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Multi-Objective Optimization Water–Nitrogen Coupling Zones of Maize under Mulched Drip Irrigation: A Case Study of West Liaohe Plain, China

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Abstract: The impact of different combinations of water–nitrogen coupling on maize yield and the environment needs investigation. Low, medium, and high levels of irrigation and N application gradients were studied through field experiments to elucidate the suitable water–nitrogen coupling zone for spring maize in the West Liaohe Plain during three hydrological year patterns under drip irrigation with plastic film. The effects of different water–nitrogen couplings on maize yield, water- and nitrogen-use efficiencies (WUE and NUE), and post-harvest soil alkali-hydrolyzable N residues were studied under integrated drip irrigation by varying the application rates of water and fertilizer. A multi-objective optimization of water–nitrogen coupling zones was performed by integrating maize yield, harvest index, WUE, and soil environmental effects. Results show that with an increase in irrigation and N application rate, the residual amount of alkali-hydrolyzable N increased slowly within a certain range. Upon exceeding a certain amount, residual N increased rapidly, and more N entered the soil environment. The NUE of moderate water–nitrogen coupling treatment was high, with lower environmental risk of residual alkali-hydrolyzable N. Moderate irrigation yielded the highest harvest index in the normal hydrological year. Irrigation rate had a higher impact on yield compared to nitrogen application, because of drip irrigation under plastic film. An appropriate irrigation amount results in a higher WUE and the application of N application must be adjusted according to the rainfall in a particular year. This study highlights the need for structuring water–nitrogen coupling zones specifically for different hydrological years.

Keywords: water–nitrogen coupling; soil alkaline hydrolysis nitrogen residue; harvest index; yield; water-use efficiency

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1. Introduction

Compared to conventional planting in bare land, mulching, drip irrigation, and N fertilization are not only separate manual regulatory factors, but also interact with and influence each other [1]. Drip irrigation under plastic film has become an important agronomic measure in arid areas [2,3], where the sealing by the plastic film blocks the direct exchange of soil water with the outside air, thereby reducing unnecessary evaporation of soil moisture [4–6]. This can provide a suitable soil environment for crops, create early sowing conditions, and reduce weed growth [6–9]. Drip irrigation directly applies water and N fertilizers at the roots of the crops, which can alter the distribution of water, nutrients, and roots in the soil [10], improve water- and nitrogen-use efficiencies (WUE and NUE) [11,12], and mitigate the drop in groundwater level caused by agricultural irrigation and groundwater pollution caused by excessive N application [13,14].

Water and N are the main limiting factors of high crop-yield under drip irrigation with plastic film, and there is a synergistic effect between them [15,16]. N participates in all metabolic processes of plants and plays an important role in their growth and development [17]. An optimal amount of appropriate N fertilizer is beneficial to the synthesis of chlorophyll, promoting plant growth and biomass accumulation [18]. However, the excessive application of N fertilizers can cause fertilizer burn on seedling tips and leaves, and the excessive vegetative growth caused by excessive N application increases unnecessary crop water evaporation and energy consumption, thereby affecting grain growth and reducing yield and quality [19,20]. An increase in N application has largely positive effects on crop growth under conditions of sufficient water and slight water shortage, but under severe water shortage conditions, stomatal conductance will be reduced and photosynthesis will be affected [21]. Excessive N application also increases the concentration of soil nitrate and osmotic pressure of the root system, and reduces the water potential difference between the root system and the soil, which is not conducive to water absorption. As a result, this exacerbates the negative impact of the water deficit on crop yield and reduces WUE [22,23]. The improper application of N fertilizer will have a negative impact on NUE and the environment [24]. Therefore, appropriate water and N inputs are critical to optimizing crop yield and nutrient management.

Liu [25] argued that a reasonable level of water and fertilizer input is key to water–N coupling. By establishing a relationship model between water–nitrogen coupling, yield, and WUE, the study obtained an elliptical "water–nitrogen optimal coupling zone". Si [26] conducted water–nitrogen coupling experiments on winter wheat over two years and concluded that the interaction of water and N has a positive effect on maize. However, the outcome is not optimized with higher irrigation and N application; instead, there was an optimal ratio of water and N for high yield, WUE, and intrinsic WUE under drip irrigation in the North China Plain. Li [27] studied the effects of water–nitrogen coupling on cotton growth, WUE, NUE, yield, quality, and economic benefits under drip irrigation in northern Xinjiang through two years of field experiments to obtain a multi-objective optimization of water and N management. Furthermore, Wang [28] derived the optimal water and fertilizer application zone for cucumbers grown in a greenhouse through multi-objective optimization and comprehensively considered yield, quality, WUE, and NUE. In recent years, the identification of the optimal water–nitrogen coupling zone for multiple objectives such as high crop yield, WUE, and quality has gained serious attention. There are few reports on the effects of different combinations of water–nitrogen coupling on maize yield, efficient use of water and fertilizer, and the environment under the integrated planting model of drip irrigation with plastic film in different hydrological years. In this study, the West Liaohe Plain was used as the climatic and geographical background to perform field experiments on maize through an integrated planting model using drip irrigation with water and fertilizer under plastic film. This paper proposes the optimal range of water and N application considering multiple objectives (maize yield, efficient use of water and N, and environmental effects) under different hydrological years, thereby providing a theoretical basis for the promotion and application of the integrated planting technology of drip irrigation with water and fertilizer under plastic film.

2. Materials and Methods

2.1. Overview of the Study Area

The experiments were performed in Yaolinmaodu Town, Horqin Left Middle Banner, Tongliao City, Inner Mongolia. The site is located on the southeastern edge of the Greater Khingan Mountains and on the north bank of the West Liao River, which is the transition zone from the Songliao Plain to the Inner Mongolia Plateau. It has a continental monsoon climate in the northern temperate zone, with an average annual precipitation of 324 mm and evaporation of 2027 mm. According to the rainfall experienced by the region, it is a semi-arid area, with a multi-year average temperature of 5.6 °C and sunshine of 2884.8 h. The daily average temperature is above 5 °C for 188-d, the cumulative temperature above

10 °C is 3048 °C , and the frost-free period is 150–160-d. Rainfall experienced during the whole growth period from sowing to harvest in the experimental years of 2016, 2017, and 2018 were 272.03, 290.42, and 212.56 mm, indicating normal year, partially wet normal year, and dry year, respectively [29]. Soil total N, P, and K contents of the cultivated layer (0–60 cm) are 0.81, 0.77 and 31.48 g/kg, and the physical and chemical properties and basic fertility of the soil are shown in Table 1.

Table 1. Physical and chemical properties and fertility of soil in the experiment field.

Soil Layers (cm)	Soil Separates (%)			Bulk Density (g/cm^3)	Field Capacity (cm^3/cm^3)	Soil Organic Matter (g/g)	Soil Available N (mg/kg)
	Sand	Silt	Clay				
0–20	36.76	52.7	10.54	1.39	0.26	15	82
20–40	21.65	48.81	29.54	1.38	0.34	24.4	79
40–60	20.18	39.15	40.67	1.23	0.45	10.9	37
60–80	77.08	21.65	1.27	1.32	0.2	11.1	26
80–100	73.01	25.58	1.41	1.32	0.17	11.4	15

2.2. Field Experiments

The maize (*Zea mays* L.) cultivated was Nonghua 106, with a growing period of 129 d. The planting mode was drip irrigation under mulch, with one drip irrigation belt (φ 16 mm) irrigating two rows of maize with wide and narrow rows (35–85 cm) and biased sowing. The distance between adjacent drip irrigation belts was 1.2 m, with the planting unit shown in Figure 1, and the irrigation volume was recorded by a digital rotary-wing water meter. The dosage of phosphate and potassium fertilizers (60 kg/ha), pests, and weeds, and supporting measures of agricultural machinery and agronomy all adopted local conventional methods. The base fertilizer N was applied with integrated agricultural machinery, and the method of topdressing N fertilizer was characterized by fully dissolving urea in the fertilization tank first to obtain an aqueous solution of amide N, and then applying it to the root zone under the mulch with irrigation water through the water pressure difference. The topdressing N fertilizer was applied at the jointing, tasseling, and grouting stage. According to the upper and lower limits of the percentage of soil moisture content in the field water holding capacity, the amount of irrigation water in the experiment was set as low (W_1, 60 to 80% before jointing and 55% to 80% after jointing), medium (W_2, 65 to 80% before jointing and 60 to 85% after jointing), and high (W_3, 75 to 95% before jointing and 70 to 95% after jointing). According to the N application gradient, the amount of N was set as low (N_1, 224 kg/ha), moderate (N_2, 270 kg/ha), and high (N_3, 330 kg/ha), giving a total of nine treatments. The quantities of irrigation and fertilization are shown in Table 2. To prevent side-seepage of water and fertilizer adjacent to the treatment, four drip irrigation belts were set up for each experimental treatment with four planting units with protection rows on both sides. Both monitoring and sampling were performed in middle units. Each plot size was 20 $\times$ 4.8 m and each treatment was repeated three times for a total of 27 plots. Maize was planted on 29 April 2016, 27 April 2017, and 27 April 2018, the emergence time was 15 May 2016, 17 May 2017, 20 May 2018; 22 June 2016, 26 June 2017, and 27 June 2018 were the jointing stage; on 13 July 2016, 17 July 2017, 20 July 2018, the tasseling period began; 14 August 2016, 18 August 2017, 18 August 2018 ended the tasseling period; and the maize was harvested on 26 September 2016, 24 September 2017, and 25 September 2018, respectively. Weeding and deworming were performed once during each seedling stage. Intertillage was performed during the jointing stage and deworming was carried out once again during the grain-filling stage.

Table 2. Test scheme of water–nitrogen coupling effect on maize.

Treatment	Irrigation Frequency			Irrigation Amount (m^3/ ha)			Nitrogen Application Amount (kg/ha)				
	2016	2017	2018	2016	2017	2018	Seeding	Jointing	Tasseling	Grouting	Total
W_1N_1	7	8	7	1496.40	1523.19	1667.92	51	69	69	34.5	224
W_1N_2	7	8	7	1692.00	1585.14	1697.90	63	82.8	82.8	41.4	270
W_1N_3	7	8	7	1710.20	1498.19	1660.42	89	96.4	96.4	48.2	330
W_2N_1	9	8	7	1905.90	1829.71	2113.70	51	69	69	34.5	224
W_2N_2	9	8	7	1975.60	1833.33	2117.60	63	82.8	82.8	41.4	270
W_2N_3	9	8	7	1924.00	1836.96	2110.19	89	96.4	96.4	48.2	330
W_3N_1	11	8	7	2279.00	2224.64	2529.98	51	69	69	34.5	224
W_3N_2	11	8	7	2326.10	2201.09	2514.99	63	82.8	82.8	41.4	270
W_3N_3	11	8	7	2431.10	2195.65	2522.49	89	96.4	96.4	48.2	330

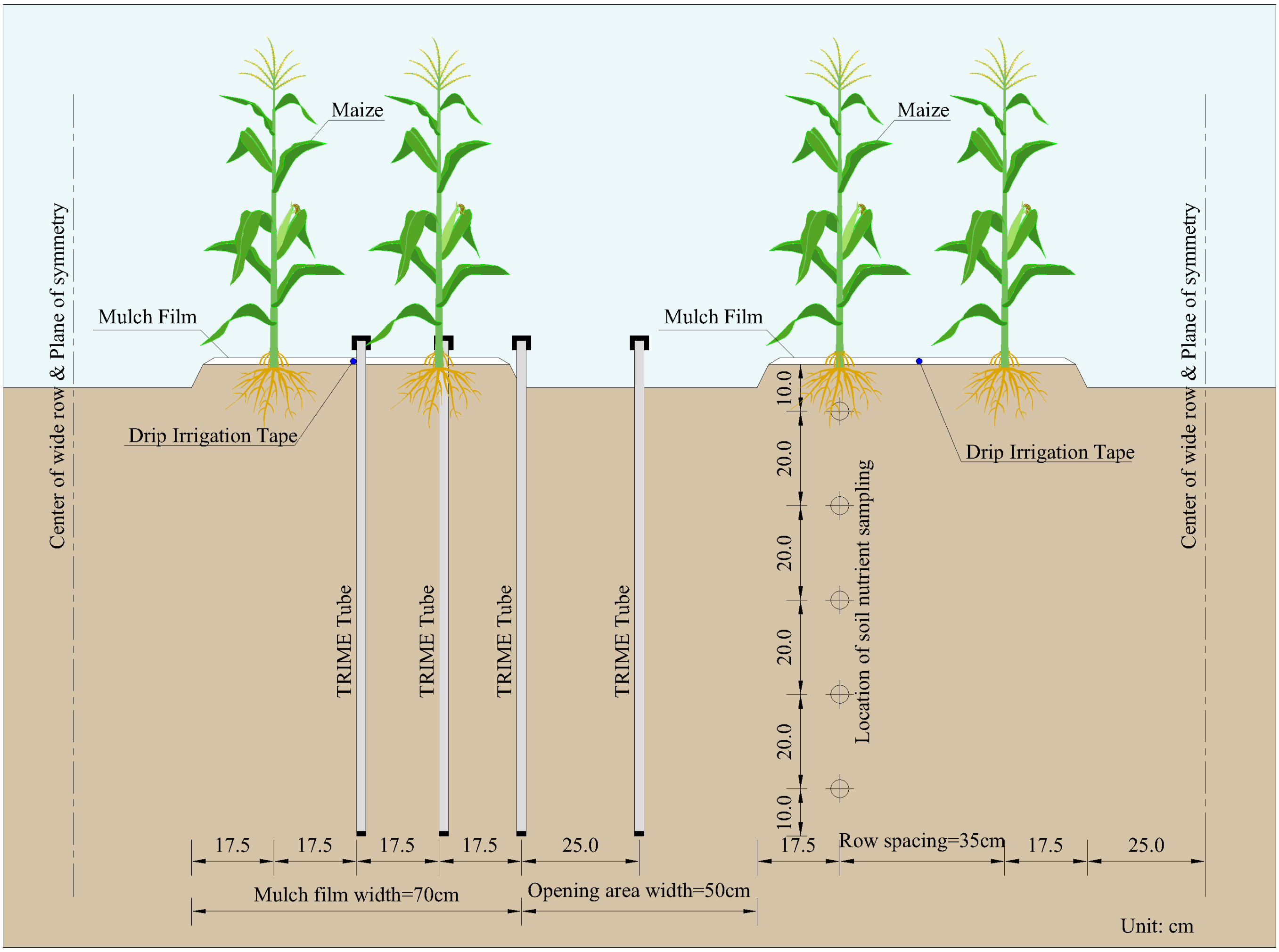

Figure 1. Schematic diagram of planting mode and sampling monitoring of soil moisture content.

2.3. Observational Parameters and Methods

The sum of the residual amount of alkali-hydrolyzable N in each soil layer is the total residual amount of alkali-hydrolyzable N in a certain depth of soil. The soil was sampled between maize plants parallel to the drip irrigation belt, with soil samples taken at a depth of 1 m before sowing and after harvest. Soil samples were also taken from a 20-cm layer. Soil alkali-hydrolyzable N was determined by the alkaline hydrolysis diffusion method, and the residual amount of alkali-hydrolyzable N in each soil layer (20 cm) was calculated according to the measured alkali-hydrolyzable N and soil bulk density of each soil layer as follows:

$$AN_i = C \cdot (D \cdot H \cdot A) \cdot 10^{-6} \tag{1}$$

where AN_i represents the cumulative amount of alkali-hydrolyzable N in each soil layer (kg/ha); C indicates the soil alkali-hydrolyzable N content of the soil layer (mg/kg); D indicates the soil bulk density of the soil layer (kg/m^3); H indicates the thickness of the soil layer (0.2 m); A indicates the area per hectare of land (100 × 100 m).

Three maize plants were harvested from each plot, the stalks and ear parts were cut longitudinally, and were then placed in an oven at 105 °C for 30 min. The temperature was adjusted to 80 °C and the plants were dried to a constant weight to measure the weight of above-ground dry matter and grain dry matter of a single plant. It was then converted into above-ground dry matter weight per hectare according to the planting density.

HI (harvest index) is the ratio of economic yield (adapt the formulation to the type of caryopsis fruit—indehiscent) to biological yield when the crops are harvested and is calculated as follows:

$$HI = \frac{dry\ weight\ of\ grains}{dry\ weight\ of\ aboveground\ biomass} \tag{2}$$

For yield measurement, three 10-m-long double rows of maize were taken in each plot parallel to the drip irrigation belt.

Monitoring of soil moisture content mainly relied on time-domain reflectometry (TDR) monitoring probes, which were used to penetrate into pre-installed buried monitoring pipes to collect data. The TDR was checked using the soil drilling and drying method, and Figure 1 shows the monitoring position of moisture content by the TDR method. Field climate data were measured by a weather station (HOBO U30 Onset, Onset Computer Corporation, Bourne, MA, USA) installed at the experimental site, and Figure 2 shows evapotranspiration and rainfall.

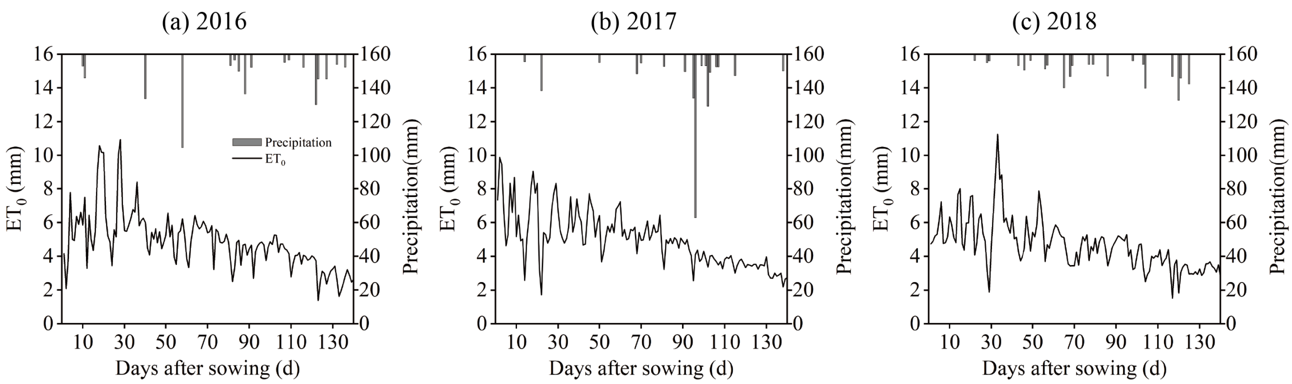

Figure 2. Precipitation and reference crop evapotranspiration (ET_0) during the maize growing seasons. (**a**) 2016. (**b**) 2017. (**c**) 2018.

For the calculation of water balance and WUE, groundwater recharge was ignored as the groundwater depth measured locally was below 6 m. As drip irrigation was used and the surface was flat, surface runoff and deep seepage were ignored, and the calculation was as follows:

$$ET_c = I + P + \Delta W \tag{3}$$

$$WUE = \frac{Y}{ET_c \cdot 10} \tag{4}$$

where ET_c is the total water consumption by evapotranspiration (mm), I and P are the depth of irrigation (mm) and effective rainfall (mm), ΔW denotes the difference in water storage (mm) during the calculation period of ET_c, WUE is the water-use efficiency (kg/m^3), and Y is the grain yield (kg/ha).

2.4. Statistical Analysis

Data processing and illustrations were performed using Adobe Illustrator 2020, Origin 2018, and Excel 2016. The combination of letters W, N, and numbers without special labels represents water and N treatments, and the rest are measurement units or statistical expressions.

3. Results

3.1. Soil Alkali-Hydrolyzable Nitrogen Residue after Harvest

Alkali-hydrolyzable N is that which can be directly absorbed by plants, also known as available N. Under each irrigation condition, the 3-year trend of the residual amount of alkali-hydrolyzable N in the 1-m soil layer increased with the increase in the rate of N application (Figure 3). In 2017, owing to the leaching of torrential rain during the grain-filling stage, the differences among the treatments were lower than those in 2016 and 2018. As the amount of N application increased from N_1 to N_2, the increase in residual amount of alkali-hydrolyzable N was less than the corresponding increase from N_2 to N_3.

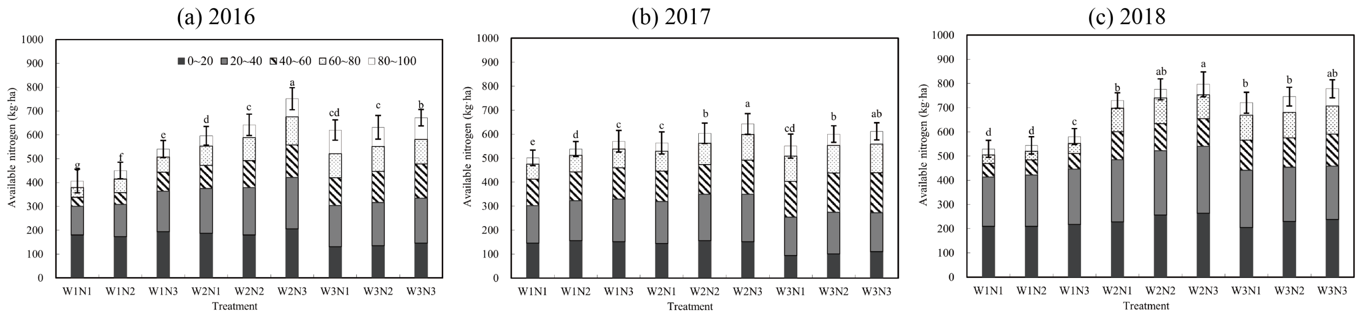

Figure 3. Soil alkaline hydrolysis nitrogen residue after harvest in 0–1 m soil layer. (**a**) 2016. (**b**) 2017. (**c**) 2018. Statistical comparisons were made by one-way ANOVA. Different characters mean significant differences found at $p < 0.05$.

As the volume of irrigation increased, the overall residual amount of alkali-hydrolyzable N first increased and then decreased, with no significant difference in the content of alkali-hydrolyzable N in the 0–40 cm surface soil of W_1 and W_2 treatments. With the increase in irrigation water, N gradually migrated downward, the content of alkali-hydrolyzed N increased in the 40–100 cm soil layer at the W_2 level. The conversion process of N fertilizer into alkali-hydrolyzable N at the W_1 level was inhibited, resulting in less available soil N. The amount of N that "escapes" from the surface soil to the atmospheric environment increased, resulting in low levels of accumulated crop dry matter and yield. Therefore, although the residual amount of alkali-hydrolyzable N in the soil under low water treatment was lower, the combination of low water at various N application rates caused a poor water–nitrogen coupling mode.

When the irrigation level was increased from W_2 to W_3, the residual amount in the 0–1 m soil layer decreased. The amount of soil N that migrated with water below 1 m increased, and the increased moisture carried soil N into the deeper soil layer. Under the drip irrigation planting mode with the film, the maize root system was mainly distributed in the 0–50 cm layer, and the root system in the soil layer below 1 m can be ignored. N leaching of W_3 leads to an increase in environmental risk. In summary, this study recommends W_2N_2 as the water–nitrogen coupling treatment with lower environmental risk of residual alkali-hydrolyzable N.

3.2. Aboveground Biomass and Harvest Index

Aboveground dry matter (Figure 4) showed an overall increasing trend with the increase in water and N input. However, the differences among the W_3N_3, W_3N_2, W_2N_3, and W_2N_2 treatments were not significant. This reflects that high water and N fertilizer supply can yield higher accumulated dry matter, but after water and N were increased to a certain level, dry matter did not increase significantly. The effect of water and N on dry matter was in line with the law of diminishing returns.

Under W_1, dry matter increased slightly and then decreased significantly with the increase of N fertilizer application. N fertilizer had little effect on dry matter accumulation, and excessive N application hindered dry matter accumulation in maize. Under W_2, dry matter increased significantly when the amount of N fertilizer increased from N_1 to N_2, but there was no significant difference between the dry matter of N_3 and N_2, and the contribution of the N fertilizer applied exceeding N_2 to the accumulation of dry matter was not obvious. Under W_3, dry matter accumulation gradually increased with the increase of N application rate, but the difference between N_2 and N_3 was not significant. Under N_1, dry matter accumulation increased significantly with the increase in irrigation level, while under N_2 and N_3 levels, when the irrigation level increased from W_1 to W_2, the dry matter increased significantly, but there was no significant difference in dry matter between W_3 and W_2 treatments. The effect of N fertilizer was different under different irrigation levels, and the effect of water was different under different fertilization levels, which indicated that there was an interaction between both factors of water and N.

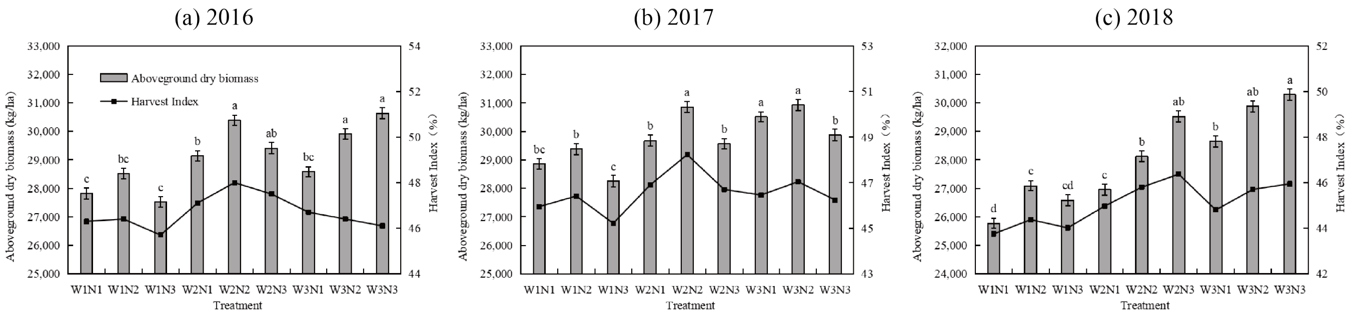

Figure 4. Dry weight of above-ground biomass and harvest index of corn after harvest. (**a**) 2016. (**b**) 2017. (**c**) 2018. Statistical comparisons were made by one-way ANOVA. Different characters mean significant differences found at $p < 0.05$.

HI can provide feedback on the distribution of photosynthetic products between reproductive organs (grains) and vegetative organs (such as leaves and straw). Under the same level of N application, the HI of W_1 and W_3 were lower than that of W_2 (Figure 4). Under W_1 conditions, maize was under water stress, resulting in a low total dry matter accumulation and grain yield. When the irrigation level was increased to W_2, the HI increased evidently but after further increasing to W_3, the HI decreased.

Under the same level of irrigation as during the normal year, as the amount of N applied increased from N_1 to N_2, the HI slightly increased. A further increase to N_3 caused the HI to decrease, and the excessive N application contributed to more vegetative organs. However, in 2018 (dry year), the HI gradually increased with the increase in fertilization. Under the conditions of this experiment, W_2N_2 can obtain a higher HI during the normal year while during the dry year, W_2N_3 can better coordinate the distribution of photosynthetic products.

3.3. Yield, Total Water Consumption by Evapotranspiration, and Water-Use Efficiency

For maize yield under different water and N treatments from 2016 to 2018 (Table 3), the yield increased with the increase of water and N input. In 2016 and 2018, the yield of W_3N_3 was the highest, and there was no significant difference with W_2N_3. In 2017, W_2N_2 had the highest yield, followed by W_3N_2. Figure 5a shows that under the three N application levels, the yield gradually increased with the increase in irrigation. The average yield of W_3 increased by 611.09 kg/ha compared with W_2, and the average yield of W_2 increased by 1068.07 kg/ha compared with W_1. The yield-increasing effect of W_3 was lesser than that of W_2. As shown in Figure 5, in 2016 and 2018, under W_1, the yield increased first, then decreased with the increase in the rate of N application. However, the overall level of yield is low, and the contribution of N fertilizer to yield cannot be effectively manifested. Under W_2 and W_3, the average yield of N_3 increased by 565.79 kg/ha compared to N_2, and the average yield of N_2 increased by 466.85 kg/ha compared to N_1, with the yield gradually increasing as N increases. In 2017, under the three irrigation conditions, the N application rate of N_2 had the highest yield, and water and N contributed to decreasing yield with increasing application.

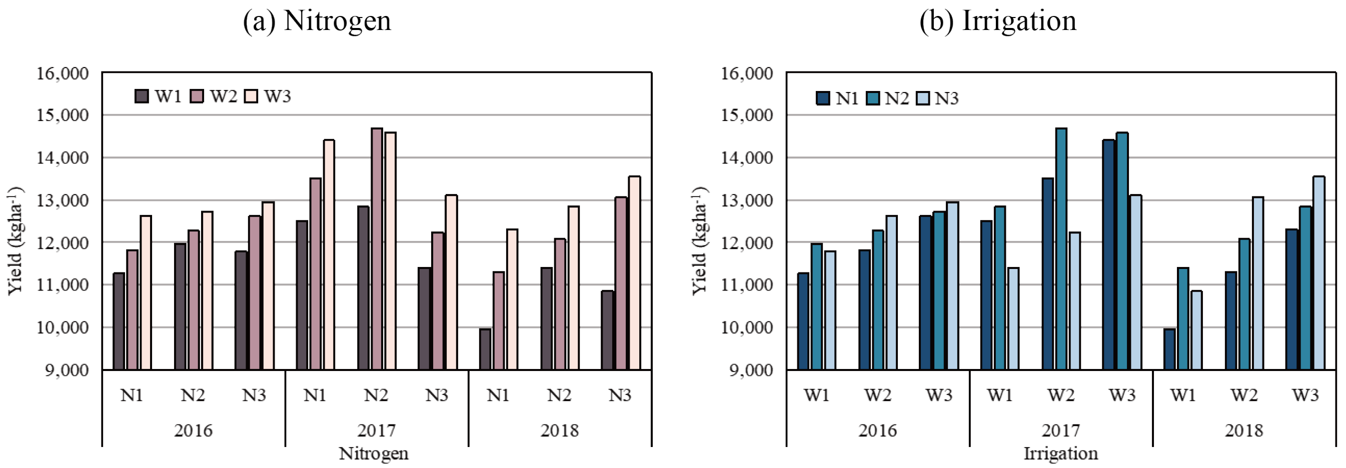

Figure 5. Maize yield under different water and nitrogen treatments. (**a**) Effect of different nitrogen inputs on yield. (**b**) Effect of different irrigation on yield.

Table 3. Effects of different water and nitrogen treatments on maize yield and WUE.

Treatment		Yield (kg/ha)			ET_c (mm)			WUE (kg/m^3)		
		2016	2017	2018	2016	2017	2018	2016	2017	2018
W_1N_1		11,266.95 c	12,499.47 c	9952.35 e	397.12 c	457.28 b	366.37 c	2.84 b	2.73 c	2.72 c
W_1N_2		11,964.75 bc	12,836.05 b	11,402.4 d	402.33 c	454.24 b	368.77 c	2.98 ab	2.83 bc	3.09 ab
W_1N_3		11,788.8 bc	11,408.49 d	10,846.95 d	402.91 c	447.28 b	365.72 c	2.93 ab	2.55 d	2.97 b
W_2N_1		11,823 bc	13,510.05 b	11,294.1 d	411.54 b	467.57 b	405.47 b	2.87 ab	2.89 b	2.79 c
W_2N_2		12,271.2 b	14,687.4 a	12,075.6 c	410.26 b	467.86 b	405.78 b	2.99 a	3.14 a	2.98 b
W_2N_3		12,618 ab	12,236.7 c	13,062.75 ab	425.38 b	468.15 b	405.18 b	2.97 ab	2.61 cd	3.22 a
W_3N_1		12,619.05 ab	14,401.65 a	12,308.55 bc	453.59 a	498.98 a	429.46 a	2.78 b	2.89 b	2.87 bc
W_3N_2		12,726.95 a	14,580.3 a	12,838.35 b	456.64 a	497.1 a	428.25 a	2.79 b	2.93 b	3 ab
W_3N_3		12,950.7 a	13,109.25 b	13,543.8 a	461.25 a	496.56 a	429.84 a	2.81 b	2.64 cd	3.16 a
F value	W	40.67 **	87.14 **	150.58 **	72.49 **	39.63 **	76.32 **	5.43 *	6.65 **	NS
	N	11.23 **	97.13 **	55.78 **	NS	NS	NS	NS	28.47 **	22.01 *
	W × N	NS	4.16 *	7.6 **	NS	NS	NS	NS	NS	NS

Different lowercase letters in the same column indicate significance ($p < 0.05$), while the same letter indicates non-significance; *, ** F value means significant at the $p < 0.05$ and $p < 0.01$ levels, respectively. NS means non-significant at the $p > 0.05$ level. Data shown in N treatment is average over the three irrigation amounts.

The WUE ranges of different water and N treatments from 2016 to 2018 were 2.79–2.99, 2.61–3.14, and 2.72–3.22 kg/m^3, respectively. In the normal year (2016), the WUE of W_2N_2 treatment was the highest, and in the dry year (2018), the WUE of W_2N_3 treatment was the highest. Under the same N application, W_2 yielded the highest WUE, while under the same irrigation level in the normal year, N_2 yielded the highest WUE. In the dry year, under W_2 and W_3, WUE continued to increase as more N was applied, but there was no significant difference between medium and high N treatments. It can be observed that the increase in application of water and N can increase WUE, but a certain amount of excessive application will lead to a decrease or no significant increase in WUE.

3.4. Confidence Interval of Water and Nitrogen Based on Frequency Analysis

Using water and N-production test data, the regression equations of the amount of irrigation and N on maize yield were obtained as follows:

For 2016:

$$Y = 5066.1194 + 4.9571W + 3.3716N + 0.0014WN - 0.001W^2 - 0.0051N^2, R^2 = 0.952 \quad (5)$$

For 2017:

$$Y = -40828.4402 + 23.3068W + 230.2579N - 0.013WN - 0.0045W^2 - 0.3886N^2, R^2 = 0.927 \quad (6)$$

For 2018:

$$Y = -10248.1296 + 8.6703W + 65.6157N + 0.0046WN - 0.0018W^2 - 0.1133N^2, R^2 = 0.973 \quad (7)$$

Plotting the equations (Figure 6), the "absolutely" high yields in 2016, 2017, and 2018 occurred in high-water and high-N coupled areas, and in medium-water-medium-N, and high-water-medium-N areas, respectively. Figure 6 shows that under the highest input of water and N, the slope of the curved surface is relatively gentle or declines, indicating a very low ability of water and N input to increase production and weakening their interaction effect. Furthermore, under very high irrigation level, the interaction effect weakened and disappeared with the decrease of N application level. Under the medium to low N application level, the yield increased gradually with the increase in irrigation level, but the increase of N application rate had almost no effect on the yield. When both water and N were at the lowest value, although the yield increased rapidly, the influence process was very short, and the eventual yield was very low.

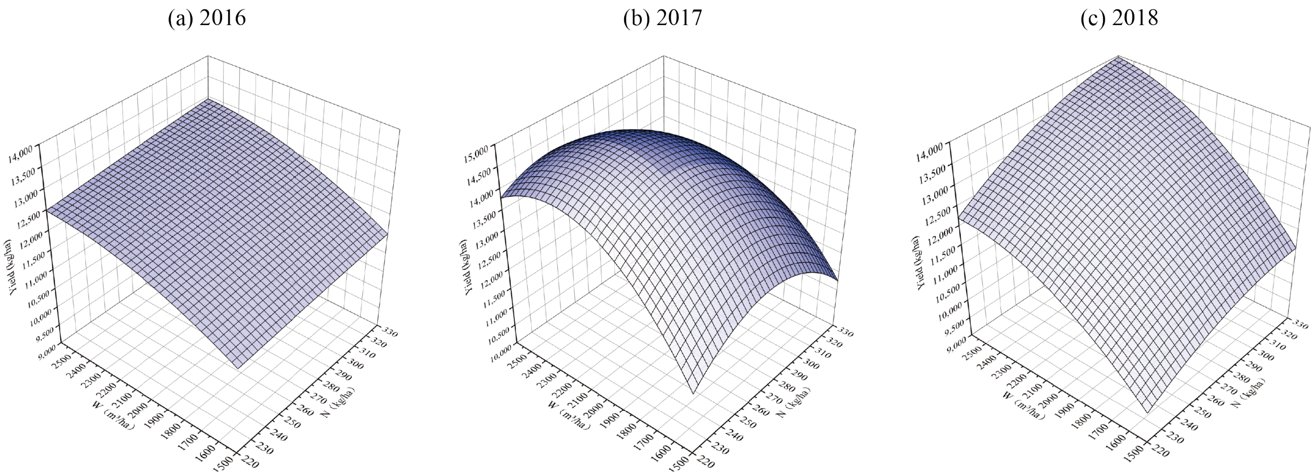

Figure 6. The effect of coupling of water and nitrogen on the yield of Maize. (**a**) 2016. (**b**) 2017. (**c**) 2018.

The units of amount of irrigation and N applied were different, so the deviations in water and N data were first standardized and linearly transformed to make the dimension uniform. The different values of the two factors of water and N were within the interval [0, 1], and according to the fitting of multiple linear regressions, the following regression equations of the amount of irrigation and N on maize yield were obtained:

For 2016:

$$Y = 11240.9043 + 2161.8605W + 338.5942N + 138.51WN - 836.3155W^2 - 56.9139N^2, R^2 = 0.952 \quad (8)$$

For 2017:

$$Y = 11715.9889 + 5034.4242W + 3885.2872N - 1001.9137WN - 2370.9727W^2 - 4377.7643N^2, R^2 = 0.927 \quad (9)$$

For 2018:

$$Y = 10028.8820 + 3307.9944W + 2401.8735N + 423.2892WN - 1269.2875W^2 - 1295.2535N^2, R^2 = 0.973 \quad (10)$$

In the [0, 1] interval, the step length of water and N was divided into seven levels (0.00, 0.17, 0.33, 0.50, 0.67, 0.83, and 1.00), forming a total of 49 sets. In 2016 and 2018, there were 32 sets of schemes that exceeded the average yield of the test (122,203.27 and 11,924.98 kg/ha), accounting for 65.31% of all schemes. In 2017 there were 30 schemes that exceeded the average yield of this experiment by 13,252.17 kg/ha, accounting for 61.22% of all schemes. Frequency analysis of different levels of irrigation and N application (Table 4) was performed, obtaining a probability of 95% for obtaining more than average maize yield with irrigation amount and N application of 2103.50–2253.31 m^3/ha and 268.34–295.39 kg/ha, 1897.17–2036.09 m^3/ha and 256.08–277.41 kg/ha, and 2198.62–2348.29 m^3/ha and 271.64–296.49 kg/ha, in 2016, 2017, and 2018, respectively.

Table 4. Factor value of the frequency distribution and proportion plan with grain yield surpass average.

Horizontal Code	2016				2017				2018			
	W(m^3/ha)		N(kg/ha)		W(m^3/ha)		N(kg/ha)		W(m^3/ha)		N(kg/ha)	
	Times	Freq	Times	Freq	Times	Freq	Times	Freq	Times	Freq	Times	Freq
0.00	0	0.00	3	10.34	0	0.00	5	16.13	0	0.00	2	6.67
0.17	0	0.00	4	13.79	2	6.45	5	16.13	0	0.00	4	13.33
0.33	2	6.90	4	13.79	5	16.13	6	19.35	4	13.33	4	13.33
0.50	6	20.69	4	13.79	6	19.35	6	19.35	6	20.00	5	16.67
0.67	7	24.14	4	13.79	6	19.35	5	16.13	6	20.00	5	16.67
0.83	7	24.14	5	17.24	6	19.35	4	12.90	7	23.33	5	16.67
1.00	7	24.14	5	17.24	6	19.35	0	0.00	7	23.33	5	16.67
Total times	29		29		31		31		30		30	
weighted mean	0.7297		0.5459		0.6448		0.4032		0.7050		0.5667	
95% confidence	0.6495–0.8098		0.4183–0.6735		0.5492–0.7405		0.3026–0.5039		0.6189–0.7911		0.4495–0.6839	
Preferred interval	2103.50–2253.31		268.34–295.39		1897.17–2036.09		256.08–277.41		2198.62–2348.29		271.64–296.49	

3.5. Multi-Objective Optimization of Water–Nitrogen Coupling Zones

W_2N_2 treatment has the lowest environmental risk in this study. In 2016 and 2017, W_2N_2 yielded a higher HI and WUE, while in 2018, W_2N_3 showed better distribution of photosynthetic products. In 2016 and 2018, W_3N_3 achieved the highest yield and the difference was not significant, while in 2017, W_2N_2 achieved the highest yield, respectively. The 95% confidence intervals for irrigation and N values that produced higher than average yield were 2103.50–2253.31 m^3/ha and 268.34–295.39 kg/ha, 1897.17–2036.09 m^3/ha and 256.08–277.41 kg/ha, and 2198.62–2348.29 m^3/ha and 271.64–296.49 kg/ha for 2016, 2017, and 2018, respectively. Using the scatter diagram to express different water–nitrogen coupling zones, an elliptical area was obtained (Figure 7). The center point was obtained by weighting the scatter points, and 20% of the difference between the extreme values was taken as the degree of deviation. The obtained rectangular area is the optimal water–nitrogen coupling range that considers WUE, high yield, and environmental effects of N residue. Irrigation and N application were 2086.65–2268.85 m^3/ha and 271.09–295.76 kg/ha, 1897.17–2036.09 m^3/ha and 256.08–277.41 kg/ha, and 2198.62–2348.29 m^3/ha and 271.64–296.49 kg/ha for 2016, 2017, and 2018, respectively.

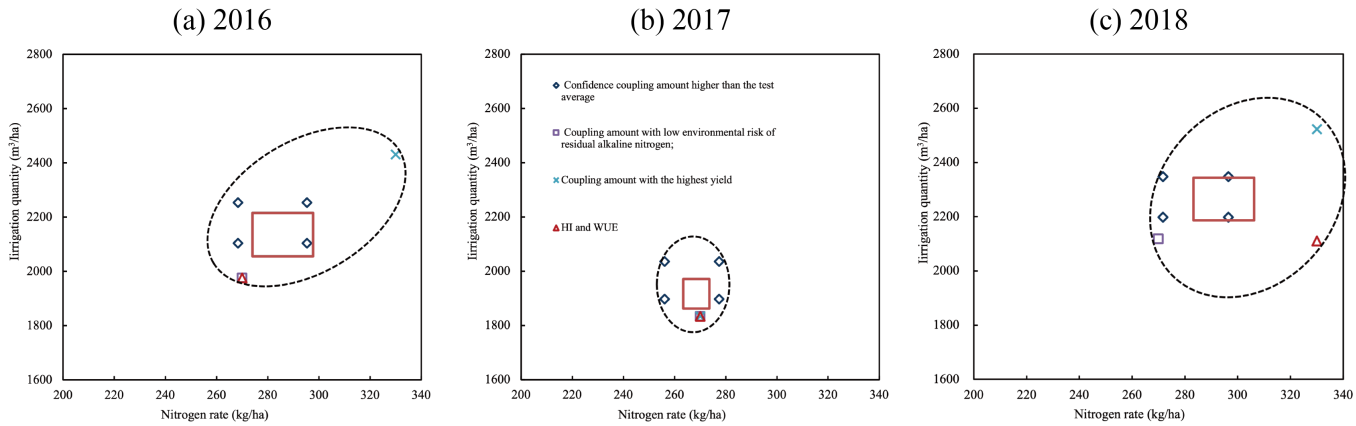

Figure 7. Graphic expression of water and nitrogen coupling area. (**a**) 2016. (**b**) 2017. (**c**) 2018. Note: rhombus represents confidence coupling amount higher than the test average; square represents coupling amount with low environmental risk of residual alkaline nitrogen; triangle represents harvest index; cross represents WUE.

4. Discussion

This study shows that with an increase in irrigation and N application rate, the residual amount of alkali-hydrolyzable N increased slowly within a certain range. Upon exceeding a certain amount, residual N increased rapidly, and more N entered the soil environment. W_2N_2 can maintain nutrients in the root zone, realize the optimal utilization of water and N by crops, and reduce potential environmental risks, which is consistent with results of recent research [13,14,24]. At an appropriate level of water–nitrogen coupling effect, higher dry matter can be obtained, with better coordination between the amount of water and fertilizer, and this finding is supported by some studies [17,18,26]. Water deficit and excess are not conducive to the transfer of plant vegetative growth to reproductive growth [30]. Increasing the amount of irrigation and fertilization after reaching the optimal amount of water and N application will reduce their rate of contribution to yield [19,20,31]. In addition, after reaching an appropriate water level and increasing the irrigation beyond the level, the contribution of irrigation to the vegetative organs is higher than that to the grains. Similarly, excessive N application contributed more to vegetative organs, with the ratio of grain yield to above=ground biomass decreasing, thereby decreasing HI.

Through experimental research on maize in Northeast China, Sun [32] found that irrigation and fertilization have a synergistic effect on the grain yield of maize, where N fertilization has the most significant effect, followed by irrigation. However, this study showed that compared with increasing N application rate, increasing irrigation rate had a higher impact on yield, probably due to the adoption of the drip irrigation under plastic film, a water-saving irrigation method, which improved the WUE [12,33]. Moreover, the impact of irrigation on yield in the dry year was significantly higher than that in the normal year in this experiment. Zamora-Re [34] studied the effects of different irrigation strategies on maize yield and concluded that in years with low rainfall, the impact of irrigation on yield is more pronounced. It is evident that the similarities and differences between the conclusions of this experiment and those of previous studies are related to the differences in the applied irrigation methods and hydrological year patterns.

This study shows that, in 2017, under the same irrigation level, the yield of the N_3 treatment was the lowest, which is related to the heavy rainfall and uneven temporal and spatial distribution in that year, which reduced the impact of irrigation on yield. Furthermore, maize with N_3 treatment consumed a high amount of nutrients in the early growth stage for vegetative growth, and the heavy rain in the later period caused the leaching of topdressing N during the grain-filling stage, resulting in a significant reduction in yield. For the other years, the higher responsiveness of water–nitrogen coupling to yield occurred in the areas with medium and high irrigation and N levels, and the highest yield occurred in the W_3N_3 treatment, but there was no significant difference between the W_2N_3 and W_3N_2 treatments. It can be observed that although a high amount of water and N can be used to obtain absolute high yields, the capacity to increase production is too low [26,27]. Some researchers studied wheat [26], cotton [27], cucumber [28], rapeseed [35], and tomato [36] arrived at similar conclusions. In the normal year, W_2N_2 treatment yielded the highest WUE, while in the dry year, W_2N_3 treatment had the highest WUE, instead of W_3N_3 treatment which had the highest yield. The highest WUE occurred under W_2 irrigation conditions. Therefore, an appropriate irrigation amount can obtain a higher WUE, and the amount of N application can be adjusted according to the change in the hydrological year. Therefore, it is reasonable to recommend water–nitrogen coupling zones according to different hydrological years.

5. Conclusions

Water and nitrogen are limiting factors for high yields in maize under drip irrigation with plastic film. Irrigation rate had higher impact on yield than nitrogen application due to drip irrigation under plastic film. Moderate irrigation and nitrogen treatment have high nitrogen-use efficiency with no negative environmental impact.

The multi-objective optimal water-nitrogen coupling area integrating corn yield, harvest index, WUE, and soil environmental effects, and irrigation in normal water years were 2086–2268 m^3/ha, nitrogen application was 271–295 kg/ha, and irrigation in flat water and partial abundance years was 1897–2036 m^3/ha; nitrogen application was 256–277 kg/ha, irrigation in dry years was 2198–2348 m^3/ha, and nitrogen application was 271–296 kg/ha.

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Abbreviations

The following abbreviations are used in this manuscript:

HI	harvest index
NUE	nitrogen-use efficiency
N_1	low nitrogen
N_2	medium nitrogen
N_3	high nitrogen
TDR	time-domain reflectometry
WUE	water-use efficiency
W_1	low water
W_2	medium water
W_3	high water

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