoring groundwater table changes after an irrigation event with water inputs over a large area. The α value was 0.1 for irrigation or effective rainfall less than 90 mm and 0.15 for irrigation or effective rainfall amounts between 90 and 120 mm (Ministry of Geology and Mineral Resources, 1986).

Net water use (*NWU*, mm) reflects net groundwater depletion for different crop rotations (Yang et al., 2015a), calculated as follows:

$$NWU = I - DP \tag{7}$$

where *DP* is deep percolation during the crop growing season (mm), and *I is* irrigation (mm).

2.5. Statistical analysis

We conducted an analysis of variance (ANOVA) using SPSS Version 21 (Statistical Product and Service Solutions, IBM SPSS Inc., Chicago, IL, USA) to test for significant differences among $ET_{c\ act}$, NWU, and annual system outputs for each crop rotation. In addition, ANOVA was used to examine variations in soil moisture storage from 0–180 cm at different time points and treatments. A least significant difference (LSD) test at a 5% probability level determined any significant differences.

3. Results

3.1. Water consumption of diversified crop rotations

The conventional WM rotation had the highest annual average actual crop evapotranspiration ($ET_{c\ act}$) (759 mm) (Fig. 3a). The five diversified crop rotations significantly decreased annual average $ET_{c\ act}$ by 7–12% compared to WM, with the greatest reduction in the millet→WM rotation (12%) followed by soybean/peanut→WM rotations (10%), and sweet potato/spring maize→WM rotations (7% and 8%, respectively). Similarly, the diversified crop rotations had lower NWU than conventional WM (Fig. 3b), with the greatest reductions in the soybean→WM and millet→WM rotations (31%), followed by sweet potato/peanut/spring maize→WM rotations (21–25%).

3.2. Annual system outputs of diversified crop rotations

Conventional WM had an annual average equivalent yield of 15.7 t·ha^{-1} from 2018 to 2020 (Fig. 4a), similar to peanut→WM (15.4 t ha^{-1}). Sweet potato→WM rotation had the highest equivalent yield (20.7 t·ha^{-1}) due to its high tuber weight, 32% higher than the WM rotation ($P<0.05$). However, the soybean/spring maize/millet →WM rotations had 16–23% lower annual average equivalent yields than the conventional WM rotation. For annual average economic benefit, the sweet potato→WM rotation had the highest value of 41.9×10^3 Yuan ha^{-1}, about 50% higher than WM (27.9×10^3 Yuan ha^{-1}) ($P<0.05$) (Fig. 4c), followed by the peanut→WM rotation with a 7% increase ($P<0.05$). In contrast, the soybean/spring maize/millet→WM rotations had 9–16% reductions in economic benefit compared to the WM rotation.

The different crop rotations followed similar trends for both WP_{EY} and WP_{EB} (Fig. 4b, d). The conventional WM rotation had annual WP_{EY} and WP_{EB} values of 2.1 kg m^{-3} and 3.7 Yuan m^{-3}, respectively. The sweet potato→WM rotation had the highest annual WP_{EY} (3.1 kg m^{-3}) and WP_{EB} (6.2 Yuan m^{-3}), 48% and 68% higher than the WM rotation, respectively, followed by the peanut→WM rotation, with 24% WP_{EY} and 36% WP_{EB} higher values than the WM rotation, respectively. No significant differences in WP_{EY} or WP_{EB} occurred between the soybean (same, +9%)/ spring maize (–8%, –2%)/ millet (–8%, +2%)→WM rotations and the WM rotation, respectively.

3.3. Soil water carryover and profile complementary in diversified crop rotations

Differences in temporal soil water storage from 0–180 cm were observed among the diversified crop rotations under different irrigation inputs (Table 1) compared to the conventional WM rotation (Fig. 5). The

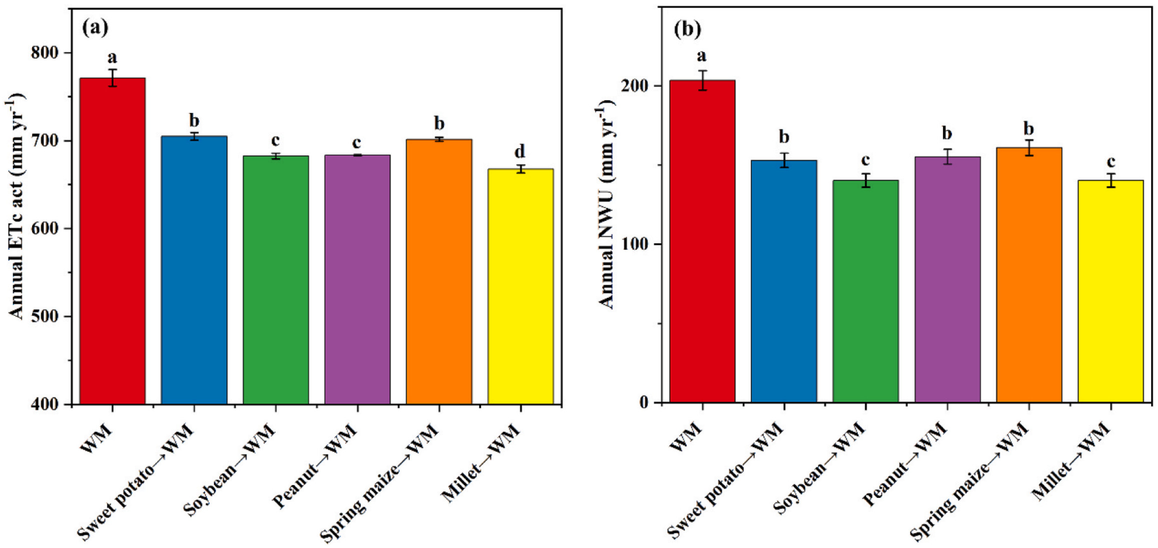

Fig. 3. Annual actual crop evapotranspiration ($ET_{c\ act}$) (a) and net water use (NWU) (b) of six different crop rotations. Bars in each column are the standard deviation of three replications. Different lowercase letters denote significant differences among different rotations for each indicator at $P<0.05$.

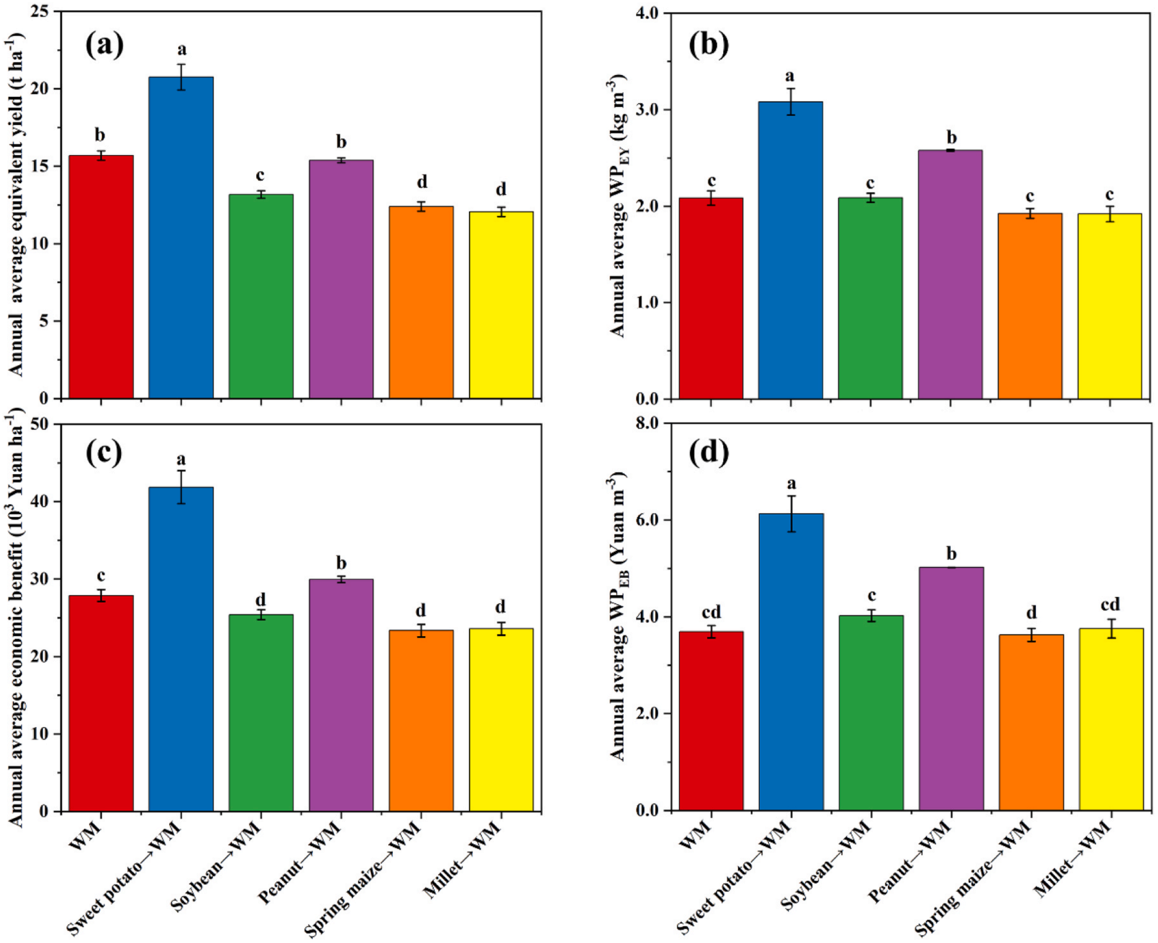

Fig. 4. Annual average equivalent yield (a), water productivity scaled at equivalent yield (b), annual average economic benefit (c), and water productivity scaled at economic benefit (d) of different crop rotations. Bars in each column are the standard deviation of three replications. Different lowercase letters denote significant differences among different rotations for each indicator at $P<0.05$.

preceding crops, including sweet potato, soybean, peanut, millet, and spring maize, significantly increased soil water storage for sowing the succeeding winter wheat at the beginning of October. At winter wheat sowing in the WM rotation, 625 mm soil water was stored after summer maize harvesting. Soil water storage increased by 9% in the millet→WM rotation ($P<0.01$), 5% in the sweet potato→WM and peanut→WM

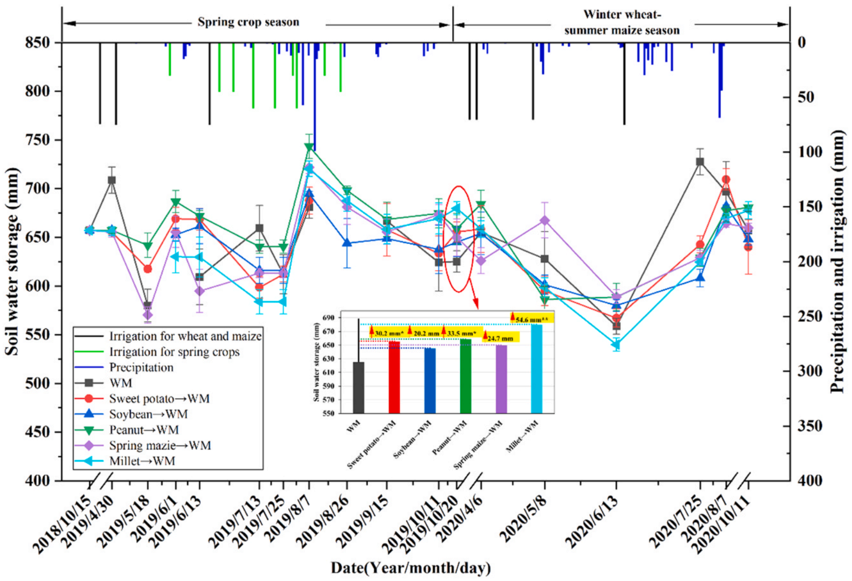

Fig. 5. Temporal variations in soil water storage in the 0–180 cm soil layers of six different crop rotations from 2019 to 2020. Error bars are the standard deviation of three replications. * and ** denote significant differences at $P<0.05$ and $P<0.01$, respectively. Values in yellow color indicate the soil water storage increase before winter wheat sowing in diversified crop rotations compared to the conventional WM rotation.

rotations ($P<0.05$), and 3% and 4% in the soybean→WM and spring maize→WM rotations, respectively, compared to conventional WM (Fig. 5).

Soil moisture variations at different soil depths during the growing season also exhibited differences among the diversified rotations under different irrigation inputs compared to conventional WM (Fig. 6). Irrigation amounts decreased by 53 mm (21%) in the sweet potato→WM rotation, 68 mm (26%) in the soybean/millet→WM rotations, and 21% (53 mm) and 18% (45 mm) in the peanut/spring maize→WM rotations, respectively, compared to conventional WM. These diversified rotations with reduced irrigation inputs but improved WP compared to conventional WM could be attributed to the root water uptake mechanism involving shallow-rooted crops rotated with deep-rooted crops.

The soil moisture changes under sweet potato mainly occurred at 0–100 cm soil depth, especially at 0–80 cm (Fig. 6a). Similar patterns were observed for soybean and peanut (Fig. 6b, c), whereas millet mainly occurred at 0–70 cm (Fig. 6e) and spring maize mainly occurred at 0–120 cm, especially at 0–100 cm (Fig. 6d). Winter wheat exhibited deep root uptake, using soil moisture from 0–180 cm (Fig. 6f), with its roots extending to 200 cm (Table S3). During the growing season from October to June with limited precipitation (113 mm in 2019 and 134 mm in 2020), winter wheat required about 200 mm of groundwater

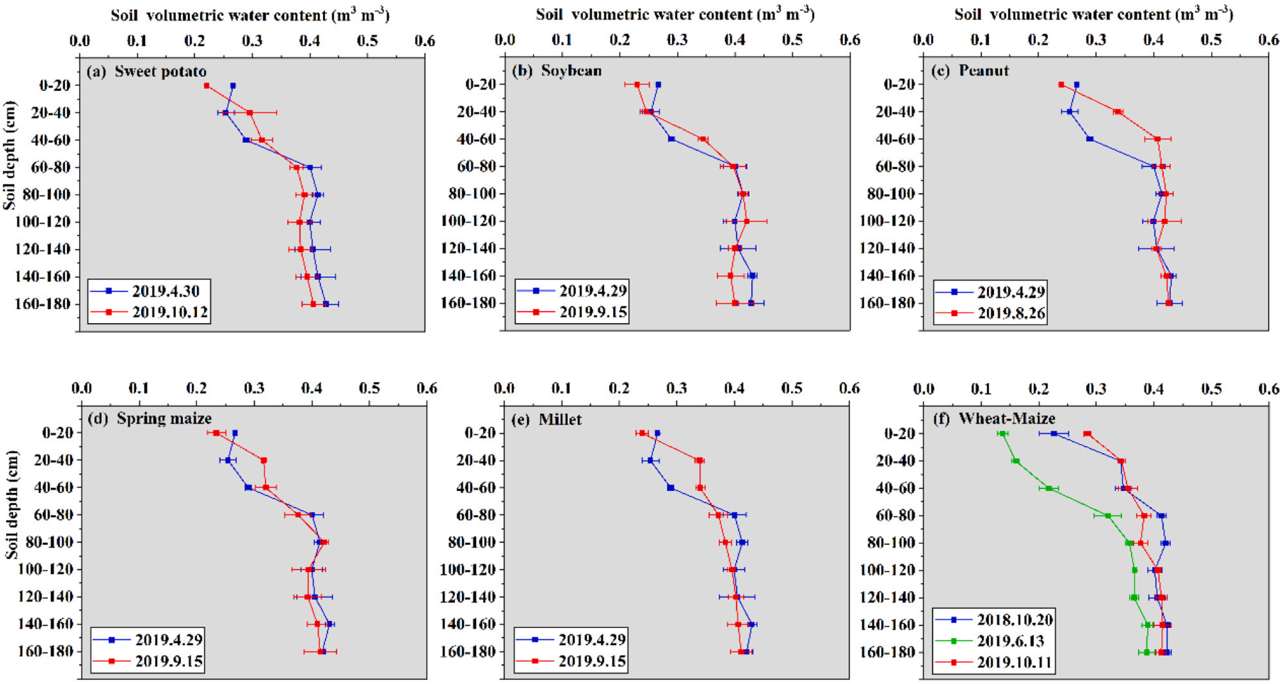

Fig. 6. Variations in soil water content at 0–180 cm soil profile depths. (a–e) soil moisture contents at the sowing dates of spring crops (blue lines) and harvest dates (red lines); (f) soil moisture contents on the sowing dates of winter wheat (blue lines), harvest dates of winter wheat or sowing date of summer maize (green lines), and harvest dates for summer maize (red line). Error bars are the standard deviation of three replications.

irrigation, therefore, root uptake resulted in the significant VSWC depletion. However, summer maize (0–120 cm root water uptake) followed winter wheat in the rotation. The rainfall over the $ET_{c\ act}$ replenished soil moisture levels during summer maize's growing season, with the soil moisture content almost recovered by the time of winter wheat sowing.

In sum, shallow-rooted crops such as sweet potato, soybean, peanut, spring maize, and millet effectively used upper soil layer moisture without depleting deeper soil layers, allowing for moisture storage for the succeeding deep-rooted winter wheat. The residual rainfall stored down to 100 cm may contribute to the emergence of winter wheat.

3.4. Rotation effect on the yield and growth of succeeding cereal crops

Diversified crops as preceding crops before WM had a positive 'lag effect' on the grain yield of succeeding wheat and maize (Fig. 7a). The conventional WM rotation produced 16.6 t ha^{-1} grain yield in 2020. The grain yields of the succeeding wheat and maize improved by 11% and 7% with peanut and sweet potato as the previous crops, respectively, and 4% and 5% with soybean and millet as the previous crops, respectively, compared to the conventional WM rotation, while the spring maize→WM rotation had similar wheat and maize grain yields compared to WM in 2020. Diversified crop rotations also improved the WP of succeeding wheat and maize crops, with a 12% increase in the peanut→WM rotation ($P<0.05$) (Fig. 7b).

These positive effects on yield were reflected in the LAI and AGB of wheat and maize (Fig. 8). Diversified crop rotations increased the LAI of wheat during the growth period, with rotations involving sweet potato, soybean, peanut, and millet increasing LAI by 6–9%, 4–18% and 2–23% at jointing, anthesis, and harvest stages, respectively, compared to conventional WM (Fig. 8a). Consequently, the AGB of wheat in diversified crop rotations increased by 1–10%, 6–15% and 3–15% at jointing, anthesis and harvest stages, respectively, compared to WM (Fig. 8b). The spring maize→WM rotation had similar LAI and AGB values as the WM rotation at critical growth stages.

Similarly, the diversified crop rotations with sweet potato, soybean, peanut, millet, and spring maize as the preceding crops before wheat and maize increased the LAI of maize by 4–16%, 6–14% and 2–12% at big trumpet, tasseling, and harvest stages, respectively, compared to the WM rotation (Fig. 8c). Consequently, the AGB of maize in diversified crop rotations increased by 7–16%, 13–19% and 12–17% at big trumpet, tasseling, and harvest stages, respectively, compared to WM (Fig. 8d).

4. Discussion

4.1. Water use in diversified crop rotations

This study demonstrated that five alternative crop rotations with fallow period, featuring diverse spring crops, instead of the one-year WM rotation, significantly reduced annual actual crop evapotranspiration ($ET_{c\ act}$) by 7–12% and growing season $ET_{c\ act}$ by 11–21% compared to conventional WM (Fig. S1), consistent with previous studies (Yang et al., 2015a, 2017; Araya et al., 2017; Wang et al., 2023a). The soil water balance components of each rotation during crop growing season was detailed in Table S4. Cui et al. (2022) showed that crop rotations involving wheat or potato rotated with oil flax decreased growing season $ET_{c\ act}$ by up to 28% compared to continuous oil flax cropping in Northwest China based on a 4-year field experiment. Wang et al. (2023a) found that winter wheat–summer soybean-based multi-rotations or spring mungbean–summer millet-based multi-rotations had lower annual $ET_{c\ act}$ than the WM rotation based on a 60-year modeling study in the NCP. Millet, known for its high drought tolerance (Shrestha et al., 2023), incorporated into a WM rotation had the lowest annual $ET_{c\ act}$ (–12%) compared to conventional WM.

In our study, the $ET_{c\ act}$ during the fallow season from October to April the following year accounted for 3–13% of annual $ET_{c\ act}$, which aligns with the 7–10% reported in a 12-year field experiment (Yang et al., 2015a, 2019). Yang et al. (2021) also reported that incorporating a fallow period and introducing high-value crops into WM can reduce growing season $ET_{c\ act}$ by 31% and mitigate groundwater decline by 19%.

In our study, the NWU of the five diversified crop rotations significantly decreased (21–31%) compared to conventional WM, which was attributed to the reduced irrigation. Using the DSSAT model, Gao et al. (2022) reported that rotating potato instead of wheat with maize in the northern part of the NCP decreased the annual average NWU by 40% compared to the WM rotation from 1985 to 2015. Therefore, introducing spring crops like peanut, potato, spring maize, or soybean into WM rotations with a fallow season could decrease groundwater depletion in the NCP (Sun et al., 2011; Jiang et al., 2021; Yadav et al., 2016).

4.2. System output of diversified crop rotations

The results indicate that reducing the cropping index from 2 to 1.5 and introducing diverse preceding crops before the WM rotation

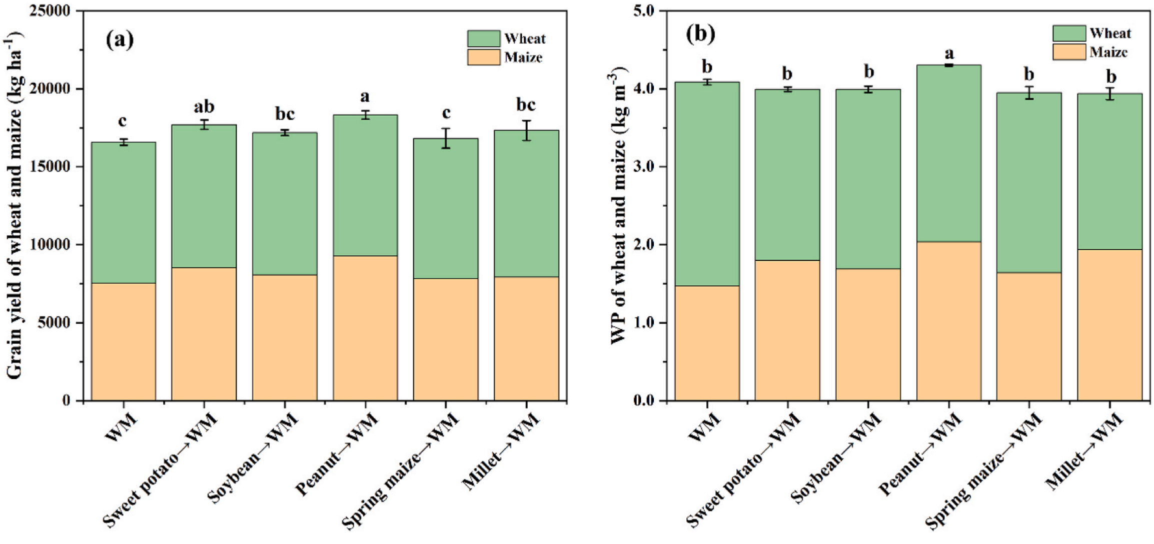

Fig. 7. Grain yield (a) and water productivity (b) of the succeeding crops of wheat and maize in different crop rotations for the 2020 cereal cropping year. Bars in each column are the standard deviation of three replications. Different lowercase letters denote significant differences among different rotations for total grain yield or water productivity of wheat and maize at $P<0.05$.

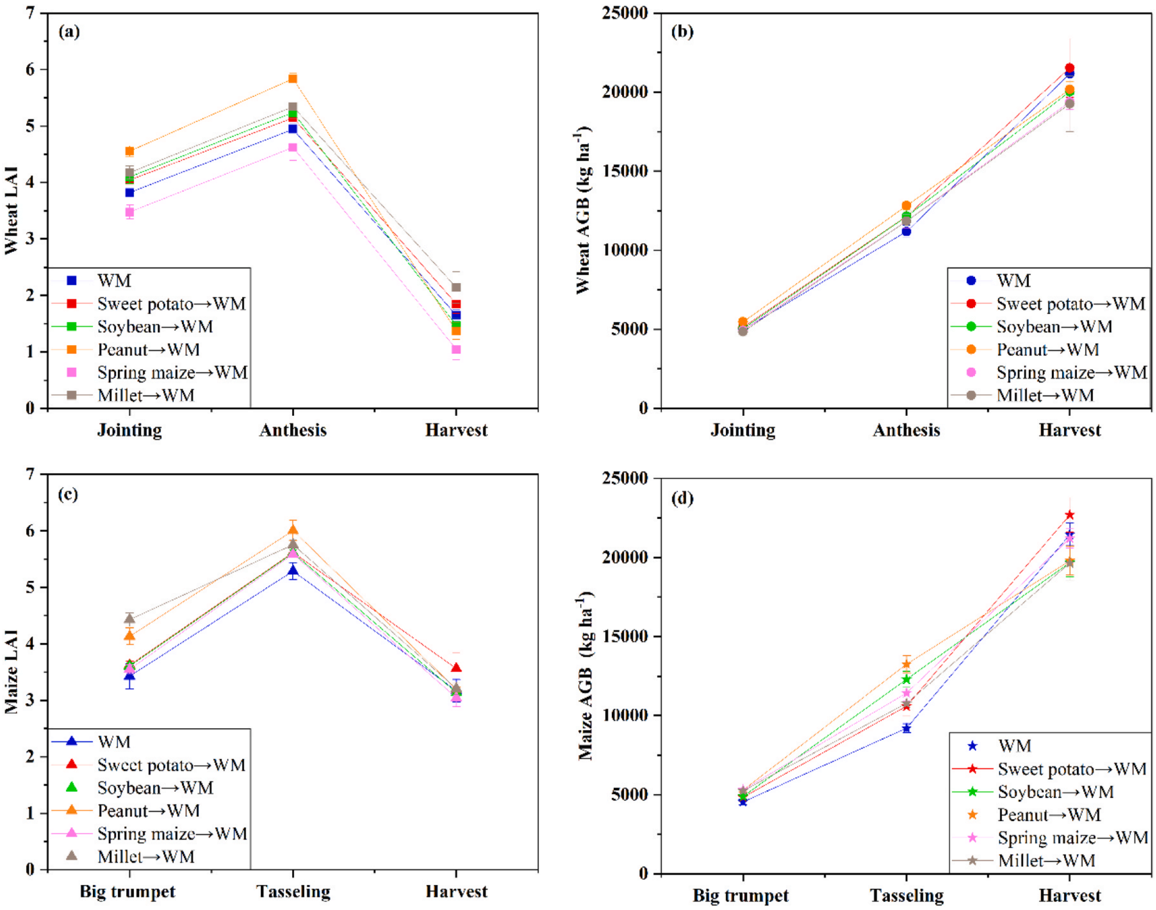

Fig. 8. Leaf area index (LAI) and aboveground biomass (AGB) of the subsequent wheat and maize in different crop rotations: winter wheat LAI (a); winter wheat AGB (b); summer maize LAI (c); summer maize AGB (d). Error bars are the standard deviation of three replications.

improved the entire system's annual equivalent yield and economic benefit. Notably, sweet potato/peanut→WM rotations with CI=1.5 showed significant improvements compared to conventional WM (CI=2), consistent with previous studies (Reckling et al., 2016; Yang et al., 2021). Research from Europe has shown that rotations with multiple crop species resulted in higher yields for winter and spring cereals, with average yield increase of 860 and 390 kg ha^{-1}, respectively, compared with continuous monoculture (Marini et al., 2020). A meta-analysis in China reported that crop rotation increased yields by 20% compared to monoculture, with 14% higher yields in legume-based rotations (Zhao et al., 2020). Diversified crop rotations increased crop yields at the system level (e.g., wheat grain yield 30% higher after pea, and 0.5–1.2 t ha^{-1} higher after oats, and improved water (18–56% with a broadleaf crop) and fertilizer use efficiencies (33%) (Liu et al., 2022).

Moreover, rotations with legumes had greater equivalent gross margins and environmental benefits, including reduced nitrous oxide emissions and nitrate-N leaching, than cropping systems without legumes (Luce et al., 2015; Reckling et al., 2016; Shah et al., 2021). Cereal crops rotated with soybean enhanced net revenue due to higher prices and lower greenhouse gas emissions than conventional WM under different tillage practices (Liu et al., 2023). In our study, the soybean→WM rotation, which received 68 mm less irrigation input per year, increased water productivities by up to 9% compared to conventional WM, and peanut-based rotations achieved 8% higher economic benefit than WM, as reported by Zou et al. (2022).

In our study, the spring maize→WM rotation reduced annual $ET_{c\ act}$ by about 8% compared to conventional WM, consistent with previous studies (Sun et al., 2011; Guo et al., 2013; Meng et al., 2017). It also decreased total grain yield by 17%, resulting in a 16% reduction in economic benefit, attributed to one fewer winter wheat season. The 'rotation effect' was not significant in the spring maize→WM rotation. However, this rotation may be favored by farmers in areas facing serious groundwater overexploitation, as it offers simple cultivation and readily available machinery for sowing and harvesting, especially when spring maize is used for silage.

4.3. *Crop rotation effect on soil moisture use and succeeding crop yield*

Diversified crop rotations have multiple effects on soil profiles, including changes in bulk density, soil pH, organic matter (Edwards et al., 1992), soil structure, organic carbon, and total N (Tiemann et al., 2015). Most importantly, diversified crop rotations enhance soil water use by introducing shallow-rooted crops preceeding deep-rooted crops, which maximizes the use of soil moisture at different depths and leads to temporal and spatial complementarity of soil water between preceding and subsequent crops (Miller et al., 2003; Lenssen et al., 2014; Yang et al., 2017). For instance, previous research showed that spring wheat in rotations involving pea increased preplant VSWC by 35 mm, with increased grain yield (+473 kg ha^{-1}) and improved water use efficiency (+0.8 kg ha^{-1} mm^{-1}), compared with continuous spring wheat cropping in the northern Great Plains (Lenssen et al., 2014, 2018). In our study, the preceding spring crops in diversified crop rotations used soil water from shallow layers, leaving more soil moisture in the deep soil for subsequent deep-rooted crops. The diversified crop rotations with 18–26% less annual irrigation amounts had 20–55 mm (3–9%) more soil water stored in the 0–180 cm layer at winter wheat sowing than continuous WM. Similarly, Yang et al. (2017) reported that diversified rotations increased the soil water storage at winter wheat sowing by

4–10% compared to the continuous WM rotation due to spatiotemporal soil moisture complementarity.

In this study, the preceding spring crops, including sweet potato, soybean, peanut, spring maize, and millet, used soil water primarily above 80 cm, consistent with the previous studies (Gomes and Carr, 2003; Hong et al., 2009). In contrast, the succeeding winter wheat consumed soil water to 180 cm as its root system extended to 2 m (Zhang et al., 2009; Xue et al., 2010; Li et al., 2016). Cutforth et al. (2013) reported that wheat used more water below 80 cm depth than pulse crops in a semiarid Canadian prairie, which partly explains why wheat following pea had greater preplant VSWC and WP than continuous wheat. This vertical complementarity of soil moisture use allows for the efficient use of deep soil moisture and is particularly valuable during normal and dry years when combating climate change with extreme weather conditions.

Access to water during prolonged dry periods is the most immediate benefit of deep roots, followed by nutrient uptake (Thorup-Kristensen et al., 2020). Diversified crop rotations that introduce the shallow-rooted crops as preceding crops create favorable soil moisture conditions for the sowing, germination, and growth of succeeding cereal crops, ultimately improving cereal yields. In our study, the diversified crop rotations improved total cereal grain yields by 4–11% compared to conventional WM. In the northern Great Plains, USA, cropping systems including legumes as preceding crops had the potential to contribute N to succeeding cereal crops, avoiding N leaching (Grant et al., 2002) and improving grain yield (Krupinsky et al., 2006; Tanaka et al., 2010; Lehman et al., 2017). A review of 29 European experiments revealed that legume yield benefits to subsequent crops were highest for subsequent crops under low N fertilization, with an average 60 kg N ha^{-1} reduction maintaining acceptable yields (Preissel et al., 2015).

LAI and AGB increased in the succeeding cereal crops in diversified crop rotations compared to continuous WM. Crop rotations incorporating soybean, peanut, sweet potato or millet as the preceding crop increased the LAI and AGB of wheat and maize at critical growth stage, in line with previous research demonstrating the benefits of preceding legumes on crop yield and NUE of subsequent cereal crops (Preissel et al., 2015; Espinoza et al., 2020; Yang et al., 2022; Virk et al., 2022). Li et al. (2018) reported that diversified rotations improved leaf greenness by 4%, shoot biomass by 25%, nodule biomass by 44%, and seed yield by 95% for chickpea and pea but not for lentil compared with legume monoculture in an 8-year rotation study.

The legacy effect of the previous year's water use on subsequent preplant available water, water use, and grain yield is an important consideration when developing diversified rotation systems, particularly in water-limited regions like the NCP. Further long-term experiments will help determine whether this legacy effect becomes more pronounced as rotation years increase.

5. Conclusion

Diversified crop rotations enhance crop water use efficiency and subsequent crop yields by introducing shallow-rooted crops into continuous cereal cropping systems. A two-year field experiment with six crop rotations in the NCP demonstrated that diversified crop rotations involvling sweet potato, soybean, peanut, spring maize, and millet as the preceding crops decreased annual average actual crop evapotranspiration and net groundwater use by 7–12% and 21–31%, respectively, compared to conventional WM. Sweet potato and peanut-based WM rotations significantly increased annual mean equivalent yield, economic benefit, and WP. The preceding crops with shallow roots improved soil water storage by 3–9% at the succeeding winter wheat sowing by absorbing soil moisture primarily above 80 cm depth and preserving deep soil moisture for the deep-rooted wheat. This temporal and vertical complementary of soil moisture use allows for the efficient use of deep soil mositure, benefiting the growth of succeeding grain crops. In this study, the total grain yield of wheat and maize increased by 4–11% compared to conventional WM. In short, this study highlighted that diversified crop rotations are a feasible approach to increasing crop production and decreasing water use in the NCP. It also sheds light on the soil water use machanism associated with crop diversifications. These findings may serve as a valuable reference for implementing diversified crop rotations in other water-scarce regions.

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CRediT authorship contribution statement

Wang Guiyan: Investigation, Formal analysis, Data curation. **Yang Xiaolin:** Writing – review & editing, Writing – original draft, Methodology, Funding acquisition, Data curation, Conceptualization. **van Dam Jos:** Writing – original draft, Software, Conceptualization. **Siddique Kadambot H.M.:** Writing – review & editing, Supervision. **Ritsema Coen:** Writing – review & editing, Supervision, Conceptualization. **Kang Shaozhong:** Supervision, Methodology, Conceptualization. **Du Taisheng:** Supervision, Funding acquisition. **Wang Bo:** Methodology, Formal analysis, Data curation.

Declaration of Competing Interest

The authors declare no conflict of interest.

Data Availability

Data will be made available on request.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.agwat.2024.108721.

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