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Coupling Regulation of Root-Zone Soil Water and Fertilizer for Summer Maize with Drip Irrigation

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Abstract: Water scarcity is the most significant constraint for grain production in the North China Plain (NCP). Water-saving irrigation technology is a valuable tool for addressing the NCP's water scarcity. Drip irrigation is considered as one of the most water-saving irrigation technologies. However, drip irrigation is not now commonly used in NCP field grain crops (particularly maize). Fertilizers are accurately administered to summer-maize root soil by recycling the drip-irrigation system of winter wheat. To increase the water and fertilizer-use efficiency of summer-maize fields, the coupling body of root-zone soil water and fertilizer for summer maize was thoroughly adjusted using a combination of emitter flow rate, irrigation quota, and fertilizer frequency. In this experiment, a split plot design with randomized blocks was employed. The primary plot was emitter flow rate (0.8 and 2.7 L/h), the subplot was irrigation water quota (120 and 150 m^3/hm^2, 1 hm^2 = 10,000 m^2), and the final plot was fertigation frequency (7, 14, and 28 days). The grain yield, water-use efficiency and fertilizer-use efficiency of summer maize were measured in this study. The results showed that grain yield and water-use efficiency (WUE) of the small-flow drip-irrigation treatment (emitter flow rate < 1 L/h) were significantly higher than the large-flow treatment (emitter flow rate > 1 L/h); the rates of grain yield increase were 8.2% and 13.3% and WUE were 3.5% and 8.0%, respectively. A higher irrigation quota can increase the yield of summer maize. The maximum yield and WUE were observed at the fertigation frequency of 7 days under small-flow drip-irrigation conditions. All comparisons and analyses showed that small-flow drip irrigation combined with high fertigation frequency could obtain higher yield and WUE in the NCP. This study proposes a new way to improve water and fertilizer utilization efficiency to achieve the goal of "increasing grain yield by fertilizing" and "adjusting the quality by fertilizing", from the perspective of winter wheat–summer maize no-tillage annual rotation planting.

Keywords: drip irrigation; fertigation frequency; small-flow rate; root zone; coupling body regulation; summer maize

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1. Introduction

The North China Plain (NCP) is China's principal grain-producing region. Cultivated land in the NCP accounts for 18.3% of total cultivated land area in China, while grain yield in the NCP accounts for 25% of total grain production in China [1,2], which is critical for food security. However, "underground funnel" and other secondary disasters caused by long-term overexploitation of groundwater in the NCP seriously threaten the agricultural development potential of this region. Furthermore, the water shortage of the NCP is becoming more and more serious, which has greatly restricted agricultural development [3,4]. In response, the Chinese government implemented a "water-saving mining" strategy to relieve water pressure, and agriculture, the traditional main area of water use [5], became a key field of "water-saving mining."

At present, most researchers believe that "water-saving mining" in the agriculture field should achieve effective water use through a variety of measures, such as adjusting crop structures and planting patterns, significantly increasing WUE by 5–10% [6]; implementing deficit irrigation, reducing the soil water deficit to 150 cm [7]; as well as strengthening the use of unconventional water resources, which could save clean water and decrease ET by over 30% [8,9]. However, the most important goal is to enhance agricultural WUE, particularly irrigation water-use efficiency [10], in the context of a winter-wheat and summer-maize rotation system in the NCP [11]. Increasing grain yield is one method for improving WUE that has been demonstrated to be totally practical [12].

Drip irrigation is regarded as one of the most efficient irrigation technologies in terms of water, energy, and fertilizer use [13,14]. Drip irrigation transports water and fertilizer to crops directly [15,16] and provides a suitable soil environment for crops. However, research on the application of drip irrigation in summer maize in North China is currently limited due to the traditional conception that summer maize does not require watering in North China [17,18]. We might, however, directly employ existing winter-wheat drip-irrigation systems on fields for summer-maize fertilization using conservation tillage techniques to control the coupling morphology of water and fertilizer in the summer-maize root area and boost summer-maize grain output. Previous studies showed that drip flow rate, irrigation quota and fertigation frequency all had a substantial impact on soil moisture, ET, yield, and WUE. For instance, Zhang et al. [19] found that irrigation frequency had significant effects on maize yield and WUE, and that short irrigation intervals could help maintain a favorable soil-moisture environment in the upper-60 cm soil layer, reduce soil-water evaporation and evapotranspiration, and produce the highest yield and WUE. Si et al. [20] studied the effects of nitrogen application rate and irrigation regime on growth, yield, and the water-nitrogen-use efficiency of drip-irrigated winter wheat in the North China Plain, and found that increasing irrigation and nitrogen application rates notably improved actual evapotranspiration, leaf area index, aboveground biomass, grain yield, and water-use efficiency (WUE). Meanwhile, Zain et al. [21] indicated that irrigation scheduling and nitrogen fertilization mode had coupled effects on growth, yield and WUE in drip-irrigated winter wheat.

Above all, 2-year field experiments were conducted at the Beijing Tongzhou experimental station of China Agricultural University to regulate and control the coupling morphology of water and fertilizer in the summer-maize root area, i.e., utilizing joint changes of emitter flow rate, irrigation amount, and irrigation–fertigation frequency. This paper assumes that drip irrigation can adjust the water and fertilizer supply through emitter flow rate and fertigation frequency to increase crop yield. The paper analyzed the effects of different regulation methods (emitter flow rate: 0.8 L/h and 2.7 L/h; irrigation water quota: 120 m^3/hm^2 and 150 m^3/hm^2; and fertigation frequency: 7 d, 14 d, and 28 d) on the crop yield of soil-water consumption, clarified the applicable regulation method, provided technical support for stabilizing high yield, and enhanced the WUE of summer maize in the NCP.

2. Materials and Methods

2.1. Experimental Site

The experiment was carried out at Tongzhou Experimental Station of China Agricultural University (39°42′ N, 116°41′ E) in the NCP, during the 2016 and 2017 summer-maize growing seasons. The experiment station is located in a temperate continental semi-humid monsoon climate zone with simultaneous rain and heat. During the summer-maize growing seasons of 2016 and 2017, total precipitation quantities were 343.5 and 467.5 mm, respectively (Figure 1). Precipitation was mostly concentrated in July during the summer-maize growing season in 2016; the precipitation quantity in July was 194.5 mm, accounting for 56.6% of the whole summer-maize growing season. During the 2017 summer-maize growing season, the precipitation distribution was primarily concentrated in July and August, reaching 323.5 mm and accounting for 69.2% of the whole summer-maize growing season. The overall number of rainfall events throughout the summer-maize growing seasons in 2016 and 2017 was 22 and 26, respectively, with highest rainfalls of 96 and 73.5 mm. The automated meteorological station at the experimental station produced the precipitation data. During the research, there was no groundwater recharge, water loss, or soil erosion. The soil texture is loam, and Table 1 shows certain physicochemical parameters. The capacity of the field water is 21%.

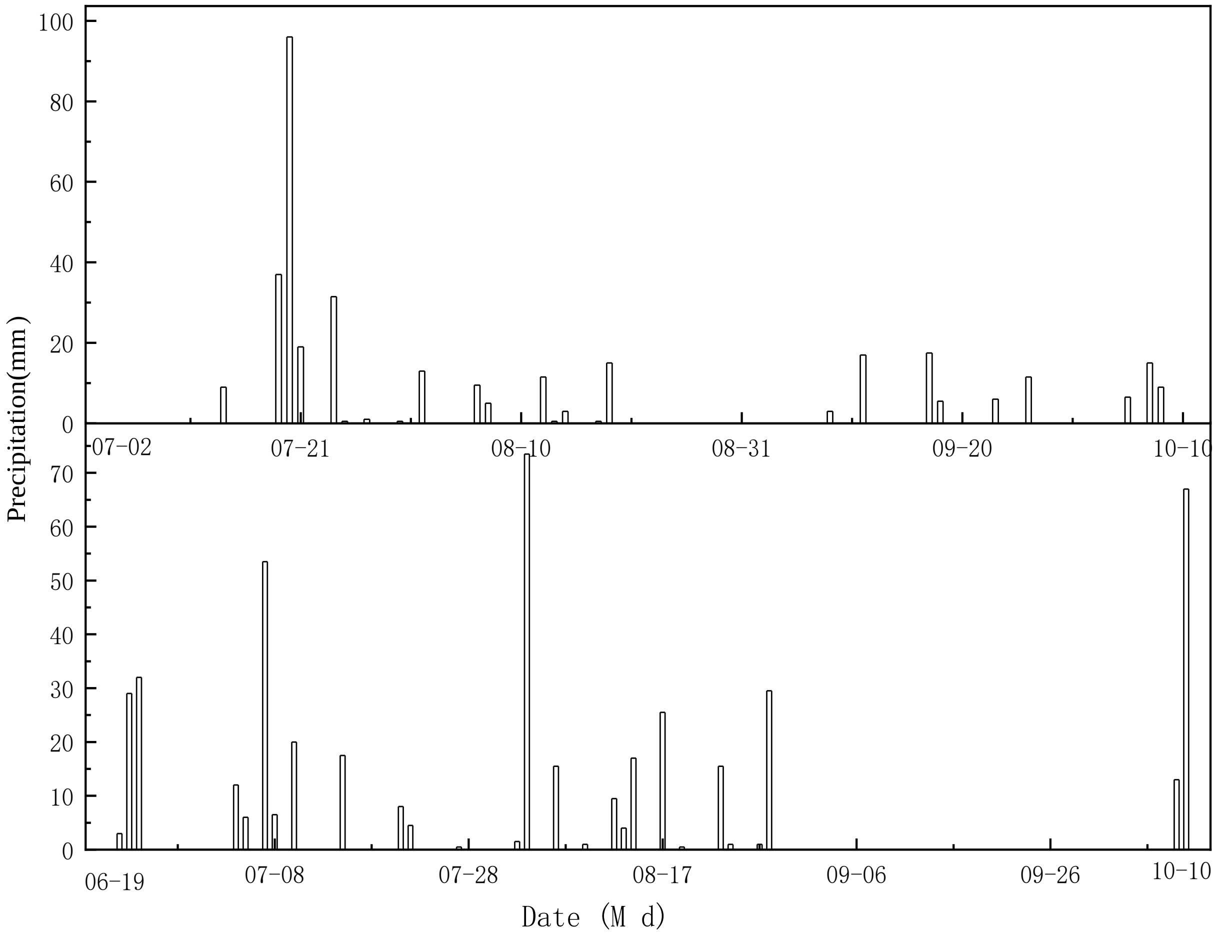

Figure 1. Precipitation during the 2016 and 2017 summer-maize growing seasons.

Table 1. Physicochemical properties of soil.

Soil Layer	Rapidly Available			Total			Organic Matter	pH
	Nitrogen	Phosphorus	Potassium	Nitrogen	Phosphorus	Potassium		
cm	mg/kg	mg/kg	mg/kg	g/kg	mg/kg	g/kg	g/kg	
0–10	634.18	32.0	168.90	2.26	639.83	11.01	296.7	7.24
20–40	591.55	33.9	187.77	2.02	661.06	12.21	282.7	7.43
20–40	372.02	26.2	216.30	1.62	359.31	20.94	256.0	7.64
40–60	417.50	25.6	204.53	1.61	374.24	12.94	257.3	7.58
60–80	714.14	24.8	205.60	2.51	371.21	13.30	306.0	7.53

2.2. Experimental Design

The experiment adopted a three-factor split-plot experiment design in randomized blocks with five replications (Table 2): the primary plot was emitter flow rate, including 0.8 L/h (code: S) and 2.7 L/h (code: H); the subplot was irrigation water quota, including

120 (code: a) and 150 (code: b) m^3/hm^2; and the final plot was fertigation frequency, including 7 d (code: 1), 14 d (code: 2), and 28 d (code: 3). All the codes of the treatments are Sa1, Sa2, Sa3, Sb1, Sb2, Sb3, Ha1, Ha2, Ha3, Hb1, Hb2, and Hb3. The summer-maize variety was "Zhengdan 958." The 2016 experiment was carried out in the north district, and the experimental field was 90 m long and 5 m wide; and the 2017 experiment was conducted in the south district, and the experimental field was 40 m long and 5 m wide. The summer maize was planted in two rows with widths of 70 cm and 30 cm (Figure 2), with a plant spacing of 25 cm. The drip-irrigation belt's emitter spacing was 30 cm. The crops were seeded on 2 July 2016 and 19 June 2017. Compound fertilizer (N-P-K 15-15-15, 375 kg/hm^2) and potassium sulphate (K-S 50–18, 360 kg/hm^2) were used during sowing, followed by drip irrigation with urea (N 46%, 375 kg/hm^2). A proportional fertilizing pump was used as fertilizing equipment.

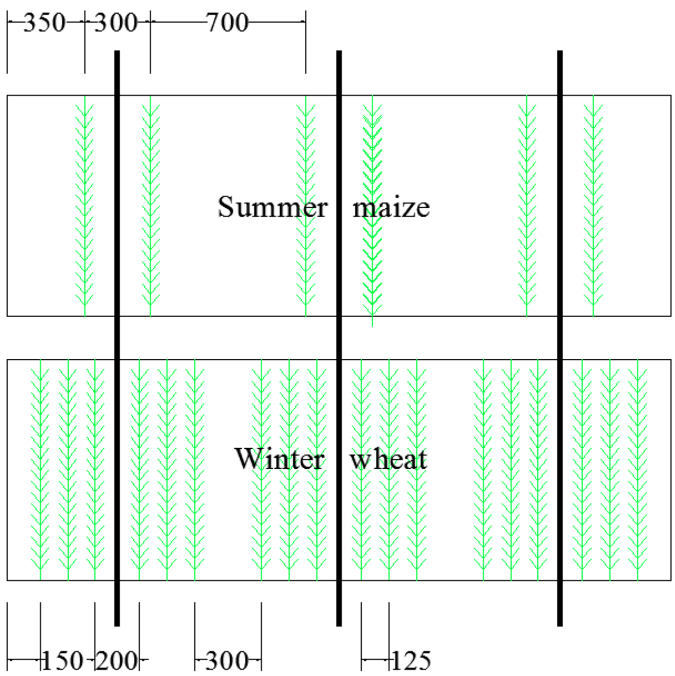

Figure 2. The planting pattern of summer maize and winter wheat (cm). Note(s): The vertical black lines represent drip irrigation belts.

Table 2. Experiment treatments.

First-Degree Regulating	Second-Degree Regulating	Third-Degree Regulating	Treatment Code
Emitter Discharge Rate (L/h^2)	Irrigating Water Quota (m^3/hm^2)	Fertilization Frequency (Day)	
0.8	120	7	Sa1
		14	Sa2
		28	Sa3
	150	7	Sb1
		14	Sb2
		28	Sb3
2.7	120	7	Ha1
		14	Ha2
		28	Ha3
	150	7	Hb1
		14	Hb2
		28	Hb3

2.3. Volumetric Soil Water Content

The volumetric soil water content of summer maize was determined using time domain reflectometry (TRIME-PICO-IPH TDR, IMKO, Germany) at 10 cm intervals down to 100 cm in the planting zone. The oven-drying technique was used to determine the water content of the top-20 cm soil layer. Soil moisture was monitored on the day of planting and harvesting, and at about 15-day intervals thereafter. Additional measurements were taken after the precipitation and irrigation. The "Trime tube" was buried in the midst of each plot between two rows of crops, at the beginning, middle, and end.

2.4. Evapotranspiration

As the groundwater table was below 6 m, the influence of groundwater on summer-maize cropland evapotranspiration was insignificant. The surface runoff produced by the experiment was ignored. The water-balance equation in farmland is [22]:

$$ET = \Delta S + P + I \quad (1)$$

where ET (mm) is evapotranspiration, I (mm) is the amount of irrigation water, P is effective precipitation during the growth period (m^3/hm^2), and ΔS is the change in amount of soil moisture content.

$$\Delta S = \Sigma(\Delta\theta_i \times Z_i) \quad (2)$$

where i is soil layer, $\Delta\theta_i$ (mm) is the volume of water at a certain soil layer, and Z_i (mm) is soil thickness.

2.5. Aboveground Dry Matter Weight

In the middle plots, typical summer-maize plants were picked at the jointing, tasseling-silking, and maturity phases; stems, leaves, and spikes were removed and placed in an envelope. The specimens were dried for 30 min at 105 °C, then decreased to 85° until they reached a steady weight, before being weighed on an electronic scale with an accuracy of 0.01 g.

2.6. Grain Yield and Yield Composition

When the summer maize reached the maturity stage, six spikes were chosen at random in each trial plot to determine the number of ear rows per spike, kernels per row, 1000-grain weight, and grain yield.

2.7. Water-Use Efficiency, Irrigation Water-Use Efficiency, and Precipitation Water-Use Efficiency

Water-use efficiency (WUE) was defined as follows [23]:

$$WUE_Y = Y/ET \quad (3)$$

where Y is summer-maize grain yield (kg/hm^2) and ET is the evapotranspiration in the whole summer-maize growing season derived from Equation (1).

Irrigation water-use efficiency (WUE_I) was defined as follows:

$$WUE_I = Y/I \quad (4)$$

where Y is summer-maize grain yield (kg/hm^2) and I is irrigation amount in the whole summer-maize growing season (m^3/hm^2).

Precipitation water-use efficiency (WUE_P) was defined as follows:

$$WUE_P = Y/P \quad (5)$$

where Y is summer-maize grain yield (kg/hm^2).

2.8. Partial Factor Productivity of Fertilizer (P_{fp})

Partial factor productivity of fertilizer (P_{fp}) was defined as follows [24,25]:

$$P_{fp} = Y/N \tag{6}$$

where Y is summer-maize grain yield (kg/hm^2) and N is the amount of N applied (m^3/hm^2).

2.9. Statistical Analysis

Origin 9.0, SPSS 25.0, and Microsoft Excel 2019 were applied for data processing and mapping, and the analysis of variance (ANOVA) method was used to determine if significant differences existed among treatment means ($\alpha = 0.05$). Multiple comparisons were conducted for significant effects using the least significant difference (LSD) test at $\alpha = 0.05$.

3. Results and Analysis

3.1. Soil Moisture Dynamics Change and Evapotranspiration

Figure 3 shows soil moisture dynamic change in the 0–100 cm soil layer during summer-maize growing seasons in 2016 and 2017. The soil moisture content of each layer decreased first and then increased with time in 2016 due to the following factors: there was a lot of rainfall accompanied by irrigation events in the early stage of summer maize; the soil moisture was used for summer-maize transpiration; there was less rainfall in the middle of the summer-maize growth period; the crop growth basically stopped; and the demand for soil moisture obviously decreased in the later period of growth. Due to the same causes as in 2016, the soil moisture content of each layer increased, decreased, and increased with time in 2017. During these two years, the topsoil moisture changed substantially, indicating that the summer-maize root regularly absorbed water in the upper soil. The difference is that the variable amount of moisture content in the lower soil was higher than that in the middle soil, which shows the trend of decrease–increase in moisture content in the middle and late summer-maize growing seasons in 2016. This was most likely driven by the following factors: less rainfall in 2016 than in 2017; summer maize consumed lesser soil moisture in growth phases, leading soil moisture to diminish; and lower growth activity in the latter growth period. As the precipitation was abundant in 2017 and the water in the upper soil layer was adequate to feed summer maize, the variation of soil moisture declined in turn in the upper-, medium-, and lower-soil layers.

Table 3 shows the total consumption of soil water and evapotranspiration (ET) in the 2016 and 2017 summer-maize growing seasons. The small-flow drip-irrigation treatment used much more soil water than the big-flow drip-irrigation treatment, with rising proportions of 12.8% and 26.1%, respectively. The low-irrigation quota treatments consumed much less soil water than the high-irrigation quota treatments. The effect of fertigation frequency on soil water consumption was inconsistent in 2016 and 2017; in 2016, the high and intermediate fertigation frequencies were much lower than the low fertigation frequency, with lowering proportions of 24.9% and 20.2%, respectively. There was no significant difference among these three fertigation frequencies. As for ET, the small-flow drip-irrigation treatment was significantly larger than the large-flow drip-irrigation treatment in two summer-maize growing seasons. ET was much lower in the high-irrigation quota treatments than in the low-irrigation quota treatments. In 2016 and 2017, the effect of fertigation frequency on ET was inconsistent. The ET value of farmland declined dramatically as fertilization frequency increased in 2016; there was no significant difference among the three fertigation frequencies in 2017 due to excessive rainfall. The more the irrigation water allotment, the greater the evapotranspiration, and the greater the frequency of fertigation, the lower the evapotranspiration in 2016. In 2017, the higher the irrigation quota, the higher the field evapotranspiration.

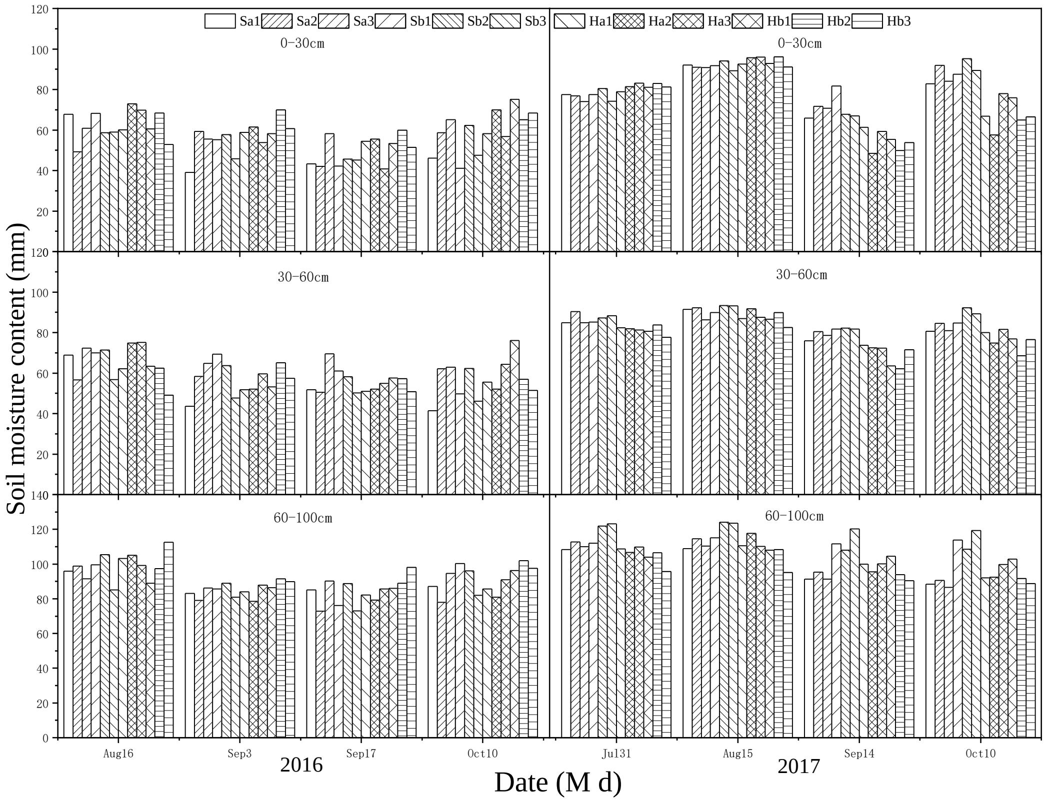

Figure 3. Soil moisture dynamic change in the 0–30, 30–60 and 60–100 cm soil layer of the 2016–2017 summer-maize growing seasons.

Table 3. Soil moisture consumption and ET of summer maize during the 2016 and 2017 growing seasons.

Treatments	Soil Moisture Consumption (mm)	ET (mm)	Soil Moisture Consumption (mm)	ET (mm)
2016			2017	
S	−91.46 ^{a}	298.3 ^{a}	−49.40 ^{a}	463.25 ^{a}
H	−104.93 ^{b}	284.83 ^{b}	−66.84 ^{b}	426.92 ^{b}
a	−104.67 ^{b}	281.35 ^{b}	−68.89 ^{b}	431.13 ^{b}
b	−91.72 ^{a}	301.78 ^{a}	−47.34 ^{a}	459.05 ^{a}
1	−106.63 ^{b}	283.13 ^{c}	−60.50 ^{a}	443.26 ^{a}
2	−102.59 ^{b}	287.17 ^{b}	−56.71 ^{a}	447.05 ^{a}
3	−85.37 ^{a}	304.39 ^{a}	−57.14 ^{a}	444.95 ^{a}
Sa1	−113.03 ^{ef}	272.99 ^{d}	−68.6 ^{cd}	421.42 ^{de}
Sa2	−83.16 ^{bc}	302.86 ^{b}	−33.89 ^{a}	456.13 ^{ab}
Sa3	−79.08 ^{b}	306.94 ^{b}	−40.57 ^{ab}	449.45 ^{ab}
Sb1	−115.04 ^{f}	278.46 ^{d}	−39.26 ^{ab}	458.24 ^{ab}
Sb2	−91.22 ^{c}	302.28 ^{b}	−45.32 ^{ab}	452.18 ^{ab}
Sb3	−67.24 ^{a}	326.26 ^{a}	−68.74 ^{cd}	428.76 ^{cd}
Ha1	−111.49 ^{ef}	274.53 ^{d}	−94.72 ^{e}	395.3 ^{f}
Ha2	−136.44 ^{g}	249.58 ^{e}	−92.71 ^{e}	397.31 ^{f}
Ha3	−104.85 ^{de}	281.17 ^{d}	−82.88 ^{de}	407.14 ^{ef}
Hb1	−86.95 ^{bc}	306.55 ^{b}	−39.42 ^{ab}	458.08 ^{ab}
Hb2	−99.52 ^{d}	293.98 ^{c}	−54.92 ^{bc}	442.58 ^{bc}
Hb3	−90.32 ^{c}	303.18 ^{b}	−36.39 ^{a}	461.11 ^{a}

Note(s): In each growing season, values followed by different letters are significantly different ($p < 0.05$) among treatments. The absolute value of "Soil moisture consumption" is equal to ΔS in Equation (1). A positive value indicates that the soil water consumption is positive, and a negative value indicates that the soil water consumption is negative.

3.2. Dry Matter Accumulation

Figure 4 shows the dry matter accumulation of summer maize in 2016–2017. Summer-maize dry matter increased with time and reached the maximum at harvest, but the difference in the early growth was not significant. From 1 September to 10 October, 2016, the laws of dry matter accumulation of summer maize were that the dry matter accumulation of the small-flow drip-irrigation treatment increased as drip frequency increased, and the dry matter accumulation of the small-flow drip-irrigation treatment at medium drip frequency was the highest; the greater the amount of irrigation, the greater the amount of dry matter on the whole. The trend of dry matter accumulation between 6 September and 10 October, 2017, is similar to that of 2016. The dry matter of small-flow drip irrigation was clearly more than that of high-flow drip irrigation.

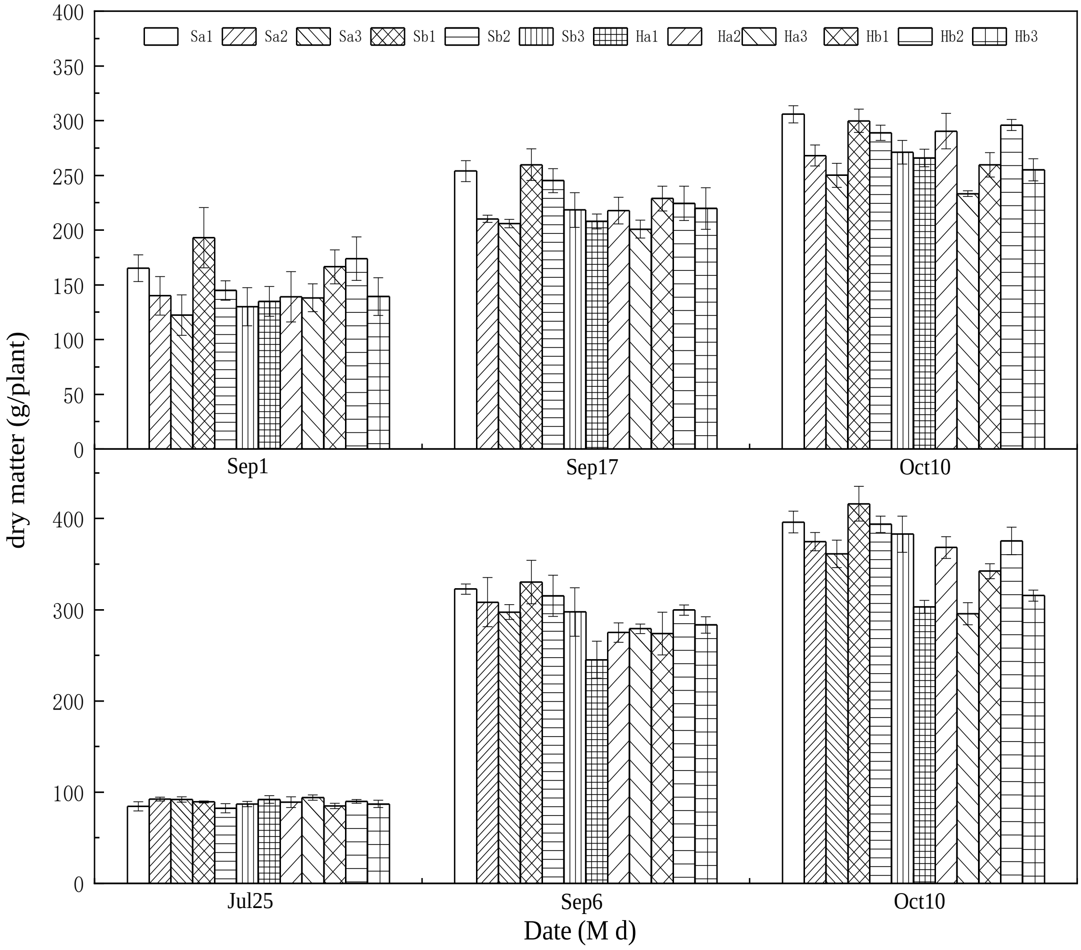

Figure 4. The dry matter accumulation of summer maize in 2016–2017.

3.3. Grain Yield and Yield Compositions

Table 4 shows grain yield and yield components for the summer-maize growing seasons of 2016 and 2017. In terms of kernels per row, the small-flow drip-irrigation treatment increased by 9.2% in 2016 but did not rise in 2017. The high-irrigation quota treatment rose by 5.8% compared to the low-irrigation quota treatment in 2016 but had no effect in 2017. With the increase in fertigation frequency, the kernels per row increased significantly in 2016, and the middle-fertigation frequency treatment was significantly higher than that of the low and high frequencies in 2017; the highest kernels per row appeared in treatment Sb1 in 2016 and 2017. The 1000-kernel weight for the small-flow drip-irrigation treatment was significantly higher than the high-flow drip-irrigation treatment. The high-irrigation quota treatment was significantly increased by 5.8% compared to the low-irrigation quota treatment. The higher the fertigation frequency, the higher the

1000-kernel weight in 2 years. For grain yield there were significant interaction effects. The grain production rose as the emitter flow rate was reduced and the irrigation quota was raised. Under the same irrigation quota, yield improved significantly with increasing fertigation frequency for the small-flow drip-irrigation treatment, while the greatest yield of the medium fertilizer frequency was attained for the big-flow drip-irrigation treatment. In a single-factor study of grain yield, the modest-flow drip-irrigation treatment outperformed the high. The high-irrigation quota treatment rose much more than the low-irrigation quota treatment. In 2016, the greater the fertigation frequency, the higher the grain yield, and the grain yield of high and moderate fertigation frequencies were considerably higher than the grain yield of low fertigation frequency.

Table 4. Grain yield and yield compositions of summer maize during the 2016 and 2017 growing seasons.

Treatments	Rows per Spike (Rows Spikes^{-1})	Kernels per Row (Kernels Row^{-1})	1000-Kernel Weight (g)	Grain Yield (kg/hm^2)
2016				
S	14.06 ^{a}	32.34 ^{a}	261.63 ^{a}	9596.85 ^{a}
H	14.15 ^{a}	29.62 ^{b}	254.30 ^{b}	8470.20 ^{b}
a	13.90 ^{a}	30.10 ^{b}	254.96 ^{b}	8825.85 ^{b}
b	14.31 ^{a}	31.86 ^{a}	260.97 ^{a}	9241.21 ^{a}
1	14.25 ^{a}	31.20 ^{b}	264.91 ^{a}	9071.12 ^{b}
2	13.99 ^{a}	32.14 ^{a}	256.14 ^{b}	9243.75 ^{a}
3	14.08 ^{a}	29.60 ^{c}	252.84 ^{c}	8785.80 ^{c}
Sa1	14.44 ^{abc}	33.30 ^{b}	264.49 ^{b}	9783.33 ^{b}
Sa2	14.00 ^{abc}	32.67 ^{b}	259.84 ^{c}	9300.45 ^{c}
Sa3	14.00 ^{abc}	30.53 ^{cd}	250.39 ^{f}	9148.65 ^{c}
Sb1	13.11 ^{c}	35.33 ^{a}	278.62 ^{a}	10,129.65 ^{a}
Sb2	14.00 ^{abc}	33.48 ^{b}	260.16 ^{c}	9934.20 ^{b}
Sb3	14.83 ^{ab}	28.74 ^{ef}	256.30 ^{de}	9284.55 ^{c}
Ha1	15.11 ^{a}	26.37 ^{g}	253.07 ^{ef}	7702.05 ^{f}
Ha2	14.44 ^{abc}	29.59 ^{de}	250.53 ^{f}	8575.50 ^{de}
Ha3	14.39 ^{abc}	28.13 ^{f}	251.44 ^{f}	8445.32 ^{de}
Hb1	14.33 ^{abc}	29.80 ^{de}	263.48 ^{b}	8669.10 ^{d}
Hb2	13.50 ^{bc}	32.83 ^{b}	254.04 ^{ef}	9164.55 ^{c}
Hb3	13.11 ^{c}	31.00 ^{c}	253.22 ^{ef}	8264.85 ^{e}
2017				
S	15.25 ^{a}	37.92 ^{a}	295.00 ^{a}	10,393.05 ^{a}
H	15.33 ^{a}	37.12 ^{a}	290.63 ^{b}	9606.60 ^{b}
a	15.17 ^{a}	37.36 ^{a}	287.15 ^{b}	9730.65 ^{b}
b	15.42 ^{a}	37.68 ^{a}	298.49 ^{a}	10,269.01 ^{a}
1	15.50 ^{a}	37.17 ^{b}	305.49 ^{a}	10,107.15 ^{a}
2	15.21 ^{a}	38.17 ^{a}	286.74 ^{b}	10,366.95 ^{a}
3	15.17 ^{a}	37.22 ^{b}	286.23 ^{b}	9525.60 ^{b}
Sa1	15.50 ^{a}	38.53 ^{a}	307.93 ^{c}	10,973.85 ^{b}
Sa2	15.17 ^{a}	38.50 ^{a}	278.06 ^{i}	9885.75 ^{g}
Sa3	14.83 ^{a}	37.20 ^{bcd}	274.93 ^{j}	9688.35 ^{i}
Sb1	15.67 ^{a}	38.60 ^{a}	316.50 ^{a}	11,024.55 ^{a}
Sb2	15.00 ^{a}	37.57 ^{a}	310.06 ^{b}	10,846.52 ^{c}
Sb3	15.33 ^{a}	37.13 ^{cd}	282.54 ^{h}	9939.15 ^{f}
Ha1	14.83 ^{a}	35.27 ^{f}	295.83 ^{f}	8623.95 ^{i}
Ha2	15.00 ^{a}	38.03 ^{a}	277.18 ^{i}	10,140.90 ^{e}
Ha3	15.67 ^{a}	36.63 ^{de}	288.98 ^{g}	9071.25 ^{k}
Hb1	16.00 ^{a}	36.30 ^{e}	301.68 ^{d}	9806.10 ^{h}
Hb2	15.67 ^{a}	38.57 ^{a}	281.67 ^{h}	10,594.21 ^{d}
Hb3	14.83 ^{a}	37.93 ^{a}	298.46 ^{e}	9403.35 ^{j}

Note(s): In each growing season, values followed by different letters are significantly different ($p < 0.05$) among treatments. In 2016, the grain yields of rainfed-summer-maize treatments were 6283.05 kg/hm^2, 5983.95 kg/hm^2, and 6151.05 kg/hm^2, respectively, which were significantly lower than drip-irrigation treatments.

3.4. WUE, WUE_I, WUE_P and P_{fp}

Values for WUE, WUE_I, WUE_p, and P_{fp} in 2016 and 2017 are presented in Table 5. In terms of the emitter flow rate factor, the WUE of the small-flow drip-irrigation treatment was significantly higher than the large-flow drip-irrigation treatment. In terms of the irrigation quota factor, the WUE of the high-irrigation quota treatment was significantly higher than the low-irrigation quota treatment. In terms of the fertigation frequency factor, the WUE of the low fertigation frequency treatment was significantly lower than the middle and high treatments in 2016 and 2017. In terms of WUE_I, the small-flow drip-irrigation treatment was significantly higher than the large-flow drip-irrigation treatment by 12.9% and 8.4% in 2016 and 2017; the low-irrigation quota treatment increased significantly by 18.2% and 26.2% compared to the high-irrigation quota treatment 2016 and 2017; and the WUE_I of the low-fertigation frequency treatment was significantly lower than the middle and high treatments in 2016 and 2017. In terms of WUE_p, the small-flow drip-irrigation treatment was significantly higher than the large-flow drip-irrigation treatment in 2016 and 2017, increasing by 13.4% and 8.3%, respectively; the WUE_p of the middle-fertigation frequency treatment was the highest in 2016 and 2017. P_{fp} of the small-flow drip-irrigation treatment was significantly higher than the large-flow drip-irrigation treatment, and the middle-fertigation frequency treatment was the highest in two years.

Table 5. WUE, WUE_I, WUE_p, and P_{fp}.

Treatments	WUE (kg/m^3)	WUE_I (kg/m^3)	WUE_p (kg/m^3)	P_{fp} (kg/kg)	WUE (kg/m^3)	WUE_I (kg/m^3)	WUE_p (kg/m^3)	P_{fp} (kg/kg)
2016						2017		
S	3.24 ^{a}	20.87 ^{a}	2.80 ^{a}	41.95 ^{a}	2.34 ^{a}	40.32 ^{a}	2.23 ^{a}	45.43 ^{a}
H	3.00 ^{b}	18.49 ^{b}	2.47 ^{b}	37.03 ^{b}	2.26 ^{b}	37.20 ^{b}	2.06 ^{b}	42.00 ^{b}
a	3.01 ^{b}	18.04 ^{b}	2.63 ^{a}	38.58 ^{b}	2.29 ^{a}	34.26 ^{b}	2.20 ^{a}	42.54 ^{b}
b	3.24 ^{a}	21.32 ^{a}	2.64 ^{a}	40.40 ^{a}	2.32 ^{a}	43.25 ^{a}	2.08 ^{b}	44.89 ^{a}
1	3.23 ^{a}	19.78 ^{a}	2.64 ^{b}	39.66 ^{b}	2.34 ^{b}	39.15 ^{b}	2.16 ^{b}	44.18 ^{a}
2	3.24 ^{a}	20.13 ^{a}	2.69 ^{a}	40.41 ^{a}	2.38 ^{a}	40.14 ^{a}	2.22 ^{a}	45.32 ^{a}
3	2.89 ^{b}	19.12 ^{b}	2.56 ^{c}	38.41 ^{c}	2.19 ^{c}	36.98 ^{c}	2.04 ^{c}	41.64 ^{b}
Sa1	3.64 ^{a}	20.28 ^{c}	2.95 ^{a}	42.77 ^{b}	2.41 ^{b}	36.79 ^{g}	2.36 ^{a}	47.97 ^{b}
Sa2	3.29 ^{b}	19.89 ^{cd}	2.89 ^{ab}	40.66 ^{c}	2.4 ^{b}	36.19 ^{h}	2.32 ^{c}	43.22 ^{j}
Sa3	2.85 ^{ef}	18.59 ^{e}	2.71 ^{c}	39.99 ^{c}	2.32 ^{c}	33.16 ^{j}	2.13 ^{f}	42.35 ^{i}
Sb1	3.59 ^{a}	23.03 ^{a}	2.85 ^{b}	44.28 ^{a}	2.61 ^{a}	48.78 ^{a}	2.35 ^{b}	48.19 ^{a}
Sb2	3.07 ^{cd}	21.9 ^{b}	2.71 ^{c}	43.43 ^{b}	2.17 ^{de}	43.94 ^{c}	2.12 ^{g}	47.42 ^{c}
Sb3	2.99 ^{de}	21.54 ^{b}	2.67 ^{c}	40.59 ^{c}	2.16 ^{de}	43.06 ^{d}	2.07 ^{i}	43.45 ^{f}
Ha1	2.52 ^{g}	15.42 ^{g}	2.24 ^{f}	33.67 ^{f}	2.14 ^{e}	32.72 ^{k}	2.1 ^{h}	37.70 ^{i}
Ha2	2.92 ^{def}	17.17 ^{f}	2.5 ^{de}	37.49 ^{de}	2.4 ^{bc}	35.35 ^{i}	2.27 ^{d}	44.33 ^{e}
Ha3	2.79 ^{f}	16.91 ^{f}	2.46 ^{de}	36.92 ^{de}	2.04 ^{f}	31.38 ^{l}	2.01 ^{j}	39.66 ^{k}
Hb1	3.16 ^{bc}	20.41 ^{c}	2.53 ^{d}	37.90 ^{d}	2.18 ^{de}	38.33 ^{f}	1.85 ^{l}	42.87 ^{h}
Hb2	3.67 ^{a}	21.58 ^{b}	2.67 ^{c}	40.06 ^{c}	2.56 ^{a}	45.08 ^{b}	2.17 ^{e}	46.31 ^{d}
Hb3	2.94 ^{def}	19.46 ^{d}	2.41 ^{e}	36.13 ^{d}	2.23 ^{d}	40.32 ^{e}	1.94 ^{k}	41.11 ^{j}

Note(s): In each growing season, values followed by different letters are significantly different ($p < 0.05$) among treatments.

4. Discussion

What type of guidelines to regulate grain production in the North China Plain were appropriate in the context of "water-saving mining"? For a long time, conventional wisdom maintained that the winter-wheat planting area and irrigated area should be lowered. Conversely, this is bound to negatively impact grain yield by compressing the planting area of winter wheat in a disorderly way [26] and increasing the ground dust and the ineffective moisture loss in the leisure period. At the same time, in recent years, the area of drip irrigation applied to winter wheat has gradually expanded to fundamentally solve the contradiction between water shortage and grain replenishment [27]. The research of many scholars shows that water-use efficiency and yield are both higher under drip irrigation than under either furrow irrigation or sprinkler irrigation [28–31]. The results of Wang et al. [32] indicated that drip irrigation increases water-use efficiency by 44.2% and stabilizes wheat yield.

Due to the rain and heat in the NCP during the summer, some believe that summer maize requires less irrigation and that fertilizer should be used as a basal dressing. However, one-time fertilizer application frequently results in volatilization, loss of efficacy, and the leaching of summer maize, which reduces the fertilizer consumption rate and even pollutes the environment, affecting the high and steady production of summer maize. Hence, it is necessary to improve the use efficiency of fertilizer and reduce the amount of fertilizer [33–35]. Using drip irrigation to combine water and fertilizer applications becomes a viable option. Meanwhile, the precision sowing of summer maize utilizing high-precision maize-sowing machines (fitted with "GPS" and "Beidou" systems, Weixian Ruifeng Agricultural Machinery Co., LTD, Xingtai, China) is now achievable without causing damage to the drip-irrigation system following the mechanical harvesting of winter wheat. Advances in conservation tillage and precision mechanization [36,37] might also be used to administer water and fertilizer to summer maize, using the residual drip-irrigation system of winter wheat to considerably enhance summer-maize productivity and water-usage efficiency. In recent years, the application area of drip irrigation in winter wheat has gradually grown, laying the groundwork for the popularization of summer maize. As a result, it is economically possible to employ a drip-irrigation system to fertilize and water summer maize. Many academic studies suggest that drip irrigation may boost maize production and WUE [38]. Sui et al. [39] found that compared with local maize cultivation, the maize yield increased by 10–29%, the WUE increased by 10–31%, and nitrogen-use efficiency (NUE) increased by 57–84% at 230 kg/hm^2 N under mulched drip irrigation. Tian et al. [40] found that compared with the flood-irrigation treatment, increased maize yields in the drip-irrigation treatment (28%) were found, and the 40% water reduction in drip fertilization is of great importance for the sustainable development of agriculture in the NCP, where water resources are extremely limited. Based on previous research, this paper proposes irrigating and fertilizing winter wheat with a drip-irrigation system to increase the yield and WUE by taking into account the winter wheat–summer maize-rotation annual planting pattern and using the drip-irrigation system left over from the winter-wheat season for proper fertilization in the summer-maize growing season. The shape, size, water content, nutrient concentration, and distribution of the water and fertilizer coupling body were optimized by adjusting the emitter flow rate (first-degree regulating), irrigation quota (second-degree regulating), and fertigation frequency (third-degree regulating), achieving the goals of "increasing grain yield by fertilizing" and "adjusting the quality by fertilizing" while realizing the highest yield and WUE of winter wheat and summer maize. At present, scholars mainly focus on the effects of drip irrigation on the yield and WUE, but there are relatively few studies on the coupling body of root-zone soil water and fertilizer, moisture, and nutrient consumption in summer-maize field production under drip irrigation.

The emitter drops the mixed liquor of water and fertilizer on the surface soil of summer maize in the form of water droplets, and the water infiltrates into the soil to create a wetting body while conveying fertilizer to the crop root area for crop consumption. The size, shape, and nutrient distribution of the wetting body control crop moisture absorption and root distribution, and are influenced by influent soil texture, emitter discharge rate, emitter spacing, irrigation quantity, and frequency [41–47]. A series of achievements have been obtained regarding soil water and fertilizer movement under drip irrigation [48–53]. Li et al. [41] indicated that soil-wetting patterns significantly affect the spatial structure of cotton root under mulched drip irrigation. Li et al. [54] found that the larger the emitter discharge rate, the shallower the wetting soil body, and the migration rate and time of the wetting front fit the power function. Small-flow drip-irrigation treatment has achieved higher yield in this experiment, which may be related to the shape of the wetting body and plant roots: (1) Under the same soil type and the same irrigation quota, when the drip emitter is small, the drip irrigation forms a deep, narrow wetting body [55]. The amount of water entering the row space is less, and the wetting front is more reasonable and supplies more nutrients for the root in the 20–40 cm range, while its shape promotes better corn root anastomosis. When the drip emitter discharge is large, the wetting body of soil is wide and shallow due to the water accumulation area under the drop emitter, so the water loss is easily formed. (2) As the soil near the emitter has more moisture, and as the irrigation emitter discharge increases, the volume of this section of the soil and the range of the earth's surface increases, and big-flow drip irrigation may be more favorable to surface evaporation. Small-flow drip irrigation, on the other hand, is likely to play a positive role in controlling surface evaporation, and as the fertilizer concentration decreases with increasing distance from the emitter, the fertilizer concentration is relatively high below the emitter, less urea is lost from the soil surface, and more urea is retained in the wetting body [51] for maize root absorption. As a result, the tiny-flow drip irrigation enhanced irrigation water and nutrient usage efficiency. (3) The bigger the emitter discharge rate under the same irrigation settings, the higher the average moisture content inside the wetted soil. The lower the average moisture content inside the wetted soil, the lower the emitter discharge rate. As a result, modest-flow drip irrigation may help to maintain adequate soil aeration and protect the soil aggregate structure, making it more favorable to crop development.

There is no consistent conclusion about the frequency of drip-irrigation fertigation on crop development. According to several researchers, a high fertilization rate has a significant impact on crop output and WUE. Xie et al. [56] found that under the same fertilizer rate, but with different fertigation frequencies to the present study, the nutrient-use efficiency was positively correlated to the fertigation frequency. Liu et al. [57] indicated that cotton yield decreased with the decrease in irrigation frequency and water quality. El-Hendawy [58] studied nitrogen fertilization on sandy soil water distribution, maize yield, and WUE under Egyptian conditions, and indicated that the WUE increased with increasing irrigation frequency and nitrogen levels, and reached the maximum values once every 2 and 3 days and at 380 kg N ha^{-1}. Cook and Sanders [59] conducted a study on the yield of tomato with underground drip irrigation, and the results showed that increasing the frequency of fertilization could promote the growth of fruit and thus increase the yield. Other scholars hold different opinions about the effect of fertigation frequency on crops [60]. Azad et al. [61] found that reducing the number of fertigation events in the sandy clay loam soil increases the nitrate plant uptake, However, in the sandy loam soil, a lesser number of fertigation events reduce nitrate uptake. Uçan et al. [62] indicated that the effects of irrigation intervals on yield were not significant. In this experiment, the results show that the higher the frequency, the higher the yield under the small-flow drip irrigation of summer maize, while the large-flow drip irrigation of medium fertigation frequency obtained the highest yield. The experimental results showed that the response of different crops to fertigation frequency was related to drip emitter discharge, and that the emitter discharge influences the size, shape, and distribution of the coupling body of soil water and fertilizer, which can affect crop growth and yield formation indirectly. The research indicated that a higher frequency can increase the plant root density in the soil layer of 0–60 cm, thus improving the soil's ability to absorb nutrients and promoting the increase of yield [63,64]. In addition, the effect of local climate and soil structure should be taken into consideration for different crops in different areas [58,65].

The coupling of root-zone soil water and fertilizer management for summer maize with drip irrigation is investigated and discussed based on the results of the experiments and prior research. However, more in-depth research is required in future experiments to investigate factors such as the movement and transformation of nutrients in moist soil under drip-irrigation conditions, the quantitative description of nitrogen-form transformation and loss under drip irrigation, and the effects of drip irrigation on nutrient utilization and crop yield.

5. Conclusions

The results showed that the volume and depths of the soil-wetting body generated by the higher irrigation quota were bigger than the low irrigation quota, which was advantageous for the use of water and nutrients by summer maize and promoted the rise in summer-maize output. In a specific range, the larger the irrigation quota, the higher the summer-maize yield and the WUE. Finally, the appropriate fertigation frequency under varied emitter discharge rates is inconsistent; higher fertigation frequency is helpful to prevent fertilizer leaching and escape, which improves fertilizer-use efficiency and boosts output. In modest-flow drip irrigation, a high fertigation frequency (every 7 days) can produce maximum yield and WUE. In the current NCP conditions, it is appropriate for summer maize to adopt modest-flow drip irrigation with high fertigation frequency, which can result in increased yield and WUE.

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