COMPARATIVE STUDY ON WATER USE CHARACTERISTICS AND PRODUCTIVITY OF SOYBEAN AND MAIZE INTERCROPPING SYSTEM UNDER DRY FARMING CONDITIONS

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旱作条件下大豆玉米复合种植系统水分利用特征和生产力的比较研究

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ABSTRACT

Quantitative investigation of the utilization characteristics of precipitation resources and the production capacity of the intercropping production system under the soybean maize intercropping mode in northern China is of great significance for improving the resource utilization rate of dryland agriculture and regional sustainable development. This study adopted a completely randomized block design, and six planting modes were set up: soybean monoculture, maize monoculture, and four soybean maize intercropping modes. Plant height and grain yield data were observed, and precipitation resource utilization efficiency was calculated. Based on the FAO-56 recommended crop coefficients, the crop coefficients were corrected according to the actual growth of crops in the experimental area; combined with meteorological data, the crop water demand under different planting modes was estimated based on the Penman-Monteith principle. The results showed that crops' daily growth water demand under different planting modes was generally deficient in water in the early and middle stages of growth, and surplus in the later stages. Compared with the monoculture mode, there were significant differences in precipitation resource utilization efficiency under different intercropping modes (P < 0.05), with soybeans reduced by 67.50% ~ 89.56%, and maize reduced by 43.99% ~ 61.05%. Based on the semi-humid and semi-arid area of the eastern Loess Plateau, an appropriate irrigation system needs to be designated for soybean and maize intercropping systems in the early and middle stages of crop growth. Under a certain proportion of water resource supply, different modes have different water resource utilization efficiency and final production capacity for the intercropping system.

摘要

定量化探究中国北方大豆玉米复合种植方式下降水资源的利用特征及复合生产系统的生产能力对提升旱作农业资源利用率和区域可续发展具有重要意义。本研究采用完全随机区组设计，布设六种种植模式，即大豆单作、玉米单作、以及四种大豆玉米复合种植模式，观测株高、籽粒产量数据，计算降水资源利用效率。基于 FAO-56 推荐作物系数，根据试验区作物实际长势进行作物系数矫正；结合气象数据，基于 Penman-Monteith 原理，估算不同种植模式下作物需水量。结果表明：不同种植模式下作物逐日生长需水量，整体呈生育前、中期水分亏缺严重，生育后期水分盈余；与单作模式相比，不同复合种植模式下降水资源利用效率存在显著差异（P < 0.05），大豆降低了 67.50% ~ 89.56%、玉米降低了 43.99 % ~ 61.05%。基于黄土高原东缘半湿润偏旱区，大豆、玉米复合种植系统下，在作物生长前、中期需要指定适宜的灌溉制度。比例水分资源供应一定下，不同的模式对复合系统的水资源利用效率及最终的生产能力是不同的。

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INTRODUCTION

Against the backdrop of global climate change and increasing water scarcity, effective water management and enhancing agricultural productivity have become crucial topics in contemporary agricultural research *(Scanlon et al., 2023; Walter et al., 2023)*. Particularly in rainfed agricultural conditions, addressing the urgent and complex challenge of efficiently utilizing limited water resources to ensure food security is paramount. In recent years, the composite planting system of soybeans and maize has garnered widespread attention due to its potential advantages in water utilization and productivity.

A study conducted in the Punjab Province, Pakistan, indicates that under rainfed conditions, the strip intercropping system of maize and soybeans may be a productive and sustainable strategy to improve water use efficiency and land productivity under irrigated conditions *(Muhammad et al., 2021).* Similarly, in Egypt, a study emphasizes the importance of intercropping in improving water use efficiency and increasing land utilization efficiency for legumes and maize *(Metwally et al., 2019)*. In northern Nigeria, a study was made on maize and soybean intercropping systems, aiming to achieve sustainable intensification of cereal-legume intercropping. The study suggests that overall, monoculture of maize and soybeans is superior to intercropping, with land equivalent ratios for all intercropping treatments greater than 1, indicating the advantage of intercropping maize and soybeans over monoculture *(Kamara et al., 2019)*. Results from a study in Serra Talhada, Pernambuco, Brazil, examining intercropping and mulching techniques in semi-arid areas for prickly pear and millet production suggest that adopting intercropping techniques can reduce water loss due to evaporation compared to sole cultivation *(George et al., 2023).* In northwest China it is also confirmed the potential of mixed planting systems in improving water use efficiency in dryland areas *(Falong Hu's et al., 2017)*. In another study from southwestern Japan *(Azizi et al., 2021)*, the yield and protein variation in intercropped soybeans and maize of different varieties were investigated, providing practical information for agricultural production in subtropical regions. Additionally, a study from Nebraska USA, by establishing water productivity benchmarks, further deepens the understanding of water use efficiency for maize and soybeans under different water resource management conditions *(Mekonnen et al., 2020)*. It reveals the impact of maize and soybean intercropping systems on water resource utilization efficiency, contributing to narrowing water productivity gaps and improving water sustainability goals for the state, providing important insights for the sustainable development of global agricultural production.

In summary, research on the soybean-maize intercropping system under rainfed conditions in different regions worldwide indicates a significant advantage of intercropping systems in improving water use efficiency and productivity. However, it is important to note that the applicability of these research findings may be influenced by specific geographical, climatic, and soil conditions.

Therefore, the main objective of this case study was to explore the water requirement patterns for soybeans and maize in a composite planting system based on the semi-humid to semi-arid conditions on the eastern edge of the Loess Plateau. Under a fixed proportional water supply, this study aims to investigate the impact of different planting patterns on the water resource utilization efficiency and the final production capacity of the composite system, with the goal of providing more precise guidance for achieving sustainable agricultural production.

MATERIALS AND METHODS

Experimental Area Overview and Experimental Material

The experimental base is located in the National Agricultural High-tech Zone of Jinzhong (112°36'E, 37°25'N, 786.7 m), situated in the northeastern part of the Jinzhong Basin. The area belongs to a warm temperate continental climate, with an annual average precipitation of about 450 mm, an annual average temperature of about 10°C, an average frost-free period of 160 ~ 190 days, abundant sunshine, and high evaporation. The soil in the experimental area is brown soil, and the basic soil fertility is shown in Table 1.

Table 1

Soil composition content at the test site

Depth	Alkaline hydrolysable nitrogen	Total nitrogen	Total phosphorous	Organic matter
[cm]	[mg/kg]	[g/kg]	[g/kg]	[g/kg]
0~20	43.30	1.02	1.13	15.65
20~40	22.10	0.61	0.83	8.19

On May 22, 2022, a completely randomized block design was adopted, with a plot area of 85 m^2 (10 m x 8.5 m). Maize "Qiangsheng 199" and soybean "Tiefeng 31" were selected as experimental materials. Six planting modes were set up, including soybean monoculture (S), maize monoculture (M), and four soybean-maize intercropping modes (S3M3, S4M2, S6M3, S4M3, with the row ratios of soybeans to maize being 3:3, 4:2, 6:3, and 4:3, respectively). Each planting mode was repeated three times (Figure 1). The planting density for each mode is shown in Table 2.

Table 2

Planting density table of soybean maize intercropping system

Planting pattern	**S**	**M**	**S3M3**		**S4M2**		**S6M3**		**S4M3**	
			Soybean	**Maize**	**Soybean**	**Maize**	**Soybean**	**Maize**	**Soybean**	**Maize**
Density [plants/hm^2]	1846	575	1272	720	1696	616	1692	520	1504	549

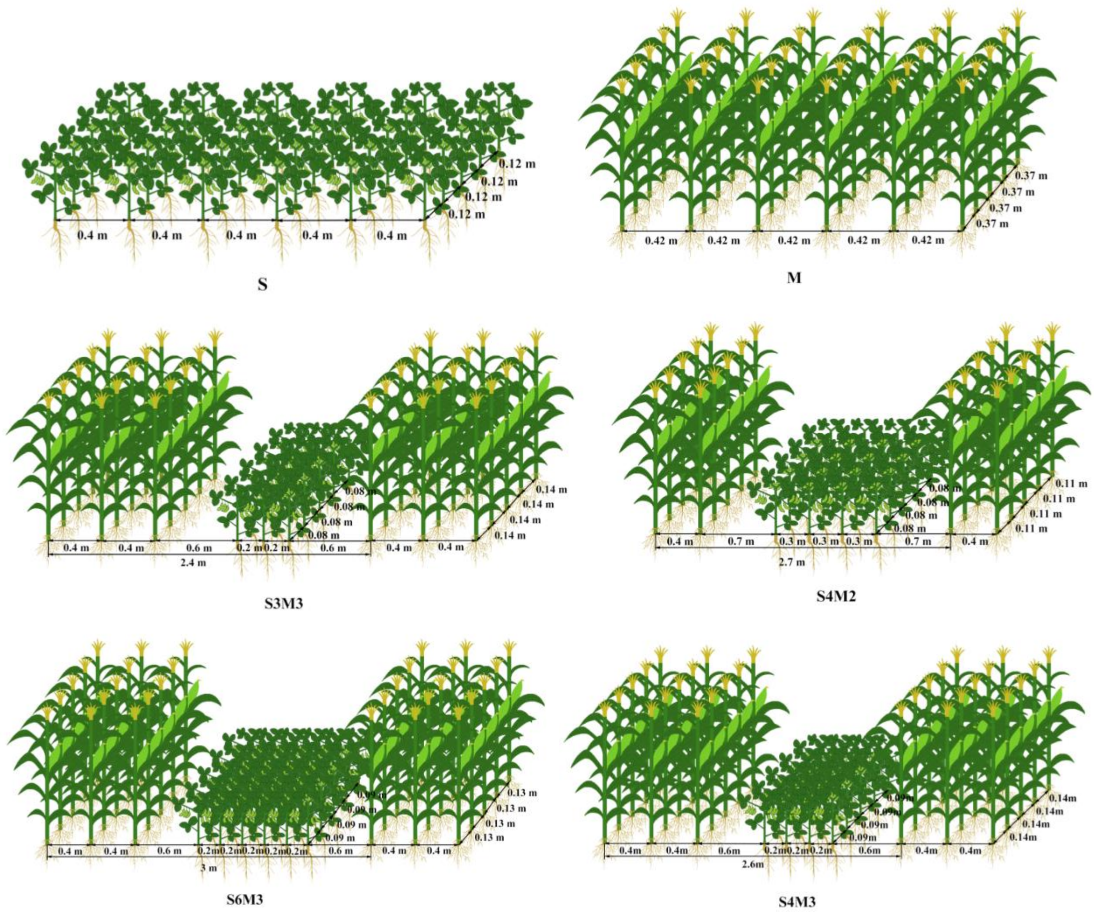


Fig. 1 - Schematic diagram of planting mode of soybean maize intercropping system

Test method

(1) Meteorological data

In the experimental area, daily observations of six meteorological elements are conducted through a small weather station, including average temperature, maximum temperature, minimum temperature, relative humidity, average wind speed, and rainfall amount, as well as sunshine duration. The small weather station comprises a platinum resistance temperature sensor, a capacitive humidity sensor, a spiral-type wind direction and speed sensor, a single tipping bucket rain gauge, and an automatic sunshine recording sensor. All these sensors are integrated into a louvered box and are programmed to automatically record and store hourly data from each sensor into its internal memory *(Central Meteorological Bureau, 2003)*.

(2) Crop coefficient

According to the FAO classification standards *(Allen et al., 1998)*, the growth period of soybeans and maize is divided into the early, middle, and late stages (Table 3).

Table 3

Soybean and maize growth stage division

Crop plant	Initial period [d]	Middle stage [d]	Late stage [d]	Whole growth period
Soybean	31	37	65	2022-05-22 to 2022-10-01(133 d)
Maize	36	58	36	2022-05-22 to 2022-09-28(130 d)

The FAO recommended values for soybean and maize at the early, middle and late stages were 0.50, 1.15, 0.50, and 0.51, 1.20, 0.60, respectively. The crop coefficients at the middle and late stages were corrected by formula (1).

$$K_c = K_{ctable} + [0.04(u_2 - 2) - 0.004(RH_{\min} - 45)][\frac{h}{3}]^{0.3} \quad (1)$$

where:

K_{ctable} is the recommended value for FAO-56 *(Allen et al., 1998)*, $RH_{\min}$ is the daily average minimum relative humidity, u_2 is 2 m high daily average wind speed, h is the average plant height of each growth stage.

(3) Crop water requirement

The Penman-Monteith formula recommended by FAO *(Allen et al. 1998)* was used to calculate the reference crop evapotranspiration, and the formula (2) was used to calculate the crop water storage.

$$ET_c = K_c \cdot ET_0 \quad [\text{mm/d}] \quad (2)$$

where:

ET_c is crop water requirement, ET_0 is reference crop evapotranspiration, K_c is the crop coefficient.

(4) Plant height

In the key growth stages of soybean and maize, the plant height of soybean and maize was obtained by manual measurement.

(5) Yield of soybean and maize under different planting patterns

Maize yield measurement. For each sampling point, measure 3 production units (e.g., each unit consisting of 2 rows of maize, totaling 6 row spaces) to calculate the average row spacing. In these 6 rows, select a representative 4 meters of double rows (avoiding the edge rows), count the number of plants and ears, and calculate the number of ears per acre. In each measured sample section, harvest one ear of maize for every two ears, totaling 10 ears as a sample to measure the number of grains per ear.

The formula for calculating yield is as follows:

Theoretical yield (kg/acre) = Number of ears per acre × Number of grains per ear ×
Average 100-grain weight (average of the past three years for the measured variety) × 85% (3)

Soybean Yield Measurement: Based on the number of soybean rows in each strip of strip compound planting, measure the distance of 3 production units (e.g., 6 rows for 2 rows per strip of soybeans, 9 rows for 3 rows per strip) or more at the sampling points, and divide by 6 or 9 (3 production units), to calculate the average row spacing (meters). Randomly determine the number of effective soybean plants in 4 meters within a strip, calculate the average plant spacing, and then calculate the number of effective plants per acre based on the average row spacing. Investigate the number of grains per plant for 10 consecutive plants in each row within the soybean strip, and then calculate the average number of grains per plant within the sampling point based on the number of rows per strip. The formula for calculating yield is as follows:

Theoretical yield (kg/acre) = 0.85 × Number of effective plants per acre × Number of grains per plant ×
Average 100-grain weight (grams) / 100 / 1000 (4)

(6) Calculation of precipitation resource utilization efficiency

Rainfall utilization efficiency can comprehensively reflect the change characteristics of land production capacity. The formula of precipitation resource utilization efficiency is (*Deng et al. 2023*):

$$RUE = \frac{Y}{PG}[kg/(ha*mm)] \quad (5)$$

RUE is the utilization efficiency of precipitation resources, Y is crop grain yield, PG is precipitation during growth period. Perform one-way mean analysis on RUE using SPSS Data Analysis software.

RESULTS AND DISCUSSION

Water requirement rule of soybean monoculture

According to the actual situation of the experiment and the analysis of the soil moisture cycle process, the annual rainfall in Shanxi Province fluctuates around 450 mm, and the frequency of heavy rainstorms in meteorology occurs five times a year. Therefore, there is no rainfall recharge to groundwater and the formation of surface runoff. If the buried depth of groundwater is more than 5 m, groundwater has no supplementary effect on crop growth water demand.

The minimum relative average humidity during the middle growth stage of soybean and maize was 47.61% and 48.58%, respectively, and the daily average wind speed at 2 m height was 1.62 m/s and 1.61 m/s, respectively. The minimum relative average humidity in the late growth stage was 31.66% and 35.47%, respectively, and the daily average wind speed at 2 m height was 1.71 m/s and 1.68 m/s, respectively. The average plant height in the middle and late stages of crops under different planting patterns is shown in table 4.

Table 4

The average plant height of crops in different planting patterns in the middle and late growth stages

Repro-ductive period	S [m]	M [m]	S3M3		S4M2		S6M3		S4M3	
			Soybean [m]	Maize [m]	Soybean [m]	Maize [m]	Soybean [m]	Maize [m]	Soybean [m]	Maize [m]
Mid- stage	0.466	1.855	0.415	1.953	0.554	2.102	0.354	1.655	0.520	2.132
Late stage	0.720	3.280	0.844	2.884	0.854	2.909	0.766	2.923	0.883	3.103

Based on the FAO-56 recommended crop coefficient as the basis of localized correction crop coefficient, the climatic factors in the test area are used as the influencing factors to localize the crop coefficient. The results of crop coefficient correction of different planting patterns are shown in table 5.

Table 5

Crop coefficients of different intercropping and planting stages

Reproductive period	S	M	S3M3		S4M2		S6M3		S4M3	
			Soybean	Maize	Soybean	Maize	Soybean	Maize	Soybean	Maize
Mid-stage	1.135	1.174	1.136	1.180	1.135	1.179	1.136	1.180	1.135	1.179
Late stage	0.527	0.626	0.529	0.625	0.529	0.625	0.528	0.625	0.529	0.626

The P-M formula was used to calculate the daily growth water demand of crops according to the six meteorological elements in the experimental area and the actual growth status of soybean monoculture. The estimated water requirement during the whole growth period was 369.60 mm. The estimated water requirements before, during and after growth were 93.98 mm, 168.80 mm and 106.82 mm, respectively. The rainfall during the whole growth period of soybean monoculture was 329.27 mm, and the rainfall before, during and after the growth period was 25.42 mm, 120.95 mm and 182.90 mm, respectively. 24 mm irrigation was carried out in each treatment area in the early stage of crop growth on June 5 in order to ensure the emergence rate of crop growth because of soil drought and atmospheric drought in the early stage of crop growth.

Therefore, the actual water supply in the early stage of crop growth was 49.42 mm. The water deficit under the condition of no irrigation in the whole growth cycle of soybean monoculture was 40.33 mm, corresponding to the water deficit of 68.56 mm and 47.85 mm in the early and middle stages of crop growth. The water surplus in the late growth stage was 76.08 mm.

There is a mismatch between water demand and water supply according to the analysis of different growth stages of soybean. The water deficit is serious in the early and middle stages of soybean growth. The water surplus occurs in the late stage of growth.

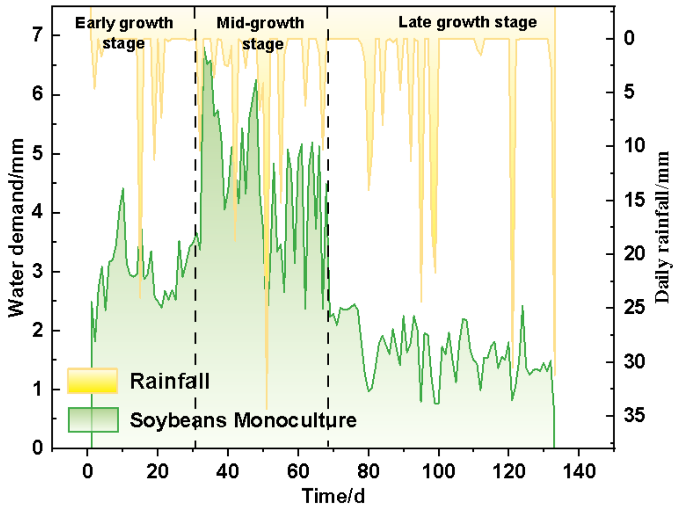


Fig. 2 - The actual water demand and daily precipitation of a single soybean species

Water requirement rule of maize monoculture

Figure 3 indicates that, in the study of water requirements for monoculture maize, the water requirement curve follows a basic pattern consistent with monoculture soybeans, represented by the equation:

$$y = -0.0006x^2 + 0.0686x + 2.3553[mm] \tag{6}$$

Where: y is water demand, x is time.

The difference is that the middle growth period of maize is longer, and the water demand is larger. The estimated water demand during the whole growth period is 427.82 mm. The estimated water demands before, during and after growth were 108.89 mm, 254.90 mm and 64.03 mm, respectively. The rainfall in the whole growth cycle of maize monoculture was 295.27 mm. The rainfalls before, during and after the growth period were 39.39 mm, 158.88 mm and 97 mm, respectively. The soil drought and atmospheric drought occurred in the early stage of maize monoculture. In order to ensure the emergence rate of maize monoculture, 24 mm irrigation was performed in each treatment area at the early stage of crop growth on June 5. Therefore, the actual water supply in the early stage of crop growth was 63.39 mm. The water deficit under the condition of no irrigation in the whole growth cycle of maize monoculture was 132.55 mm, corresponding to the water deficit of 69.5 mm and 96.02 mm in the early and middle stages of crop growth. The water surplus in the late growth stage was 32.97 mm.

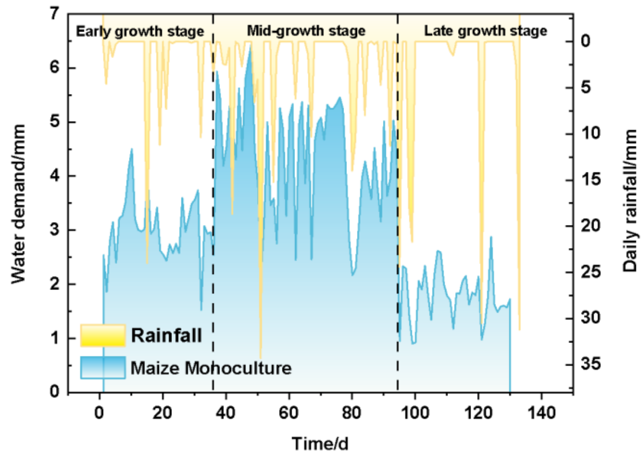


Fig. 3 - Actual water demand and daily precipitation of a single species of maize

The water demand and water supply of maize monoculture also appeared mismatch according to the analysis of three different growth periods. The water deficit was serious in the early and middle stages of maize monoculture. The water surplus appeared in the later stage of maize monoculture. Therefore, according to the rainfall situation of the test area and the estimated water demand of the crop, the irrigation system suitable for the water demand of the maize is formulated in ten days or weeks, which has achieved the maximization of resource utilization.

Water requirement law of soybean-maize intercropping

In different intercropping systems of soybean and maize, the estimated water requirements of soybean and maize during the whole growth period were 370.15 mm and 429.02 mm under intercropping S3M3. Under intercropping S4M2, the estimated water requirements of soybean and maize during the whole growth period were 370.00 mm and 428.81 mm, respectively. Under intercropping S6M3, the estimated water requirements of soybean and maize during the whole growth period were 369.94 mm and 429.02 mm, respectively. Under intercropping S4M3, the actual water requirements of soybean and maize during the whole growth period were 370.15 mm and 428.91 mm, respectively. The estimated water demand and water deficit of soybean and maize under different intercropping patterns in each growth period are shown in Table 6.

Table 6

Estimation of water demand and water gain and deficit at different growth stages under different intercropping modes

Reproductive period			Early stage	Middle stage	Late stage
S3M3	Soybean	Estimate water demand [mm]	93.98	168.94	107.23
		water deficit [mm]	-68.56	-47.99	75.67
	Maize	Estimate water demand [mm]	108.89	256.2	63.93
		water deficit[mm]	-69.5	-97.32	33.07
S4M2	Soybean	Estimate water demand [mm]	93.98	168.79	107.23
		water deficit [mm]	-68.56	-47.99	75.67
	Maize	Estimate water demand [mm]	108.89	255.99	63.93
		water deficit [mm]	-69.5	-97.11	33.07
S6M3	Soybean	Estimate water demand [mm]	93.98	168.94	107.02
		water deficit [mm]	-69.5	-97.11	32.97
	Maize	Estimate water demand [mm]	108.89	256.2	63.93
		water deficit [mm]	-69.5	-97.32	33.07
S4M3	Soybean	Estimate water demand [mm]	93.89	168.94	107.23
		water deficit [mm]	-68.56	-47.99	75.67
	Maize	Estimate water demand [mm]	108.89	255.99	64.03
		water deficit [mm]	-69.5	-97.11	32.97

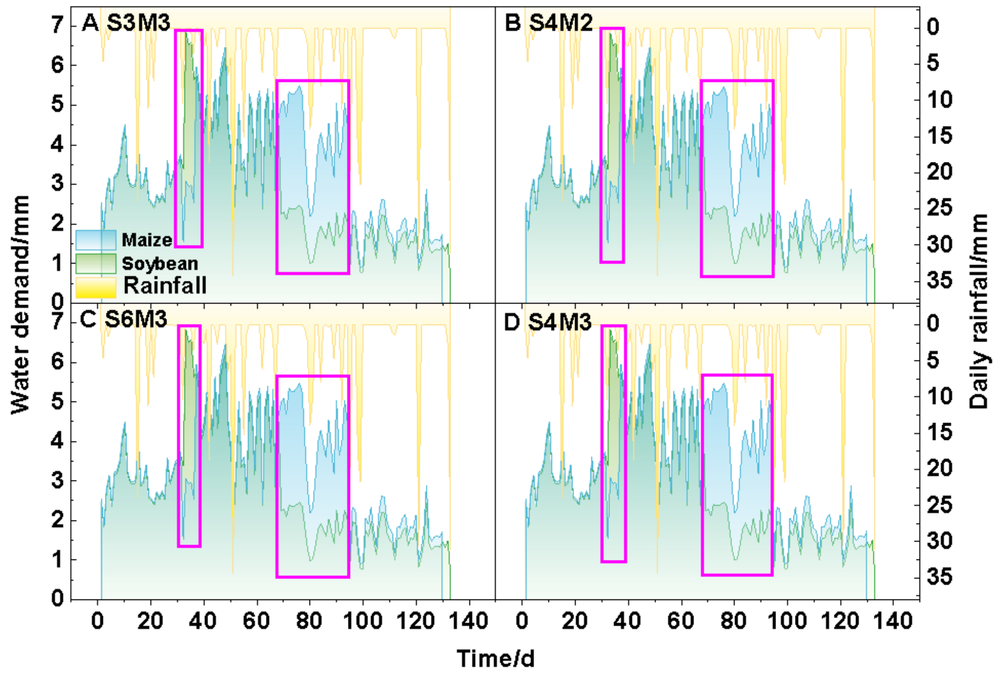
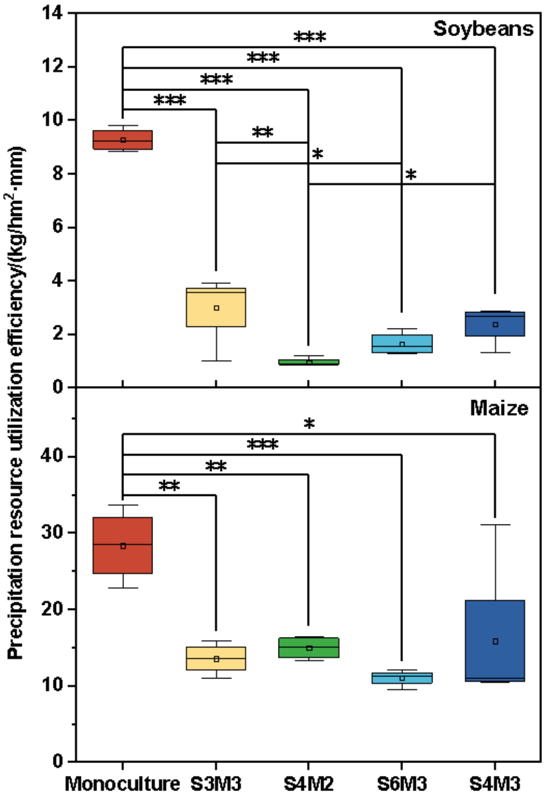


Fig. 4 - Estimation of water requirement and daily precipitation of soybean and maize intercropping planting

Figure 4 shows that the vigorous water demand period of soybean is maintained for 37 days. The vigorous water demand period of maize is maintained for 58 days. In addition, the vigorous water demand period of soybeans was about 5 days earlier than that of maize. After the end of the vigorous water demand period of soybeans, the vigorous water demand period for maize remained for 26 days. The coexistence period of water demand in the soybean-maize intercropping system was 32 days. It is possible to select in the early stage of crop growth less irrigation or no irrigation in the four intercropping patterns of soybean and maize without affecting the emergence rate. The period of vigorous water demand enters quickly in the middle stage of crop growth. It is necessary to make scientific irrigation decisions in combination with soil moisture in order to ensure the growth of crops under stress.

Precipitation use the efficiency of different planting patterns

The difference between different planting ratios was analyzed by one-way analysis of variance (ANOVA), and the significant level was set at $P < 0.05$. Soybean monoculture (S) and maize monoculture (M) were 9.29 and 33.89 kg ha^{-1} mm, respectively. In S3M3 mode, soybean and maize were 3.01 and 16.22 kg ha^{-1} mm, respectively. The RUE of soybean and maize under S4M2 were 0.96 and 17.89 kg ha^{-1} mm, respectively. In S6M3 mode, soybean and maize were 1.66 and 13.20 kg ha^{-1} mm, respectively. Under S4M3, the yield of soybean and maize were 2.40 and 18.98 kg ha^{-1} mm, respectively. Compared with soybean and maize monoculture, the utilization efficiency of crop precipitation resources under different intercropping patterns decreased significantly ($P < 0.05$). The utilization efficiency of soybean and maize decreased by 67.50 % - 89.56 % and 43.99 % - 61.05 %, respectively. Compared with S4M2 mode, S3M3 mode soybean increased by 211.38 %, compared with S6M3 increased by 82.04 %, and S4M3 mode increased by 147.52 % compared with S4M2 mode. The decrease of crop precipitation resource utilization efficiency in intercropping mode is mainly due to the large decrease of yield. There are two reasons: (1) planting time is too late. (2) Some seedlings of supplementary inoculation did not grow out.



*The t-test is used to test the significance of RUE * P < 0.05, ** P < 0.01, *** P < 0.001*

Fig. 5 - Different planting methods reduce the efficiency of water use

CONCLUSIONS

A comparison of water resource utilization efficiency and yield in the mixed planting mode revealed that the reduction in precipitation resource utilization efficiency for soybean and maize ranged from 67.50% to 89.56% and 43.99% to 61.05%, respectively.

The intercropping of soybeans and maize essentially involves the competition and mutual supplementation of resources between grass crops and legumes, such as sunlight and groundwater resources.

Due to the complex relationship between crop root development and water resources, future efforts will require the use of partial differential equation models and the laws of soil water movement to model and analyze the water requirements of crops in intercropping systems accurately, particularly focusing on understanding the water characteristics of soybeans and maize.

As intercropping systems are conducted in field experiments, they are susceptible to external factors such as climate and regional differences, which may lead to unstable productivity. In the future, employing principles of resistance to interference for data modeling is necessary to obtain a crop interaction model under intercropping conditions. This research aims to investigate the mechanisms that stabilize and increase productivity in intercropping systems.

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