

Article

Water Requirements and Comprehensive Benefit Evaluation of Diversified Crop Rotations in the Huang-Huai Plain

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Abstract: An intensified farming system can significantly increase crop productivity but can also cause major groundwater overdraft for irrigation and the loss of crop diversity. It is imperative to develop alternative crop rotations beyond the simplified conventional winter wheat–summer maize (W–M) rotation for alleviating the groundwater over-extraction in China’s Huang-Huai Plain. This study systematically quantified crop water requirement (ET_c) and irrigation water requirement (ET_{aw}) of eight crops from 2013 to 2018 based on the SIMETAW model applied to the Shangqiu area in the Huang-Huai Plain. Fourteen crop rotations (CI (i.e., crop harvests per rotation cycle year) 1.5 or 2) were constructed based on the ROTAT model. Results showed that compared to W–M rotation, the alternative rotations (CI = 1.5) significantly reduced the annual ET_c in wet, normal, and dry years by 9–21%. Replacing winter wheat in the double cropping system did not significantly decrease annual ET_c . Wheat–soybean rotation had similar annual ET_c and ET_{aw} accompanied by higher economic output and equivalent yield about 1.2 times, with 9% more protein output than the W–M rotation. There were eight crop rotations having greater comprehensive evaluation index (CEI) than W–M rotation by Entropy-TOPSIS when considering 10 indicators including water requirements, yield, economic benefits, water use efficiency, energy, and nutritional values. Spring potato–summer soybean had the highest CEI of 0.627. Sweet potato and potato showed advantages when included in rotations by increasing yield. “Wheat–soybean”-based rotations (CI = 1.5) also performed well in profitability and protein output. Replacing summer maize with soybean is promising for profitability and nutrition output without increasing irrigation requirements. Therefore, decreasing the cropping index, or involving soybean or sweet potato in rotations can be a useful way to improve sustainable land use, save water, and ensure food products in this water stressed region.

Keywords: crop configuration; water requirement; irrigation demand; precipitation coupling degree; Entropy-TOPSIS



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1. Introduction

People face the grand challenge of how to produce sufficient food for a growing population under changing climate and environmental conditions [1]. Intensive agricultural management must maximize agricultural output [2]. Although intensive agriculture increased crop productivity in prior decades, it simplified production by

lowering crop diversification, created higher uniformity of management practices, and created higher uniformity of agricultural landscapes [3]. Crop diversification has been proposed to enhance crop production [4], reduce groundwater over depletion [5], and improve system resilience [6].

The Huang-Huai Plain is one of the intensive agricultural regions in China, where winter wheat (*Triticum aestivum* L.) and summer maize (*Zea mays* L.) (W–M) rotation is the staple cropping system [7]. The majority of annual precipitation is concentrated in the summer maize growing season after winter wheat harvest, which has resulted in a chronic annual water deficit of 200–300 mm per year to support wheat growth [8]. Irrigation pumped from groundwater became a prerequisite for winter wheat production. Groundwater is responsible for approximately 70% of irrigation water use in this area [6,9]. Therefore, it is urgently imperative to build up new water-saving crop rotations to substitute on some land under conventional W–M rotation to mitigate further over-exploitation of groundwater and make crop production in this area more sustainable.

Diversified crop rotations have been applied in current agricultural production to improve crop diversity [10], and provide higher crop yields [11,12]. In the Northern Great Plains of the USA, diversified crop rotations improved wheat aboveground biomass 16–85%, increased preplant soil water 23–118%, and enhanced water productivity 28–61% compared to continuous wheat farming [13]. In India, diversified crop rotations significantly raised system productivity by 45% and profitability by 61% with lower energy consumption (5%) and carbon footprint (22%) compared to conventional pearl millet–wheat rotation [14]. Long-term diversified crop rotations with small grain cereals and cover crops in Canada mitigated maize water stress at the leaf and canopy scales and reduced yield losses to drought by 17% [15]. Garbelini et al. found that diversified crop rotations enhanced soybean yield and profit in Brazil [12]. A diversified crop rotation improved spring wheat yield by up to 30% in no-tillage and by 13% under plowing compared with monoculture [16]. In North China Plain (NCP), advantages of crop rotations included improving sustainability of groundwater use [17]. Yang et al. replaced the traditional W–M with alternative crop rotations that switched between shallow and deep rooted crops and found that promising to reduce groundwater depletion [5,18]. Wang et al. illustrated that diversified crop rotations changed soil indicators and improved wheat productivity [19]. Sun et al. suggested that critical irrigation combined with spring maize→W–M rotation could mitigate groundwater over-exploitation and ensure grain production [20]. Crop rotations involving three harvests in two years have been recommended to be better alternative rotations for water savings than the conventional W–M rotation, which could save 19–45% of the annual water consumption, with a grain yield loss of approximately 16% [21,22].

The multiple benefits of diversified crop rotations should be considered in the adjustment of planting structure toward sustainable land use. Sustainable food systems should provide adequate dietary nutrition, be resilient to climate changes, and limit resource needs and environmental impacts [6]. Zhang et al. reported that optimized planting structure could reduce water consumption up to 0.25 billion m³ [23]. Luo et al. suggested optimizing the planting structure by lowering high water-consumption crops planting, while coordinating the import of water resources (4.6–5.5 billion m³ yr^{−1}) from China's South-to-North Water Transfer project, which could achieve a balance between groundwater exploitation and replenishment and food production in the Beijing–Tianjin–Hebei region, China [24]. Davis et al. reported that crop production adjusted in India to include more coarse cereals like sorghum and millets, could make the food supply more nutritious, cut resource needs, lower greenhouse gas emissions, and improve climate resilience without sacrificing calorie yield or increasing farmland area [25]. An evolutionary multi-objective optimization analysis was conducted to determine how 30 different crop rotations practiced in the North China Plain could be combined regionally to improve balance among food products, profitability, and environmental costs [26]. Reasonable adjustment of planting

structure and establishment of water-saving crop rotations is an important way to reduce agricultural water use in Huang-Huai Plain.

Few studies exist on alternative water-saving crop rotation establishment and comprehensive benefit evaluation considering grain production, nutrition, water use, and water productivity, specifically for the Shangqiu area, a typical groundwater depletion area within the Huang-Huai Plain. Therefore, this study aimed to (1) quantify the water requirements in the region for eight staple crops from 2013 to 2018, (2) configure alternative crop rotations taking into account the high precipitation coupling degree, (3) evaluate the multiple functions of alternative crop rotations comprehensively. This simulation provides background for assembling diversified crop rotations for water-stressed agricultural regions to ensure food sufficiency and enhance economic output and water use efficiency.

2. Materials and Methods

2.1. Study Area

This study was conducted for the Shangqiu area, located in the eastern part of Henan Province (33°43′–34°52′ N, 114°49′–116°39′ E) in the Huang-Huai Plain (Figure 1a). The dominant cropping system in this region is winter wheat–summer maize (W–M) double cropping system. The average annual precipitation from 2013 to 2018 was 615 mm, ranging from 355 to 786 mm (Figure 1b), with uneven distribution of precipitation during the year. The precipitation, mainly concentrated in May to September, accounts for about 69% of the annual precipitation, with the highest value in July (114 mm) and the lowest in January (6 mm) (Figure 1c). The average annual total radiation is 5022 MJ m^{−2}—rich light resources. The average annual temperature is 15.4 °C, with the highest monthly average temperature in July (28.3 °C) and the lowest in January (2.2 °C). The soil texture at the 0–15, 15–30, 30–65, and 65–150 cm layers were loamy clay, clay, loamy clay, and sandy loam, respectively. The soil layer of 0–30 cm has soil organic matter of 9.8 g kg^{−1}, available N of 0.78 mg kg^{−1}, available phosphorus of 10.5 mg kg^{−1}, and available potassium of 52.6 mg kg^{−1}. The deep groundwater has been overdrafted during recent decades, resulting in a serious groundwater cone of depression in this area.

2.2. Data Sources

2.2.1. Meteorological Data

Daily meteorological data, including maximum temperature, minimum temperature, average temperature, average relative humidity, average wind speed, sunshine hours, and 24 h accumulated precipitation from 2013 to 2018 were selected from the China Meteorological Data Sharing Network (<http://data.cma.cn/> accessed on 1 January 2021), as well as the values of geographical features (latitude, longitude, and altitude, etc.) of Shangqiu Station.

2.2.2. Crop and Crop Parameters

Eight crops were selected including winter wheat, summer maize, summer soybean, summer millet, autumn potato, spring potato, spring mung bean, and spring sweet potato. The parameters of each crop including sowing date, harvest date [27–35], protein content [36–42], and energy value [43–45] are shown in Table 1. Crop yield and sown area were obtained from the Henan Agricultural Statistical Yearbook [46].

2.3. Classification of Precipitation Year Type

In this study, the classification of wet year, normal year, and dry year were calculated as follows [47].

$$\begin{aligned} \text{Wet year : } P_i &> \bar{P} + 0.33\delta \\ \text{Normal year : } \bar{P} - 0.33\delta &\leq P_i \leq \bar{P} + 0.33\delta \\ \text{Dry year : } P_i &< \bar{P} - 0.33\delta \end{aligned} \quad (1)$$

where P_i is the i th year's precipitation (mm), $\bar{P}$ is the average annual precipitation (mm), δ is the standard deviation. The average annual precipitation from 2013 to

2018 was 615.5 ± 179.5 mm, the precipitation > 747.9 mm for wet years (2015 and 2016), $482.9 \text{ mm} \leq \text{precipitation} \leq 747.9$ mm for normal years (2013 and 2014), and precipitation < 482.9 mm for dry years (2017 and 2018).

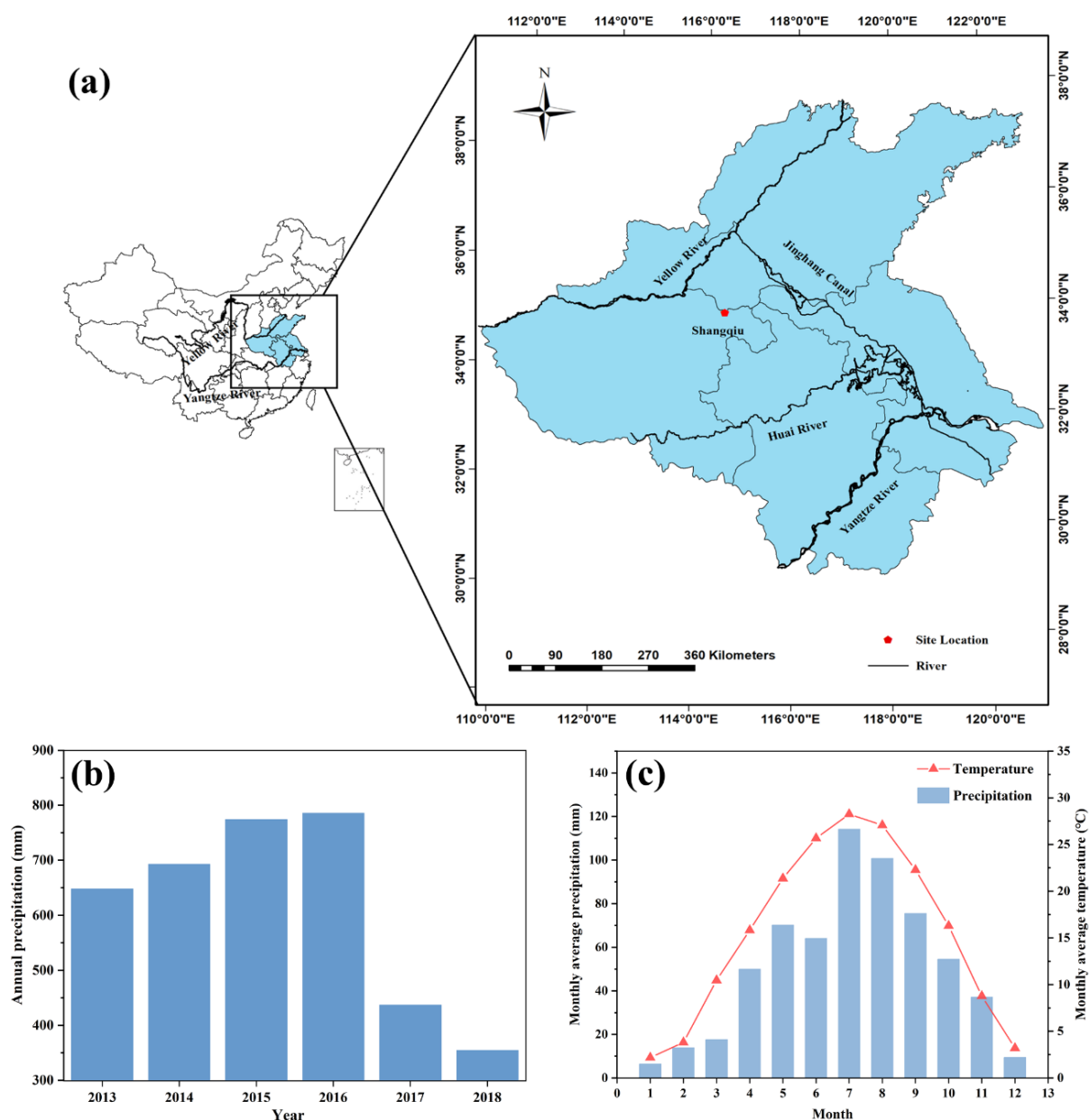


Figure 1. Location of Shangqiu station in the Huang-Huai Plain (a) and annual precipitation (b) and average monthly precipitation and temperature (c) in Shangqiu from 2013 to 2018.

Table 1. Sowing and harvest date, protein content, and energy of the tested field crops.

Crops	Sowing Date	Harvest Date	Protein Content (%)	Energy (J g ⁻¹)
Winter wheat	10.08 [27]	06.10 [28]	12.00 [36]	15,320 [44]
Summer maize	06.12 [29]	09.26 [29]	10.40 [37]	14,200 [44]
Summer soybean	06.25 [33]	09.30 [33]	42.55 [40]	24,139 [43]
Summer millet	06.15 [35]	09.20 [35]	12.71 [41]	14,410 [44]
Autumn potato	08.10 [32]	11.10 [32]	1.66 [38]	3800 [43]
Spring potato	03.05 [34]	06.15 [34]	1.66 [38]	3800 [43]
Spring mung bean	04.25 [31]	06.22 [31]	69.50 [42]	17,651 [45]
Spring sweet potato	04.10 [30]	07.20 [30]	1.60 [39]	4200 [43]

2.4. Alternative Crop Rotations Establishment

Fourteen potential crop rotations including the conventional W–M rotation were defined using the ROTAT model [48] based on the selected eight crops, shown in Table 2. The crop rotation list was generated considering the local soil conditions, climate, water resources, and crop properties (including crop water requirement), crop growth timing and development traits, interactions between previous and succeeding crops, planting frequency, agronomic practices, crop attributes, and the duration to complete a rotation cycle. Meanwhile, exclusion screens were defined to drop agronomically infeasible crop successions and for farm-specific reasons, impractical or undesirable. The exclusions encode a quantitative and explicit indication of the expert knowledge. The final crop rotations newly built in this study included five within-year double cropping systems—CI = 2, cropping index (CI) as the number of crop harvests per year within a cropping system cycle—and nine multi-year crop rotations (CI = 1.5) (Table 2).

Table 2. The new established crop rotations.

No.	Crop Rotations	Rotation Cycle (Years)
1	Winter wheat–summer maize	1
2	Winter wheat–summer soybean	1
3	Winter wheat–summer millet	1
4	Spring potato–summer soybean	1
5	Spring potato–summer millet	1
6	Spring potato→winter wheat–summer maize	2
7	Summer millet→winter wheat–summer maize	2
8	Spring mung bean→winter wheat–summer maize	2
9	Spring sweet potato→winter wheat–summer maize	2
10	Spring potato→winter wheat–summer soybean	2
11	Summer millet→winter wheat–summer soybean	2
12	Spring sweet potato→winter wheat–summer soybean	2
13	Summer millet→winter wheat–autumn potato	2
14	Spring mung bean→winter wheat–autumn potato	2

2.5. Calculation Method

(1) Crop water requirement:

The locally-parametrized SIMETAW (Simulation of Evapotranspiration of Applied Water) model [49–51] was used to quantify the water requirement in the growing season (ET_c), effective precipitation in the growing season (E_r), and irrigation water requirement in the growing season (ET_{aw}) for eight selected crops in Shangqiu from 2013 to 2018. The SIMETAW model includes the Penman–Monteith equation for crop water requirements, as shown in Equation (2) [50]. This widely-applied model quantifies the water and irrigation requirements of staple crops such as maize, wheat, and cotton in the research area (e.g., [6]).

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \quad (2)$$

where ET_0 is the reference crop evapotranspiration ($\text{mm} \cdot \text{d}^{-1}$); R_n is the net canopy surface radiation, ($\text{MJ m}^{-2} \text{d}^{-1}$), G is the soil heat flux density ($\text{MJ m}^{-2} \text{d}^{-1}$), T is the average temperature at 2 m height ($^{\circ}\text{C}$), e_s is the saturation vapor pressure (kPa), e_a is the actual vapor pressure (kPa), Δ is the slope of the saturation vapor pressure–temperature curve ($\text{kPa } ^{\circ}\text{C}^{-1}$), γ is the psychrometric constant ($\text{kPa } ^{\circ}\text{C}^{-1}$), and u_2 is the wind speed at 2 m (m s^{-1}).

The crop water requirement is calculated as follows:

$$ET_c = ET_0 \times K_c \quad (3)$$

where ET_c is crop water requirement in the growing season (mm); ET_0 is the reference crop water requirement (mm); K_c is the crop coefficient, using the parameter choices built in the SIMETAW model as recommended by FAO-56. The parameters of each crop and soil were selected based on the local condition.

The SIMETAW model requires input of daily rainfall, effective rooting depths, and soil water holding characteristics. SIMETAW simulations produce effective rainfall (E_r) and derive hypothetical irrigation time series for summing to seasonal and annual ET_{aw} (in which ET_{aw} represents the net amount of irrigation water needed by the cropped field during the growing season) [50], as follows:

$$ET_{aw} = ET_c - E_r \quad (4)$$

where ET_{aw} is the crop irrigation water requirement, ET_c is the crop evapotranspiration, and E_r is the effective rainfall, all in mm during the growing season; when $ET_c - E_r < 0$, $ET_{aw} = 0$.

(2) Water requirement of crop rotations:

$$AWR = \sum_{i=1}^n ET_{ci} + \sum_{j=1}^m E_j \quad (5)$$

$$E_j = OK_c \times ET_0 \quad (6)$$

where AWR is the total water requirement of a whole rotation (mm); ET_{ci} is the crop water requirement in the i th growing season within one complete cycle of that certain crop rotation (mm); E_j is the evapotranspiration in the j th fallow season (mm); OK_c is a multiplier (recommended by SIMETAW) adjusting bare soil during the fallow period, and ET_0 is from Equation (2). The annual ET_c of a certain rotation equals AWR divided by the number of years in one rotation cycle including the fallow period.

(3) Precipitation coupling degree of crop rotations:

The precipitation coupling degree (PCD , λ) has been defined as the degree to which precipitation meets the water requirement of a crop or a crop rotation in the growing season (s), ranging from 0.0 to 1.0 [52]:

$$\lambda_i = \begin{cases} 1 & (P_i \geq ET_{ci}) \\ P_i / ET_{ci} & (P_i < ET_{ci}) \end{cases} \quad (7)$$

where λ_i is the coupling degree between water requirement and natural precipitation during the growing season for an individual crop in the rotation, P_i is the natural precipitation in the i th growing season of each crop in the rotation (mm), and ET_{ci} is the crop water requirement in the i th growing season of each crop in the rotation (mm).

(4) Economic efficiency, equivalent yield, energy, protein content and efficiencies:

This study further analyzed several system output indicators of each crop rotation. The indicators of system output included EB (economic output), EY (equivalent yield to wheat) [9], E (crop energy content), PC (crop protein content), and corresponding water use efficiencies such as $EbWUE$ (economic output water use efficiency), WUE (equivalent yield water use efficiency), $EWUE$ (energy water use efficiency), and $PWUE$ (protein water use efficiency) [6]. Calculations were as follows:

$$EB = \sum_{i=1}^n (Y_i \times P_i) \quad (8)$$

$$EY = \sum_{i=1}^n (M_i \times P_i / P_w) \quad (9)$$

$$E = \sum_{i=1}^n (M_i \times A_i) \quad (10)$$

$$PC = \sum_{i=1}^n (M_i \times B_i) \quad (11)$$

$$EbWUE = EB / AWR \quad (12)$$

$$WUE = EY / AWR \quad (13)$$

$$EWUE = E / AWR \quad (14)$$

$$PWUE = PC / AWR \quad (15)$$

where EB is the total economic output of each crop rotation (Yuan ha^{-1}), M_i is the crop yield of the i th crop in a certain crop rotation (kg ha^{-1}), P_i is the market price of the i th crop in a certain crop rotation (Yuan kg^{-1}); EY is the summed wheat-equivalent yield of a crop rotation (using relative prices as weights); P_w is wheat price (Yuan kg^{-1}), E is the energy contained in one crop rotation (10^9 J ha^{-1}), A_i is the energy content coefficient of the i th crop product (10^9 J kg^{-1}), PC is the total protein content of each crop rotation (kg ha^{-1}), B_i is the protein content per kg of the i th crop product (%); $EWUE$ is the economic water use efficiency of one certain crop rotation (Yuan m^{-3}); AWR is the total ET_c of each crop rotation (mm), WUE is the equivalent yield water use efficiency of one crop rotation (kg m^{-3}), $EWUE$ is the energy water use efficiency of one crop rotation (10^9 J m^{-3}), $PWUE$ is the protein water use efficiency of one crop rotation (kg m^{-3}). For comparison, USD 1 = CNY 6.9 in May 2023.

(5) Comprehensive assessment for multiple functions of different crop rotations:

Entropy-TOPSIS [53] was used to calculate the comprehensive benefits of 14 crop rotations. In this study, ten indicators, including EB , EY , E , PC , AWR , PCD , and their corresponding WUE s were considered for the comprehensive evaluation of each crop rotation system. The calculations were as follows.

(1) Normalize the indicators:

$$r_{ij} = \frac{x_{ij} - x_{\min}}{x_{\max} - x_{\min}} \quad (\text{positive indicator}) \quad (16)$$

$$r_{ij} = \frac{x_{\max} - x_{ij}}{x_{\max} - x_{\min}} \quad (\text{negative indicator}) \quad (17)$$

where r_{ij} is the normalized value of the i th index in the j th crop rotation, x_{ij} is the average value of the i th index in the j th crop rotation, and $x_{\max}$ and $x_{\min}$ are the highest and the lowest values of a single index, respectively.

(2) The proportion (f_{ij}) of the i th index represented by the j th crop rotation was calculated as follows:

$$f_{ij} = \frac{r_{ij}}{\sum_{i=1}^n r_{ij}} \quad (18)$$

where $i = 1, 2, \dots, m$; $j = 1, 2, \dots, n$.

(3) The entropy value (e_i) of each evaluation index was calculated as follows:

$$e_i = \begin{cases} \frac{-1}{\ln n} \sum_{j=1}^n f_{ij} \ln(f_{ij}) & , f_{ij} \neq 0 \\ 0 & , f_{ij} = 0 \end{cases} \quad (19)$$

(4) The entropy weight (W_i) of the evaluation index was calculated as follows:

$$W_i = \frac{1 - e_i}{m - \sum_{i=1}^m e_i} \quad (20)$$

(5) A weighted normalized decision matrix (Z) was constructed by the normalized matrix f_{ij} and the weights of each index W_i :

$$Z = (W_i \times f_{ij})_{m \times n} = [z_{ij}]_{m \times n} = \begin{bmatrix} z_{11} & z_{12} & \dots & z_{1n} \\ z_{21} & z_{22} & \dots & z_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ z_{m1} & z_{m2} & \dots & z_{mn} \end{bmatrix} \quad (21)$$

(6) The positive ideal solution vector Z^+ and the negative ideal solution vector Z^- were determined to form by the positive ideal solution (Z_i^+) and the negative ideal solution (Z_i^-):

$$Z_i^+ = (\max z_{i1}, \max z_{i2}, \dots, \max z_{in}) \quad (22)$$

$$Z_i^- = (\min z_{i1}, \min z_{i2}, \dots, \min z_{in}) \quad (23)$$

(7) The Euclidean distance between each index and the positive and negative ideal solutions were calculated as follows:

$$D_j^+ = \sqrt{\sum_{i=1}^m [W_i \times (z_{ij} - Z_i^+)]^2} \quad (24)$$

$$D_j^- = \sqrt{\sum_{i=1}^m [W_i \times (z_{ij} - Z_i^-)]^2} \quad (25)$$

(8) The comprehensive evaluation index CEI_j of each crop rotation was calculated. The proximity between the evaluation object and the optimal scheme was calculated as follows:

$$CEI_j = \frac{D_j^-}{D_j^+ + D_j^-} \quad (0 \leq C_j \leq 1) \quad (26)$$

2.6. Statistical Analysis

Statistical methods including analysis of variance (ANOVA), cluster analysis, and principal component analysis (PCA) were carried out by SPSS (Statistical Product and Service Solutions, IBM SPSS Inc., Chicago, IL, USA) version 21. The yearly mean data of the diverse crops or diversified crop rotations were statistically analyzed using multi-way ANOVA. Differences between rotation mean values were compared using the least significant difference (LSD) test for post-hoc comparisons at a 95% probability level. Cluster analysis and PCA were used to analyze the relationships among multiple indicators in each crop rotation.

3. Results

3.1. Water Requirements of Eight Crops in the Growing Season

Winter wheat had the highest growing season ET_c at 405 mm, followed by spring sweet potato (351 mm), spring potato (310 mm), summer maize (305 mm), summer soybean (266 mm), summer millet (305 mm), autumn potato (192 mm), and spring mung bean was lowest at 187 mm, 55% lower than winter wheat (Figure 2a). Summer millet and summer maize had the highest E_r during the growing season at 229 mm and 227 mm, respectively. They were followed by winter wheat (189 mm), spring sweet potato (188 mm), and summer soybean (156 mm). The lowest E_r were from spring potato and autumn potato (114 and 111 mm) and spring mung bean (80 mm) (Figure 2b). Winter wheat had the highest ET_{aw} of 216 mm, followed by spring potato (196 mm), spring sweet potato (163 mm), summer soybean (110 mm), spring mung bean (107 mm), and then autumn potato (81 mm), summer maize (85 mm), and summer millet (63 mm) (Figure 2c).

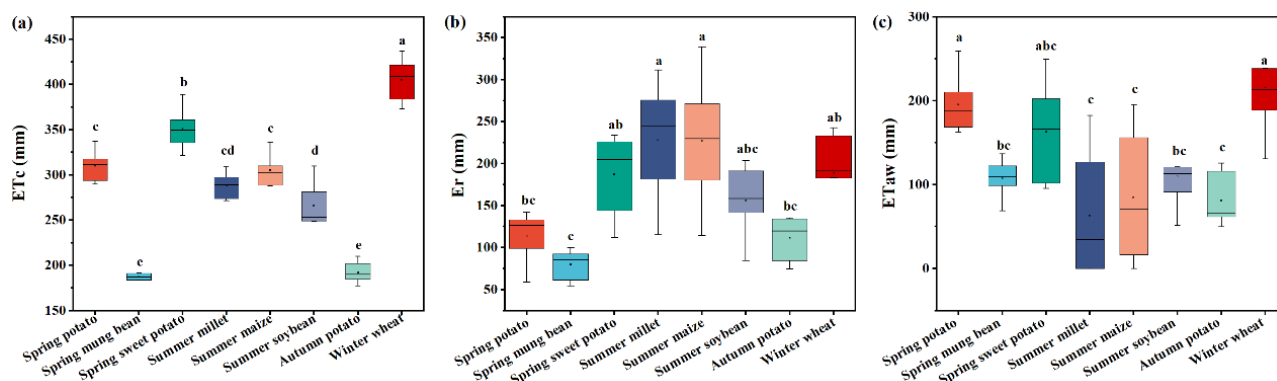


Figure 2. ET_c (a), E_r (b), and ET_{aw} (c) in the growing season of eight crops in Shangqiu area from 2013 to 2018. Different lowercase letters show significant differences of each variable of different crops at $p < 0.05$.

3.2. Water Requirements of Different Crop Rotations during the Growing Season

The conventional, reference W–M rotation had the highest ET_c during the crop growing season of 710 mm across all six years (Figure 3a). The winter wheat-based double cropping systems (CI = 2) had similar ET_c to the W–M rotation. Sp–S and Sp–Sm rotations (CI = 2) had lower ET_c by 16–19% compared with the reference W–M. Four “W–M”-based crop rotations having additional crops spring potato, summer millet, spring mung bean, or spring sweet potato (CI = 1.5) decreased their ET_c by 25–37% relative to the reference W–M. Three “W–S”-based rotations (CI = 1.5) with the previous crop spring potato, summer millet, or spring sweet potato had lower ET_c by 28–31% relative to the conventional W–M. Two “W–P”-based rotations (CI = 1.5) with the previous crop summer millet or spring mung bean had lower ET_c by 38–45% relative to the W–M rotation. ET_c of these crop rotations in wet and normal years were higher than in dry years.

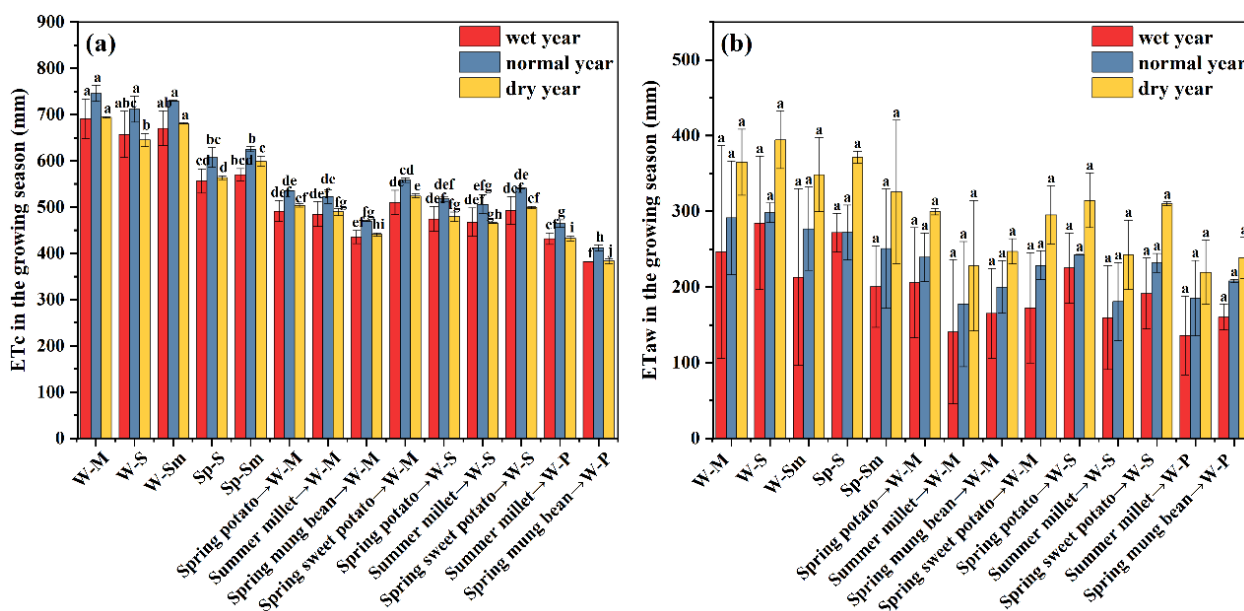


Figure 3. ET_c (a) and ET_{aw} (b) of different crop rotations under different precipitation years from 2013–2018. Different lowercase letters indicate significant differences of different crop rotations in the same precipitation type years. (W–M: Winter wheat–summer maize, W–S: Winter wheat–summer soybean, W–Sm: Winter wheat–summer millet, Sp–S: Spring potato–summer soybean, Sp–Sm: Spring potato–summer millet, W–P: Winter wheat–autumn potato).

The conventional W–M rotation had the greatest ET_{aw} in the growing season of 301 mm across all years (Figure 3b). Sp–S rotation had a similar ET_{aw} to W–M rotation. Two winter wheat-based double cropping systems (CI = 2) had lower the ET_{aw} by 7–8%. The Sp–Sm rotation (CI = 2) had ET_{aw} 14% lower than W–M rotation. Four “W–M”-based crop rotations with the previous crop as spring potato, summer millet, spring mung bean, and spring sweet potato (CI = 1.5) had lower the ET_{aw} by 17–39% compared with the conventional W–M rotation. Three “W–S”-based crop rotations (CI = 1.5) with the previous crop of spring potato, summer millet, or spring sweet potato had lower the ET_{aw} by 13–35% compared with the conventional W–M rotation. Two “W–P”-based crop rotations (CI = 1.5) with the previous crops as summer millet or spring mung bean had lower ET_c by 33–40% compared with the conventional W–M rotation. The ET_{aw} in dry years was significantly higher than in normal and wet years for each crop rotation, because less precipitation was available to support crops. The trends of ET_{aw} for each crop rotation in dry, normal, and wet years are similar across all the tested years.

3.3. Annual Water Requirement and Precipitation Coupling Degree of Different Crop Rotations

The W–M rotation had the highest annual ET_c of 725 mm across all the years (Figure 4a). The annual ET_c values of W–M rotation in wet and normal years were higher than in dry years. Two winter wheat-based rotations (CI = 2) had similar annual ET_c across all the years to the W–M rotation. Sp–S and Sp–Sm rotations (CI = 2) had 2–6% lower annual ET_c than W–M rotation. Four “W–M”-based rotations (CI = 1.5) involving spring potato, summer millet, spring mung bean, and spring sweet potato had lower annual ET_c by 9–16% than the conventional W–M. Three “W–S”-based rotations (CI = 1.5) with previous crop as spring potato, summer millet, and spring sweet potato had lower ET_{aw} by 11–17% than the conventional W–M. Two “W–P”-based rotations (CI = 1.5) with previous crops as summer millet or spring mung bean had lower ET_c by 20% and 21%, respectively, than the conventional W–M rotation.

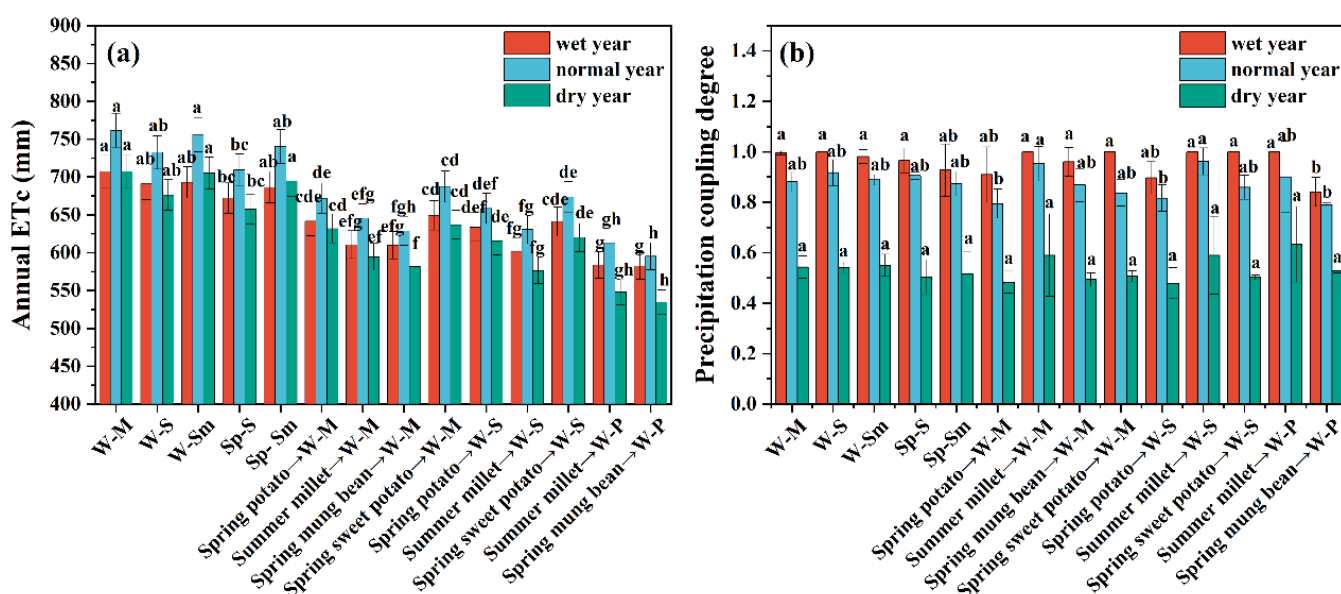


Figure 4. Annual ET_c (a) and precipitation coupling degree (b) of different crop rotations in Shangqiu area from 2013 to 2018. Different lowercase letters indicate significant differences of different crop rotations in the same precipitation type years. (W–M: Winter wheat–summer maize, W–S: Winter wheat–summer soybean, W–Sm: Winter wheat–summer millet, Sp–S: Spring potato–summer soybean, Sp–Sm: Spring potato–summer millet, W–P: Winter wheat–autumn potato).

The precipitation coupling degree (*PCD*) of each crop rotation all showed trends from high to low as wet year > normal year > dry year (Figure 4b). In the wet year, the *PCD* of 14 crop rotations was ≥ 0.84 , averaging 0.96, with most rotations having a *PCD* close to 1. The *PCD* of all tested crop rotations ranged from 0.79 to 0.96 in normal years, with the highest value in summer millet $\rightarrow$ W-S rotation ($CI = 1.5$) and lowest value in spring mung bean $\rightarrow$ W-P rotation ($CI = 1.5$). The *PCD* of all test crop rotations ranged from 0.48 to 0.63 in dry years, with spring potato $\rightarrow$ W-M or W-S rotation having the lowest *PCD* while summer millet $\rightarrow$ W-P rotation had the highest *PCD* in dry years. Autumn potato with low ET_c and ET_{aw} was preferable above spring potato within the considered crop rotations.

3.4. System Output of Different Crop Rotations

The economic efficiency, equivalent yield, and energy and protein nutritional content of 14 crop rotations were further analyzed, as shown Figure 5. The W-M rotation had the annual economic output of 22,174 Yuan ha^{-1} (Figure 5a). The spring potato-based crop rotations (Sp-S and Sp-Sm) had the highest economic output, 2.1 and 1.7 times higher than W-M rotation. W-S rotation increased the economic output by 20% over the W-M rotation. Summer millet and spring mung bean as single, partial year crops alternated with W-M or W-S ($CI = 1.5$) decreased the economic output by 25–35%. Six other crop rotations involving sweet potato and potato rotated in W-M and W-S rotations increased economic output by 12–52% compared with the conventional W-M. The average annual equivalent yield of W-M rotation was 12,319 $kg\ ha^{-1}$ (Figure 5b). The trend of equivalent yield for different crop rotations was similar to the trend of economic output. The rotations involving millet and mung bean (e.g., W-Sm rotation ($CI = 2$), summer millet $\rightarrow$ W-M, spring mung bean $\rightarrow$ W-M, summer millet $\rightarrow$ W-S rotations ($CI = 1.5$) had lower equivalent yield by 20–35% below the W-M rotation. Other crop rotations specified in this study all increased the equivalent yield by 12–113% compared to W-M rotation. The W-M rotation had an annual protein content of 848 $kg\ ha^{-1}$ (Figure 5c). The W-S rotation yield increased protein content by 9% due to soybean inclusion. Other crop rotations did not perform as well in protein output due to the lower protein content in sweet potato and potato. The energy content of diversified crop rotations had a similar trend to protein content (Figure 5d). The W-M rotation had an annual average energy content of 173 $GJ\ ha^{-1}$. Other crop rotations all had lower energy in calories to different degrees.

3.5. Comprehensive Evaluation of Diversified Crop Rotations by Entropy-TOPSIS

Heat map and principal component analysis (PCA) were adopted to reveal the relationships among multiple indicators in each crop rotation (Figure 6). Sp-B and Sp-Sm formed a small cluster with high equivalent yield, economic output, and corresponding WUEs and low annual ET_c . W-M and W-S rotations were a second cluster with similar annual ET_c and *PCD*. Spring sweet potato rotated with W-M or W-S rotations were another cluster, as was spring potato rotated with W-M or W-S rotations, grouping into a larger cluster (Figure 6a). Soybean-based rotations were associated with higher protein contents, economic benefits, and growing season precipitation. The PCA revealed that the cropping index was positively related to annual ET_c , therefore, decreasing the cropping index, such as including a fallow season and involving cash crops like soybean, sweet potato, or potato for multi-year crop rotations could be a way to decrease irrigation water requirements (Figure 6b).

The Entropy-TOPSIS analysis can be used to explore which crop rotations have overall advantages over the W-M rotation and could be promising alternative crop rotations for the research area. There were eight crop rotations with advantages over the W-M rotation according to the comprehensive evaluation index (*CEI*) (Table 3). The W-M rotation had a *CEI* of 0.417. The W-S rotation exceeded in *CEI* by 12% over the W-M rotation, ranking sixth of fourteen. Sp-S had the highest *CEI* of 0.627. Spring sweet potato $\rightarrow$ W-S or $\rightarrow$ W-M and summer millet $\rightarrow$ W-P rotations ($CI = 1.5$) exceeded in *CEI* by 18–29% above the W-M rotation. Spring mung bean $\rightarrow$ W-P ($CI = 1.5$) and Sp-Sm ($CI = 2$) rotations increased *CEI*

by 7–12% above W–M rotation. Summer millet or spring potato→W–S had similar *CEI* to the W–M rotation (Figure 7). “W–S”-based rotations performed better than “W–M”-based rotation. It is promising to partially substitute summer maize with summer soybean for more nutritional output without irrigation increase. In this study, three of the “W–M”-based multi-year rotations ($CI = 1.5$) did not perform better than W–M rotation. W–Sm had the lowest *CEI* due to the low yield of millet in this region (Table 3).

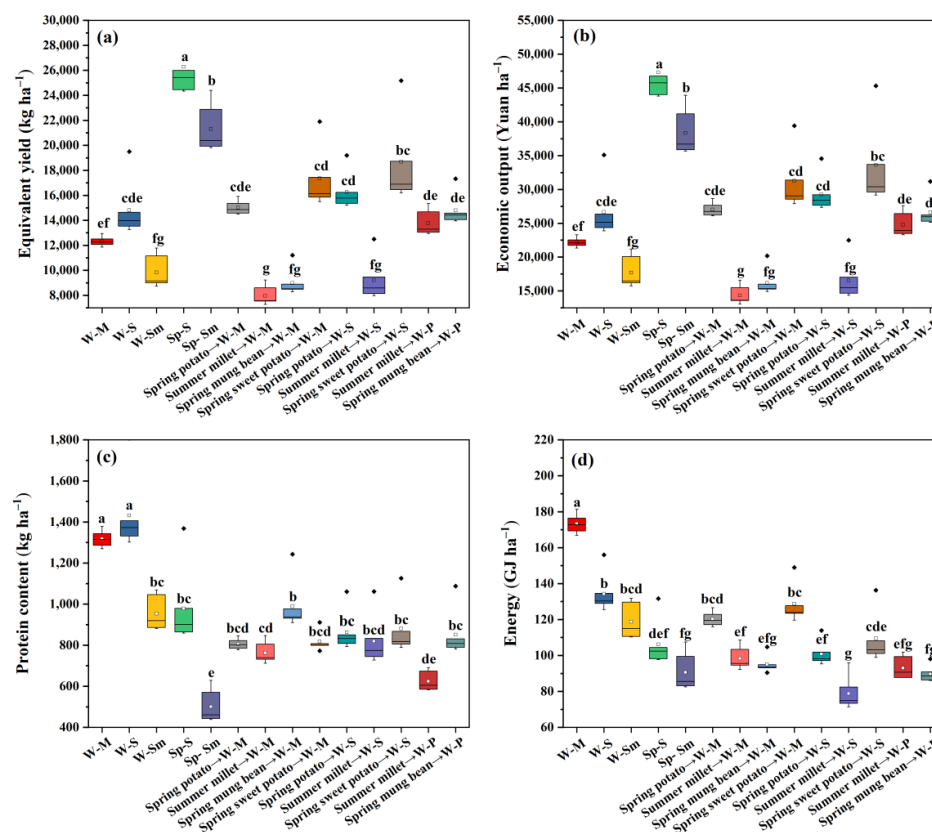


Figure 5. Economic benefit (a), equivalent yield (b), protein content (c), and energy (d) of diversified crop rotations in Shangqiu area from 2013 to 2018. Different lowercase letters show significant differences of each variable of different crop rotations at $p < 0.05$. (W–M: Winter wheat–summer maize, W–S: Winter wheat–summer soybean, W–Sm: Winter wheat–summer millet, Sp–S: Spring potato–summer soybean, Sp–Sm: Spring potato–summer millet, W–P: Winter wheat–autumn potato).

Table 3. Euclidean distances (D^+ and D^-) and comprehensive evaluation index (*CEI*) for each crop rotation ranked by Entropy-TOPSIS.

Crop Rotations	D^+	D^-	<i>CEI</i>	Rank
Sp–S	0.131	0.078	0.627	1
Spring sweet potato→W–S	0.095	0.082	0.538	2
Summer millet→W–P	0.108	0.094	0.535	3
Spring sweet potato→W–M	0.086	0.089	0.493	4
Spring mung bean→W–P	0.097	0.110	0.468	5
W–S	0.092	0.106	0.466	6
Sp–Sm	0.088	0.110	0.444	7
Summer millet→W–S	0.095	0.127	0.427	8
W–M	0.090	0.126	0.417	9
Spring potato→W–S	0.077	0.107	0.416	10
Summer millet→W–M	0.089	0.132	0.402	11
Spring potato→W–M	0.069	0.112	0.381	12
Spring mung bean→W–M	0.073	0.130	0.359	13
W–Sm	0.058	0.142	0.289	14

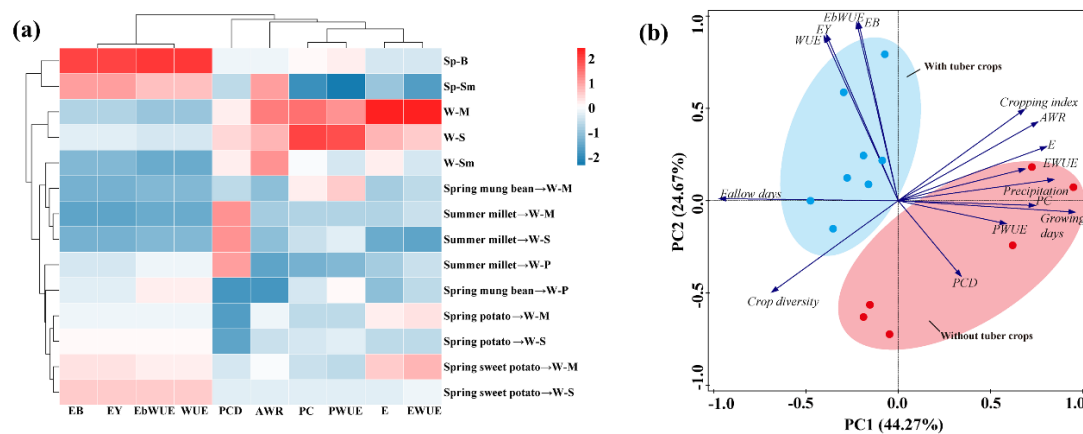


Figure 6. Heatmaps (a) and principal component analysis (b) for showing the performance of different relative indicators for diversified crop rotations from 2013 to 2018 (W–M: Winter wheat–summer maize, W–S: Winter wheat–summer soybean, W–Sm: Winter wheat–summer millet, Sp–S: Spring potato–summer soybean, Sp–Sm: Spring potato–summer millet, W–P: Winter wheat–autumn potato, EB: Economic output, EY: Equivalent yield, E: Energy, PC: Protein content, AWR: Annual ET_c , EbWUE: Economic water use efficiency, WUE: Water use efficiency, EWUE: Energy water use efficiency, PWUE: Protein water use efficiency, PCD: Precipitation coupling degree, Crop diversity is the crop numbers in one rotation cycle).

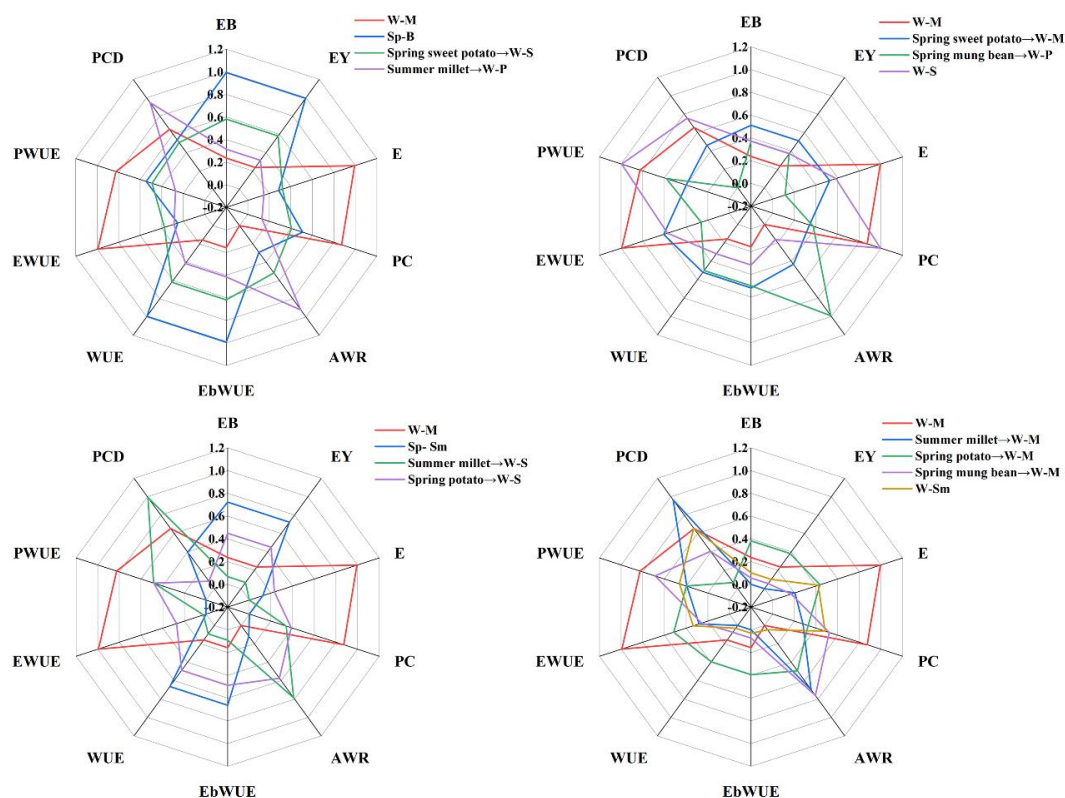


Figure 7. Multiple objectives analysis of diversified crop rotations in Shangqiu area from 2013 to 2018. (W–M: Winter wheat–summer maize, W–S: Winter wheat–summer soybean, W–Sm: Winter wheat–summer millet, Sp–B: Spring potato–summer soybean, Sp–Sm: Spring potato–summer millet, W–P: Winter wheat–autumn potato, EB: Economic benefits, EY: Equivalent yield, E: Energy, PC: Protein content, AWR: Annual water requirement, EbWUE: Water efficiency and economic use efficiency, WUE: Water use efficiency, EWUE: Water and energy use efficiency, PWUE: Water and protein use efficiency, PCD: Precipitation coupling degree).

4. Discussion

4.1. Water Requirements of Diversified Crop Rotations

This study supplies valuable water requirement information for eight staple crops for the region representable by the Shangqiu research station's soil and climate. Previous studies focused more on winter wheat and summer maize (e.g., [54,55]). This study adds several other crops with limited studies in Shangqiu area, such as millet, potato, sweet potato, soybean, and mung bean to the water requirement database. It was already well known that winter wheat had higher ET_c than spring and summer crops. Spring mung bean had the lowest ET_c and ET_{aw} due to greater resistance to drought [56]. Potato had good adaptability to both high and low temperatures, and had low water demand [57]. Millet can maintain a high photosynthetic rate under drought conditions compared with wheat and rice [58]. The information from this study is helpful to build alternative diversified crop rotations including soybean, millet, mung bean, sweet potato, and potato with cereal crops to lower water requirements in the water stressed area.

Alternative water-saving crop rotations are important for mitigating groundwater overuse in Huang-Huai Plain [9]. This study designed 14 crop rotations including 4 double cropping systems ($CI = 1.5$) and 10 multi-year crop rotations ($CI = 2$), generated using agronomic criteria in the ROTAT model [48]. The reference W–M had the highest annual ET_c in wet, normal, and dry years, in which winter wheat was the main contributor. Replacing summer maize with soybean or millet in W–M rotation did not reduce annual ET_c because such rotations retained the high water consumption wheat crop and kept double cropping every year (i.e., CI remained at 2); the annual ET_c was barely lower, by only 2–6%. Inserting diversified crops into W–M for multi-year rotations could decrease annual ET_c by 8–18%, similar to the result of “W–S”-based multi-year rotations with 9–19% reductions. “W–P”-based multi-year rotations made more progress with 18–24% lower annual ET_c . This is evident in the PCA result in Figure 6b. Decreasing cropping index from 2 to 1.5 reduced the average annual ET_c by 12%. These results were consistent with previous studies. Annual ET_c was reduced by 13–15% [6] and 10–54% [9] when decreasing CI from 2 to 1.5. In this study, the evapotranspiration in the fallow period of 10 multi-year rotations contributed 18–34% of annual ET_c , in line with previous studies. The fallow period contributed 15–17% to annual ET_c in simulation [6] and 4–15% in field studies [5,9,59].

Considered crop rotations had average precipitation coupling degrees in different precipitation type years as wet year (0.96) > normal year (0.87) > dry year (0.53). Consequently, annual ET_{aw} of all tested crop rotations under different precipitation type years showed dry year > normal year > wet year. The average ET_{aw} decreased by 24% when the cropping index decreased from 2 to 1.5. Compared to the conventional W–M, crop rotations involving soybean, millet, sweet potato, and potato as alternating single crops ($CI = 1.5$) had lower average ET_{aw} by 17–40%. These results are consistent with previous studies [60–63]. Li et al. highlighted the water-saving benefit for millet when rotated with rye [60]. Millet required less soil moisture, and its transpiration efficiency and WUE were much higher than other species (sorghum, maize, and wheat) [64,65]. Yang et al. reported that a shallow rooted crop, such as sweet potato, drawing soil moisture from 0–120 cm could preserve deeper soil moisture content for the succeeding deep-rooted crop of winter wheat reaching down to 180 cm or deeper [18]. In addition, excessive root zone soil moisture late in the season was reported to negatively influence storage root yield and quality of sweet potato [66,67]. Growing less water-consuming crops (e.g., maize, soybean, mung bean, and cassava) instead of rice in Thailand proved to show greater tolerance with drought [68]. Including soybean in diversified crop rotations reduced the water footprint in the North China Plain [69] and lowered carbon footprint in Thailand [70].

4.2. Multiple Utilities of Diversified Crop Rotations

In this study, the “W–M”-based rotations (CI = 1.5) with summer millet, spring potato, and spring mung bean, the “W–S”-based rotations (CI = 1.5) with summer millet and spring potato, and W–Sm rotations had lower *CEI* than W–M rotation, mainly due to the lower yield of soybean and millet, and lower protein content in potato and sweet potato.

The soybean-based double cropping system performed better than W–M rotation. Sp–S and W–S rotations increased *CEI* by 11% and 57%, respectively, compared with the conventional W–M rotation. Thus, replacing the summer maize with summer soybean could increase the nutrition output and *CEI*, which is worth considering in building new crop rotations. However, a primary obstacle for soybean development has been the low yield due to the germplasm resources and limited available planting area in Huang-Huai Plain. In this study, the yield of soybean referenced from statistical yearbooks was only $1.6 \pm 0.44 \text{ t ha}^{-1}$, which resulted in low rotation output. This was in line with previous studies. Zhang et al. summarized the soybean yield as $2.1 \pm 0.18 \text{ t ha}^{-1}$ from 1998 to 2016 in the North China Plain (NCP) [71]. Yang et al. reported that the yield of summer soybean averaged only $3.0 \pm 0.26 \text{ t ha}^{-1}$ from surveys conducted in three representative counties across the NCP [63]. Meanwhile, the annual grain yield of wheat–soybean was lower by around 49% than the W–M rotation in this study, consistent with [63] in which the annual grain yield of wheat–soybean was 11.5 t ha^{-1} , lower by 29% than yield from the W–M rotation. The low productivity level of soybean is partly due to the low adoption of improved varieties, the use of poor-quality seed, and inefficient and traditional production technologies [72,73]. Zhang et al. reported that, in the southern North China Plain, the total soybean production change was mainly contributed by yield improvement while in north it was mainly caused by the increased sowing area [71]. Soybean planting area expansion and yield improvement was beneficial for reducing reliance on imports to meet the national self-sufficiency goal [74]. It is promising that W–M rotation could be partly converted to W–S in the research area [71,75]. Therefore, it is important to develop and disseminate improved high-yield soybean varieties and complementary agronomic practices to improve yield, and thus increase the economic return of soybean production and reduce the dependence on subsidy.

In this study, sweet potato and potato were involved in some diversified crop rotations. Potatoes are fat-free, rich in vitamin C and vitamin B6, and can supply good amounts of other micronutrients and dietary fiber that feature in the food-based dietary guidelines of many countries [76]. Since 2015, potato has been proposed as the fourth major staple food crop for improving food security in China. Sweet potatoes have become a trending research topic in recent years due to their special nutritional and functional properties [77]. Sweet potatoes are rich in protein, dietary fibers, vitamin B, β -carotene, minerals (e.g., iron, calcium, magnesium, and zinc), and other dietary bioactive compounds such as polyphenol compounds [77–80]. Sweet potato has become the sixth ranking food crop all over the world, and fifth most essential food crop on a fresh weight basis in developing countries after rice, wheat, maize, and cassava [81], which contributes to reducing food shortages in times of crisis. In this study, when summer millet rotated with a potato-based crop rotation, the values of *CEI* were higher than W–M. When summer millet is included in gramineous crops-based rotations, such as W–Sm or Sm→W–M rotation, the system *CEI* did not have an advantage over W–M rotation due to its lower grain yield compared with summer maize. However, millet has advantages to grow on rainfed marginal lands that are often exposed to water stress [82]. Meanwhile, millet is a major source of energy and protein and has high nutritive value (e.g., high calcium, iron, potassium, magnesium, phosphorous, zinc, dietary fiber, polyphenols, and protein content), comparable to major cereals such as wheat, rice, and maize [83–85]. More recent studies have found that millet fits well in rotation with winter annual crops like winter wheat or warm-season broadleaf crops such as sunflower, which can extend and diversify this cropping system to provide multiple benefits [86,87]. In a millet–sunflower or millet–wheat rotation, millet’s shallow roots could

reserve deeper soil moisture for the succeeding sunflower or wheat with their deep and extensive roots which often deplete soil water up to 1.8 to 2 m [88].

Summarily, after comprehensively evaluating the multiple functions of 14 crop rotations, we recommended including soybean, potato, sweet potato, and millet into the cereal crop rotations to form the diversified crop rotations to reduce groundwater pumping, improve system output and increase crop diversification.

4.3. Implications

The novelty of this study was that diversified crop rotations with more crop species and lower cropping index decreased the water requirements, slowed groundwater depletion, and increased product output. Limited water availability poses significant challenges to agricultural intensification. Water scarcity, competition for water resources, inadequate infrastructure, environmental concerns, water quality issues, and climate change impacts [89–92] all contribute to the difficulties. By systematically alternating the types of crops grown, farmers can optimize water use, enhance soil fertility, control pests and diseases, conserve soil, and diversify risk. Incorporating crops with lower water demands reduces overall water consumption, while improved nutrient management and pest control reduce the need for chemical inputs. This study employed the SIMETAW model to quantify the water requirements of several staple crops and used ROTAT model to redesign and generate realistic crop sequences and rotations, which supplied valuable information for the spatial reconfiguration and landscape transformation for sustainable agricultural futures.

This study highlights potential, promising alternative crop rotations which can be considered in the future for sustainable agricultural development in the study region. Candidate rotations for such regions would be defined according to the local weather, soil, social, and economic conditions. Regarding the multiple values of diversified crop rotations in soil health, managing pests and diseases, and optimizing resource use, those are beyond of scope of this study; however, they are definitely worthy of expounding in future studies. In addition, an obvious extension is to apply longer time series data (historical or synthetic) to better understand the effect of different precipitation type years on the water requirements on different crop rotations with different CI and rotation years. Long-term field experiments of diversified crop rotations, while expensive in calendar and resources, are encouraged to obtain first-hand parameters for each crop and model validation data, particularly to reveal the sequencing effects between the rotated crops. The specific carryover effect between the previous crop and succeeding crops should be considered and emphasized when designing new crop rotations. The approach used in this study could be used to design superior crop rotations for other water shortage areas.

5. Conclusions

Well-designed crop rotations are a key element of good agricultural practice, but have been partly lost in the course of specialization and intensification of agricultural production. This study systematically quantified the water requirements of eight crops based on the SIMETAW model, designing 14 crop rotations by ROTAT model for Huang-Huai Plain, and combined multiple outcome dimensions of diversified crop rotations using Entropy-TOPSIS. Results showed that, compared to the W–M rotation, 12-month double cropping system without winter wheat only decreased annual ET_c by 2–6%. Decreasing cropping index from 2 to 1.5, including fallow time, reduced the annual ET_c by 9–21% in all of the three precipitation-type years. Changing summer maize to soybean (the W–S rotation) had the similar annual ET_c and ET_{aw} but with 1.2 times higher economic output and equivalent yield, meanwhile with 9% more protein output than W–M rotation. Eight designed crop rotations had higher CEI than W–M rotation. Compared to W–M rotation, spring potato–summer soybean increased CEI by 57%. Wheat–soybean rotation had higher CEI by 12%. Spring sweet potato→W–M (or S), and “wheat–potato”-based rotations (CI = 1.5) increased CEI by 12–29%. Therefore, decreasing cropping index and including soybean, potato, sweet

potato, and millet into cereal crop rotations could save groundwater irrigation and ensure food products in the water stressed regions.

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