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Effect of Planting Date on Accumulated Temperature and Maize Growth under Mulched Drip Irrigation in a Middle-Latitude Area with Frequent Chilling Injury

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Abstract: Given that chilling injury, which involves late spring cold and early autumn freezing, significantly affects maize growth in middle-latitude cold areas, a highly efficient cultivation technique combining suitable planting date (PD) and mulched drip irrigation is being studied to guarantee maize production. A field experiment for medium-mature variety "Xianyu 335" was conducted in 2015 to 2016 in Chifeng, Inner Mongolia, China, to explore the effects of PD on the active accumulated temperature (AAT) distribution and maize growth under mulched drip irrigation. Based on the dates (around May 1) of late spring cold occurring in the area, four PDs were designed, namely, April 20 (MD_1), May 2–3 (MD_2), May 12 (MD_3), and May 22 (MD_4), and a non-film mulching treatment ($NM\text{-}D_2$) was added on the second PD. Results indicated that: (1) the warming effect of film mulching effectively compensated for the lack of heat during the early stages of maize growth. Compared with that in $NM\text{-}D_2$, the soil temperature under mulching in MD_2 for the sowing–emergence and seedling stage increased by 14.3% and 7.6%, respectively, promoting maize emergence 4 days earlier and presenting 5.6% and 9.7% increases in emergence rate and grain yield, respectively; (2) the AAT reduction caused by PD delay was mainly observed in reproductive stage, which reached 96.6 °C for every 10 days of PD delay in this stage; (3) PD markedly affected maize growth process and yield, which were closely related to the chilling injury. The late spring cold slowed down the emergence or jointing for maize (under MD_1 and MD_2), but brought insignificant adverse effect on maize later growth and grain yield (16.1 and 15.9 $Mg{\cdot}ha^{-1}$, respectively). While the maize in both MD_3 and MD_4 treatments suffered from early autumn freezing damage at the anthesis–maturity stages, resulting in shortening in reproductive period by 4–8 days and decrease in grain yield by 11.4–17.3% compared with those in MD_1 and MD_2; and (4) taking the typical date (May 1) of late spring cold occurring as the starting point, the grain yield penalty reached 8.5% for every 10 days of PD delay; for every 100 °C of AAT decrease during reproductive stage, the grain yield decreased by 6.1%. The conclusions offer certain reference values for maize cultivation in the same latitude areas with similar ecological environments.

Keywords: planting date; mulched drip irrigation; chilling injury; active accumulated temperature; maize growth

1. Introduction

Global warming significantly affects agricultural production in middle-high latitude areas. An increasing number of studies have indicated that crop varieties with a long growth period (GP) should be selected for temperature increasing and frost-free season extension, and photo-thermal resources should be fully utilized to promote crop production [1–3]. However, the selection of planting date (PD), which corresponds to the expanded planting of crop varieties with a long GP, remains challenging [4]. In recent years, researchers have conducted extensive discussions on the changing trend of the PDs for rice, maize and other crops [4–7]. The Corn Belt in Northeast China is located in cold middle-latitude regions. Insufficient accumulated temperature caused by chilling injuries (such as late spring cold and early autumn freezing) is a crucial ecological factor that limits grain yield [8]. Therefore, film mulching has become a primary cultivation practice. However, owing to the lack of systematic research on the effects of PD on maize growth and regulation mechanism of heat factors, wide PD intervals have made the effects of improving production in cold weather imperceptible.

Planting date influences crop growth by changing the corresponding relationship between hydrothermal factors and growth stages. The main obstacles that restrict maize growth in different ecological regions should be identified to determine the optimal PD. In cold middle-latitude regions, the limitation of PD delay should be based on the required accumulated temperature for crop growth [9]. Maize growth is accelerated with PD postponement, leading to a shortening growth period and an adverse effect on biomass accumulation [10,11]. Moreover, delayed sowing increases the probability of early autumn freezing occurring at latter stages in maize growth, thereby restraining grain maturity and leading to output reduction [12,13]. Early planting with film mulching is regarded as an effective measure to increase production against the cold, because despite crop exposure to a low-temperature environment at the prophase, the growth point is not endangered; besides, no adverse effect was observed in middle-later stages, and maize can reach physiological maturity before early autumn freezing occurs [14,15].

The U.S. Corn Belt is located in the same latitude as the China Corn Belt, and the appropriate PDs for maize are from late April to early May, which tends to be advanced in recent years [2,16,17]. Maize planting season ranges from late April to mid-May in the China Corn Belt, and several reports showed that the appropriate PDs for medium-late maturing varieties are from April 25 to May 10, but with considerable yield differences [18,19].

Most of the aforementioned conclusions are drawn from studies on traditional surface irrigation. Mulched drip irrigation technology combines the characteristics of film mulching and drip irrigation. The application of this technology for maize is becoming increasingly widespread in Northeast China these years. According to the latest reports, the mulched drip irrigation area for maize in the region increased 135×10^4 ha during 2012–2015, which made a significant contribution to food security [20]. Film mulching can improve soil temperature and reduce water evaporation [21–24], whereas drip irrigation can achieve accurate and efficient management of soil moisture and nutrients [25,26]. The regulation effects of mulched drip irrigation and PD on the microclimate around the crop will perform a certain role in the maize growth process, yield formation and utilization of hydrothermal resources. However, related research under drip irrigation remains rare and unsystematic, and the reported conclusions were mainly concentrated in arid areas, wherein the primary objective was to improve yield- and water-use efficiency [27–29]. Furthermore, current studies on maize PD under mulched drip irrigation are little. Therefore, identifying a reasonable PD that corresponds to mulched drip irrigation in cold middle-latitude areas with different ecological factors under consideration is important.

This study aims to investigate the warming effect and yield-increasing potential of mulched drip irrigation for maize, to analyze maize growth response to chilling injury (that is, late spring cold and early autumn freezing) at certain growth stages caused by different PDs, quantify the accumulated temperature loss and yield reduction with PD delay, and provide a theoretical basis for improving the rational utilization of heat resources and minimizing production loss in cold middle-latitude areas.

2. Materials and Methods

2.1. Site Description

The field experiment was conducted in 2015 to 2016, Chifeng in Inner Mongolia, China (42°56′53′′N, 119°4′20′′E). The area has a semi-arid and continental monsoon climate with an approximately 135-day frost-free period. Early autumn freezing generally occurs from the end of September to the beginning of October, and the late spring cold always occurs around May 1. The effective accumulated temperature (≥10 °C) is 2000–3200 °C, and the annual average rainfall and evaporation amounts are 350–450 and 1500–2300 mm, respectively.

Temperature and precipitation during maize GPs in 2015 and 2016 are shown in Figure 1. The late spring cold occurred in both years (the minimum daily temperature dropped to −1.8 °C in 2015 and to 1.4 °C in 2016) and the dates of the early autumn freezing in 2 years were October 2 and September 28, respectively. The weather conditions during maize GPs in 2015 and 2016 were in line with the environmental climate characteristics of years in the region [30]. Total precipitation values during maize GPs for 2 years were 180 and 250 mm, respectively. Note that the climate feature of "late spring cold" in the region is that the daily average temperature exceeding 10 °C lasts for 5–10 days at least in late Spring, but then the daily minimum temperature dropped to about 0 °C for a sudden strong cold air attack (the cold snap always continue 1–2 days), and then the temperature increases again gradually.

The soil layer of 0–60 cm in the test site belong to silt loam soil with a soil bulk density of 1.49 g·cm^{-3} and a field water-holding rate of 34.45% (volumetric water content). Soil organic matter was 10.6 g·kg^{-1}, mass fraction for total nitrogen was 0.60 g·kg^{-1}, and available potassium and phosphorus were 167 and 7.6 mg·kg^{-1}, respectively.

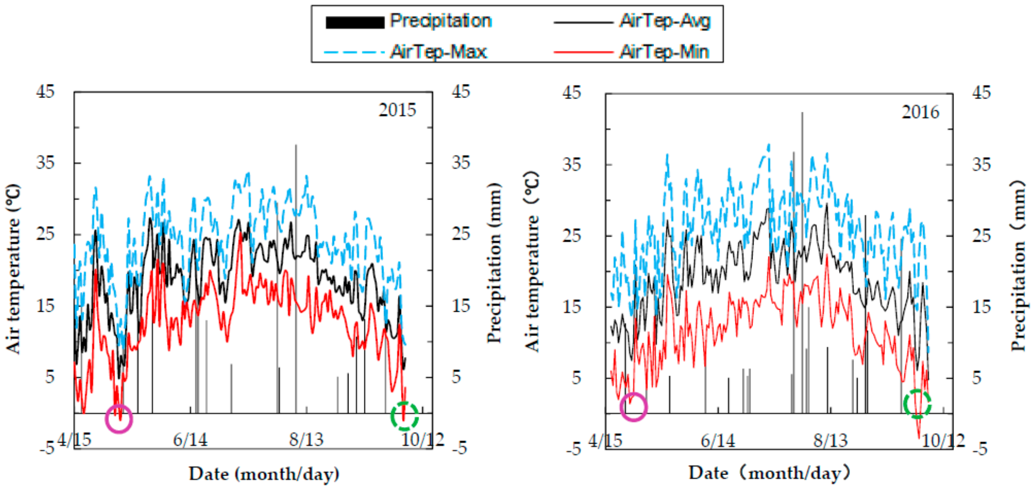

Figure 1. Daily temperature and precipitation during maize growing season in 2015 and 2016. Purple circle with full line marked position for the late spring; green broken circle marked position for the early autumn freezing.

2.2. Field Experiment

The experiment used a completely randomized design for the variable factor of PD, which involved four levels. Based on the date of late spring cold (around May 1), four PDs were set under mulched drip irrigation, namely, MD_1 (April 20), MD_2 (May 2–3), MD_3 (May 12), and MD_4 (May 22). And a treatment (NM-D_2) without mulching was added on the second PD under drip irrigation. Each treatment was performed in triplicate, thus, 15 plots in total were arranged randomly. The size of each plot was 40 m × 6 m.

Maize varieties need to match the light and heat resources of a certain ecological zone otherwise the yield and utilization rate of resources will be reduced [31]. For testing, we selected the medium variety "Xianyu 335", which is a high-yield plant in the Corn Belt of Northeast China [32,33]. Maize was planted in the alternate wide–narrow rows (80–40 cm) with a planting density of 83,330 plants·ha^{-1}. The drip tape with a wall thickness of 0.2 mm, a drip flow of 1.38 L·h^{-1}, and a drip spacing of 40 cm was placed in the middle of the narrow line. The maize cropping pattern and lateral layout of drip tapes under mulched drip irrigation are shown in Figure 2.

The treatments were irrigated according to the lower irrigation limit and crop water requirement, and the lower limit of irrigation at both seedling and mature stages was 70%, whereas that in other growth stages was 75%. The precipitation and irrigation amounts in each GP of maize for all treatments are shown in Figure 3. In treatments of MD_1–MD_4, the total irrigation amounts were 170, 155, 151, and 151 mm, respectively, in 2015 and 135, 135, 125, and 115 mm, respectively, in 2016. The irrigation amount in NM-D_2 treatment was same as that in MD_2 for 2 years. The total precipitation during maize growth season was 180 mm in each treatment in 2015, whereas those in MD_1–MD_4 in 2016 were 251, 242, 232, and 215 mm, respectively.

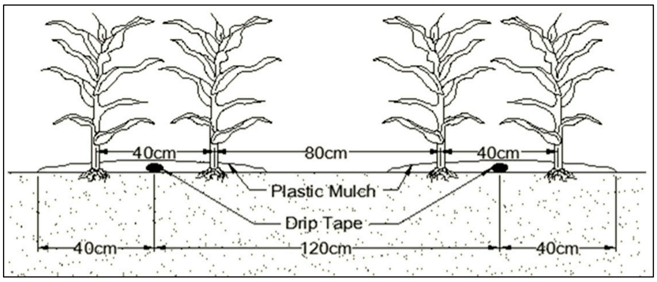

Figure 2. The schematic diagram of cropping pattern and lateral layout of drip tapes under mulch for maize.

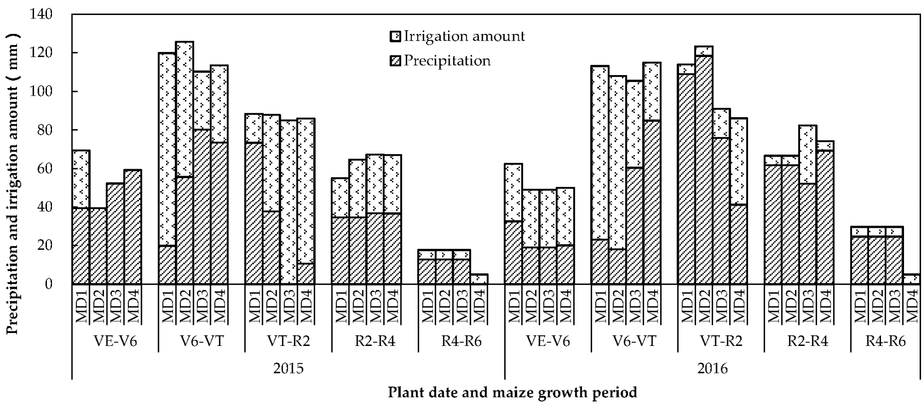

Figure 3. The precipitation and irrigation amount in various growth stages of maize for different treatments. VE—emergence, V6—sixth leaf, VT—tasseling, R2—filling, R4—dough, R6—physiological maturity.

Fertilizer schedule in all treatments was the same for 2 years, and the application amounts of N, P_2O_5, and K_2O were 285, 135, and 135 kg·ha^{-1}, respectively. Fertilizer application percentages in each GP are shown in Table 1. Seed fertilizer, which included urea (N 46%), calcium superphosphate (P_2O_5 46%), and potassium sulfate were applied to the field by a seeder. The remaining fertilizer was applied in proportion with water by drip tapes, and the soluble fertilizers included urea (N 46%), MAP (monoammonium phosphate, P_2O_5 61%, N 12%), and potassium chloride (K_2O 62%). Other farm tasks were performed as the management in local high-yield farmlands.

Table 1. Fertilizer application percentages in each growth period.

Fertilizer	Sowing	V6–V12	VT	R2	R4
N	20%	45%	15%	15%	5%
P_2O_5	50%	30%	20%	–	–
K_2O	50%	50%	–	–	–

V6—sixth leaf, V12—twelfth leaf, VT—tasseling, R2—filling, R4—dough.

2.3. Observation Indexes and Methods

ET107 automatic meteorological station manufactured by USA Campbell Scientific was used to continuously monitor meteorological data, such as daily temperature and precipitation during the maize growing season.

Soil water content was regularly measured using the gravimetric method. The soil samples were collected by an auger boring in 20 cm increments to a depth of 80 cm, then were dried at 105 °C for 8 h. The measurement range of the electronic scale used is 500 g with an accuracy of 0.01 g. Soil moisture is calculated as the following formula.

$$\omega = \frac{m_w - m_d}{m_d} \times 100\% \quad (1)$$

ω—soil water content, %; m_w—the mass of wet soil, g; m_d—the mass of dry soil, g.

A set of curved tube thermometers were embedded in the narrow lines (under mulching) and wide lines (in bare land) of each treatment to measure the soil temperature at depths of 5, 10, 15, 20 and 25 cm. The observation times were 8:00, 14:00, and 18:00 daily, and the average value of three observations was taken as the daily soil temperature [34,35].

Dates of VE (emergence), V6 (sixth leaf), VT (tasseling), R2 (filling), and R6 (physiological maturity) were recorded according to maize growth traits. Five plants were removed from the ground except for the roots to measure height, stem diameter and dry matter (DM) accumulation (plants were separated into leaves, stems, and ears, which were heat-treated at 105 °C for 30 min and dried at 75 °C to a constant weight).

During harvest season, 10 m of maize from the middle six lines in each plot were harvested separately, grain moisture content was measured, and yield with a standard moisture content of 14% was calculated. Five maize ears from each plot were selected to measure the yield components, such as bald tip length, hundred-grain weight, and grain number per ear.

Statistical analysis and plotting were performed using Microsoft Excel 2010 and IBM SPSS Statistics 17.0.

3. Results

3.1. Effects of Planting Date and Film Mulching on Heat Distribution

3.1.1. Soil Temperature

The dynamic changes of daily soil temperature (DST) in the depth of 5–25 cm under film mulching and in bare land during maize growing season in 2015 and 2016 are shown in Figure 4. The increasing rate of the average DST under film mulching at various GPs, compared with those of bare land in different treatments, are shown in Figure 5.

From MD_1 to MD_4, the accumulated soil temperature (AST) under mulching during maize entire GP for two years averagely increased by 149.9 °C, 136.6 °C, 116.5 °C, and 99.6 °C, respectively, compared with those in bare land. The AST increments of seedling stage in MD_1–MD_4 accounted for 59.7%, 59.1%, 55.0%, and 54.8% of those during the total GP, respectively. Results indicated that the warming effect of film mulching decreased with the PD delay.

For maize plants with different PDs at two stages, namely, sowing–emergence and seeding, the average increasing rates of DST under mulching were 11.2% and 6.7%, respectively. Moreover, the warming effect gradually weakened with continuous GP progress, and the average increasing rates of DST under mulching were 2.3–3.0% during V6–harvest stage with different PDs. The results demonstrated an evident warming effect of film mulching in the prophase of maize.

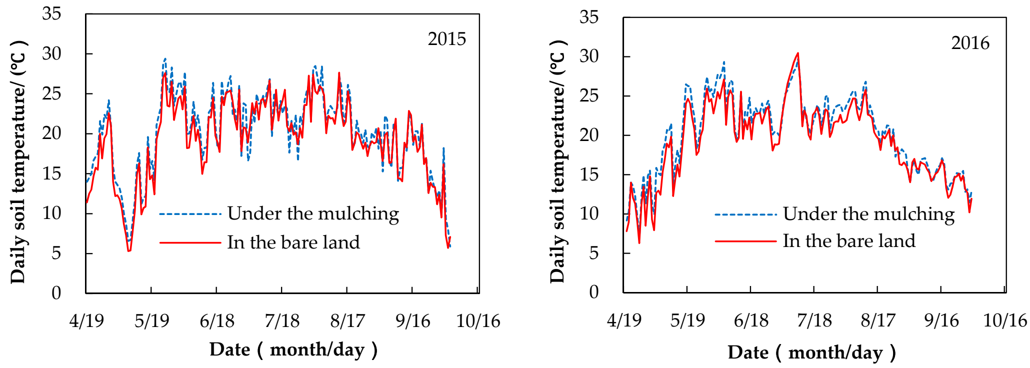

Figure 4. Changes of daily average soil temperature at 5–25 cm depth during maize growing season in 2015 and 2016.

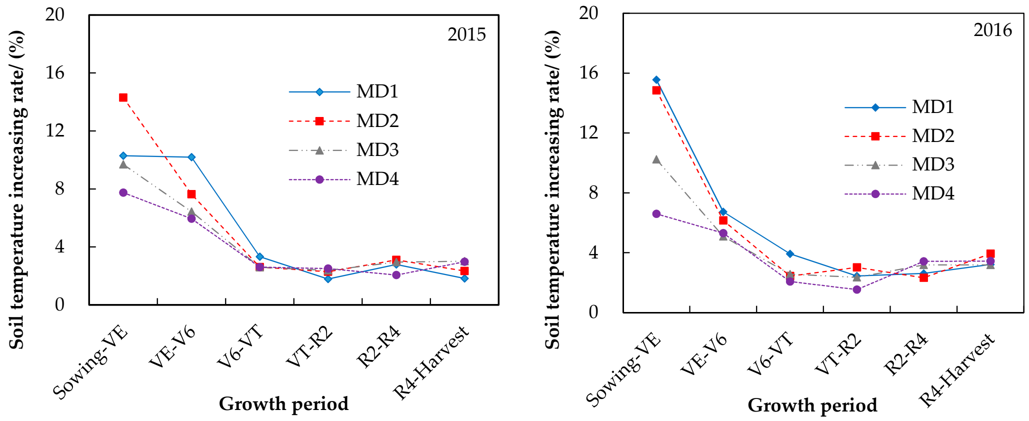

Figure 5. Daily soil temperature increasing rate under mulching compared with that in bare land of various maize growth periods in different treatments. VE—emergence, V6—sixth leaf, VT—tasseling, R—filling, R—dough.

3.1.2. Active Accumulated Temperature

The AATs (≥10 °C) in different treatments for various GPs of maize under mulched drip irrigation are shown in Table 2.

The total AATs exhibited a decreasing trend with the delay in PD, decreasing under MD_2–MD_4 treatments by 73 °C, 226 °C, and 365 °C, respectively, compared with those in MD_1.

The AATs at maize's different GPs were determined based on daily temperature and stage duration. The average AAT required for maize emergence was approximately 208 °C, and the annual variation was caused by fluctuation in the occurrence of late spring cold.

The AATs at both vegetative and reproductive growth stages decreased with the postponement of PD. The AATs at these two stages under MD_1–MD_4 treatments were on the average 1494–1430 °C and 1327–1022 °C, respectively. Compared with those in MD_1, AATs of the maize reproductive stage in MD_2–MD_4 decreased by 89 °C, 198 °C, and 305 °C, respectively, illustrating that PD particularly affected AATs of this stage and insufficient AATs at this stage were unfavorable for grain filling and dehydration.

Table 2. The active accumulated temperature of sowing–harvest, sowing–VE, VE–VT and VT–harvest stages for maize in different treatments (°C).

Year	Treatment	Sowing–Harvest	Sowing–VE	VE–VT	VT–Harvest
2015	MD_1	3050	183	1544	1323
	MD_2	2927	210	1487	1229
	MD_3	2793	235	1435	1122
	MD_4	2677	207	1447	1023
	Mean	2862	209	1478	1174
2016	MD_1	2993	219	1443	1330
	MD_2	2969	214	1508	1247
	MD_3	2798	214	1450	1134
	MD_4	2635	186	1413	1020
	Mean	2849	208	1454	1183
Mean	MD_1	3021	201	1494	1327
	MD_2	2948	212	1498	1238
	MD_3	2796	225	1443	1128
	MD_4	2656	197	1430	1022

VE—emergence, VT—tasseling.

3.2. Effect of Planting Date on Maize Growth Process

The durations of various maize GPs under different treatments are shown in Table 3, and no statistically significant differences occurred between years for the average parameter values of all treatments.

Table 3. The durations of sowing–harvest, sowing–VE, VE–VT and VT–harvest stages for maize in different treatments (d).

Year	Treatment	Sowing–Harvest	Sowing–VE	VE–VT	VT–Harvest
2015	MD_1	155d	9a	81b	65c
	MD_2	150c	17c	69a	64c
	MD_3	139b	11b	68a	60b
	MD_4	133a	10a	66a	57a
	F-test	89.9 **	42.9 **	52.0 **	22.7 **
	NM-D_2	153	21	67	65
	Mean	146A	14A	70A	62A
2016	MD_1	154d	18d	69b	67c
	MD_2	149c	14c	69b	66c
	MD_3	141b	12b	67a	62b
	MD_4	131a	10a	64a	57a
	F-test	200.5 **	143.9 **	16.3 **	45.2 **
	NM-D_2	152	18	67	67
	Mean	145A	14A	67A	64A
Mean	MD_1	155d	14ab	75b	66c
	MD_2	150c	16b	69a	65c
	MD_3	140b	12ab	67a	61b
	MD_4	132a	10a	65a	57a
	F-test	200.7 **	4.6 *	8.5 **	51.2 **
	NM-D_2	153	20	67	66

1 The different lowercase letters in the same column show significance at $p < 0.05$. 2 * means significant ($p < 0.05$), ** means extremely significant ($p < 0.01$). 3 Column values for the various years with same uppercase letters are insignificantly different at $p < 0.05$. 4 VE—emergence, VT—tasseling.

Compared with that under NM-D_2 treatment, the duration of total maize GP under MD_2 decreased by 3 days, and that of sowing–VE period shortened by 4 days, whereas the differences in growth durations of middle–late stages were minimal.

For treatments under mulched drip irrigation, the duration of total maize GP decreased gradually with the delay in PD, and the differences among MD_1–MD_4 reached 5–23 days. The total GP duration for maize in both MD_1 and MD_2 exceeded 150 days, which guaranteed the physiological maturity for grain. Whereas, maize in MD_3 and MD_4 experienced early autumn freezing during later growth stages, resulting in evident shortening in GP duration (10–18 days) and failing to reach physiological maturity.

A significant difference reaching 2–8 days was found in sowing–VE duration among MD_1–MD_4 treatments. When sowing was performed on April 20, maize sowing–VE duration was highly unstable with a 9-day difference within 2 years because of the fluctuation in late spring cold. In 2015, maize had entered seedling stage as late spring cold occurred, whereas the occurrence of chilling injury during sowing–VE stage delayed emergence by 9 days in 2016. In MD_2–MD_4 treatments, the sowing–VE duration decreased gradually with PD delay with insignificant inter-annual differences.

The duration of VE–VT for maize showed a decreasing trend with the PD delay. A 12-day difference in this period appeared in MD_1 treatment for 2 years because the seedlings underwent a long period of recovery after acquiring frostbite in 2015; by contrast, no chilling injury occurred during this period in 2016. The inter-annual differences of this period for 2 years were insignificant under MD_2–MD_4 treatments.

The effects of PD on the VT–Harvest duration were highly evident. MD_1 and MD_2 didn't show significant difference during this period, but shortened by 4–8 days when PD delayed to May 12 or later (MD_3 and MD_4) because of early autumn freezing.

3.3. Effects of Planting Date on Maize Growth Indexes

Planting date significantly affected maize emergence rate, plant height, stem diameter, and single plant dry weight (DW) and its allocation proportions in each organ under mulched drip irrigation in varying degrees (Table 4). No significant difference occurred in maize growth indexes under MD_1 and MD_2, but the plant height increased significantly and the stem diameter and DW per plant decreased considerably with the continuous delay in PD. And no appreciable differences existed in most growth indexes between years, other than plant height and single plant DW (with greater values in the first year).

The maize emergence rate under treatments of MD_1, MD_3 and MD_4 did not appear to be markedly different, but that in MD_2 decreased by 1.6–2.3%. The reason why maize in MD_2 obtained a lower emergence rate was that the PD (May 2–3) was near the date of late spring cold, the average temperature during maize sowing–VE period was lower than that in other treatments.

A comparison of the distribution ratios of DW in nutritive and reproductive organs of maize under mulched drip irrigation showed that the proportions of DW in stem and leaves exhibited an upward trend with the delay in PD, whereas those in the ears presented a downward trend. No significant difference was found in single-plant DW and its distribution proportion in each organ between MD_1 and MD_2; however, in MD_3 and MD_4 treatments, single-plant DW decreased by 10.0–14.5%, and the proportions of DW in stem and leaves increased by 11.7–15.4% and 16.4–22.8%, respectively, whereas those in ears decreased by 8.6–6.4%. Results indicated that the delay in PD led to "slim" plants, which are not conducive to the translocation of dry matter to ears.

In the comparison of the maize growth indexes between treatments with film mulching and NM-D_2, film mulching improved the maize emergence rate by 5.6–8.1% on average; the single-plant DW in MD_1 and MD_2 increased by 8.0–8.4%, while those in MD_3 and MD_4 decreased by 2.6–7.5%, compared with those in NM-D_2.

Table 4. Maize growth indexes of different treatments in harvest season.

Year	Item	Emergence Rate (%)	Height (cm)	Stem Diameter (cm)	Dry Matter Per Plant			
					($g \cdot Plant^{-1}$)	Proportion (%)		
						Stem	Leaves	Ear
2015	MD_1	94.5b	311.5a	2.6b	434.9b	19.9a	11.9a	68.2b
	MD_2	92.1a	314.2a	2.6b	440.2b	20.2a	12.1a	67.7b
	MD_3	93.5ab	317.3ab	2.4ab	400.0a	23.0ab	14.6b	62.4a
	MD_4	93.9ab	322.0b	2.3a	378.5a	23.9b	15.4b	60.8a
	F-test	6.6 *	4.2 *	6.8 *	11.8 **	11.5 **	16.7 **	18.7 **
	NM-D_2	86.7	316.2	2.4	412.5	22.7	14.1	63.2
	Mean	92.1A	316.2B	2.5A	413.2B	21.9A	13.6A	64.5A
2016	MD_1	93.5a	306.0a	2.5 b	426.1b	19.6a	12.4a	68.0c
	MD_2	93.0a	309.0b	2.5b	423.7b	20.0a	13.1ab	66.9bc
	MD_3	95.2a	314.4c	2.3ab	376.4a	21.5a	14.2bc	64.3ab
	MD_4	95.6a	319.3 c	2.1a	359.3a	22.1a	15.0c	62.9a
	F-test	3.3	6.9 **	15.2 **	39.4 **	1.9	6.6 *	7.3 *
	NM-D_2	88.5	311.5	2.3	384.7	21.6	13.8	64.6
	Mean	93.2A	312.0A	2.3A	394.0A	20.9A	13.7A	65.3A
Mean	MD_1	94.0ab	308.6a	2.6	430.5c	19.8a	12.1a	68.1b
	MD_2	92.5a	311.8a	2.6	432.0c	20.1a	12.6a	67.3b
	MD_3	94.3ab	315.9ab	2.4	388.2b	22.2b	14.4b	63.4a
	MD_4	94.7b	320.7b	2.2	368.9a	23.0b	15.2b	61.8a
	F-test	4.4 *	5.6 **	9.6 **	27.2 **	8.6 **	22.3 **	21.5 **
	NM-D_2	87.6	313.9	2.4	398.6	22.2	14	63.9

1 The different lowercase letters in the same column show significance at $p < 0.05$. 2 * means significant ($p < 0.05$), ** means extremely significant ($p < 0.01$). 3 Column values for the various years with different uppercase letters are significantly different at $p < 0.05$.

3.4. Effects of Planting Date on Maize Yield Indexes

The maize yield indexes under different treatments are shown in Table 5.

A comparison of the maize yield indexes with different PDs under mulched drip irrigation showed that the bald tip length and grain moisture content exhibited an increasing trend with a delay in PD, whereas the hundred-grain weight, grain number per ear (2016), yield, and total DM displayed a decreasing trend. The grain number per ear under MD_2 in 2015 was the largest in terms of relatively lower emergence rate and large ear length. And no statistically evident differences existed in most yield indexes other than the bald tip length and grain number per ear between years, with smaller bald tip length and greater grain number in the first year.

No evident difference was found in the yield indexes between MD_1 and MD_2. Under MD_3 and MD_4, the bald tip length increased by 34.3% and 54.3%, the hundred-grain weight decreased by 4.3% and 9.1%, and grain number per ear decreased by 7.5% and 9.9%, respectively, compared with those in MD_1 and MD_2. The results illustrated that delayed sowing is unfavorable for the formation of yield components. Compared with those in MD_1, under MD_2, MD_3, and MD_4 treatments, DM decreased by 1.2%, 9.5%, and 13.7%, grain moisture content increased by 1.8%, 13.5%, and 17.9%, and yield (14% moisture content) decreased by 1.4%, 11.4%, and 17.3%, respectively. The findings indicated no significant difference in total biomass and economic yield of maize sowed on April 20 and May 2, whereas delayed PD to May 12 or later resulted in a significant yield reduction.

Compared with those yield indexes under non-plastic film mulching (NM-D_2), the bald tip length and grain moisture of maize planted before May 3 (MD_1 and MD_2) averagely decreased by 20.5% and 3.8%, respectively, but the total DM and yield increased by 6.5% and 9.7%, respectively; while under MD_3 and MD_4 treatments, the bald tip length and grain moisture averagely increased by 9.1–22.7% and 8.0–12.3%, respectively, whereas the total DM and yield decreased by 1.5–8.0% and 2.2–6.6%, respectively. The results showed an apparent effect of film mulching on improving yield for the early sowing maize.

Table 5. Maize yield indexes in different treatments.

Year	Treatment	Bald Tip Length (cm)	Hundred-Grain Weight (g)	Grain Number Per Ear	Grain Moisture Content (%)	Yield (14%) ($Mg \cdot ha^{-1}$)	Total Dry Matter Accumulation ($Mg \cdot ha^{-1}$)
2015	MD_1	1.6a	35.5c	592b	24.9a	16.24c	34.25b
	MD_2	1.7a	35.1bc	604c	25.4a	16.02c	33.77b
	MD_3	2.2b	33.4ab	560ab	28.1b	14.45b	31.15a
	MD_4	2.4b	31.8a	548a	29.6b	13.55a	29.60a
	F-test	15.3 **	9.6 **	10.2 **	14.2 **	24.9 **	10.9 **
	NM-D_2	2	34.7	576	26	14.62	31.45
	Mean	2.0A	34.1A	576B	26.8A	15.20A	32.20A
2016	MD_1	1.8a	35.3b	591b	24.8a	15.91b	33.18b
	MD_2	1.9a	35.2b	587b	25.2a	15.68b	32.83b
	MD_3	2.5b	34.1b	538a	28.3b	14.04a	29.86a
	MD_4	3.0b	32.4a	521a	28.9b	13.06a	28.62a
	F-test	48.1 **	6.9 *	29.6 **	14.5 **	9.9 **	28.5 **
	NM-D_2	2.4	34.3	558	26.27	14.29	30.91
	Mean	2.3B	34.3A	559A	26.7A	14.53A	31.04A
Mean	MD_1	1.7a	35.4c	592b	24.8a	16.08c	33.71c
	MD_2	1.8a	35.1c	595b	25.3a	15.85c	33.30c
	MD_3	2.4b	33.7b	549a	28.2b	14.24b	30.50b
	MD_4	2.7c	32.0a	535a	29.3b	13.30a	29.11a
	F-test	30.3 **	41.8 **	21.7 **	30.4 **	59.9 **	26.9 **
	NM-D_2	2.2	34.5	567	26.1	14.46	31.18

1 The different lowercase letters in the same column show significance at $p < 0.05$. 2 * means significant ($p < 0.05$), ** means extremely significant ($p < 0.01$). 3 Column values for the various years with different uppercase letters are significantly different at $p < 0.05$.

According to the significance F-test based on the mean dates of 2 years, illuminating that no evident differences were found in yield indexes between MD_1 and MD_2, whereas significant differences appeared in maize bald tip length, hundred-grain weight, and grain yield among treatments of MD_2, MD_3, and MD_4. We use the regressions to present the relationships of maize bald tip length, hundred-grain weight, and grain yield with the days of PD delay (in Figures 6–8). When the typical date of late spring cold (around May 1) was regarded as the starting point, an evident linear relationship existed between the grain yield indexes and the days of PD delay (MD_2–MD_4). That is, for every 10 days of PD delay, bald tip length increased by 23.2%, whereas hundred-grain weight and grain yield decreased by 4.5% and 8.5%, respectively. According to the regression equation, it concluded that the yield penalty (4.2%) was less than 5.0% with a yield exceeding 15 $Mg \cdot ha^{-1}$ when PD delayed to May 8.

Therefore, obtaining a super high yield is possible under mulched drip irrigation when the medium-mature maize varieties with close-planting are sown from April 20 to May 8 in the area.

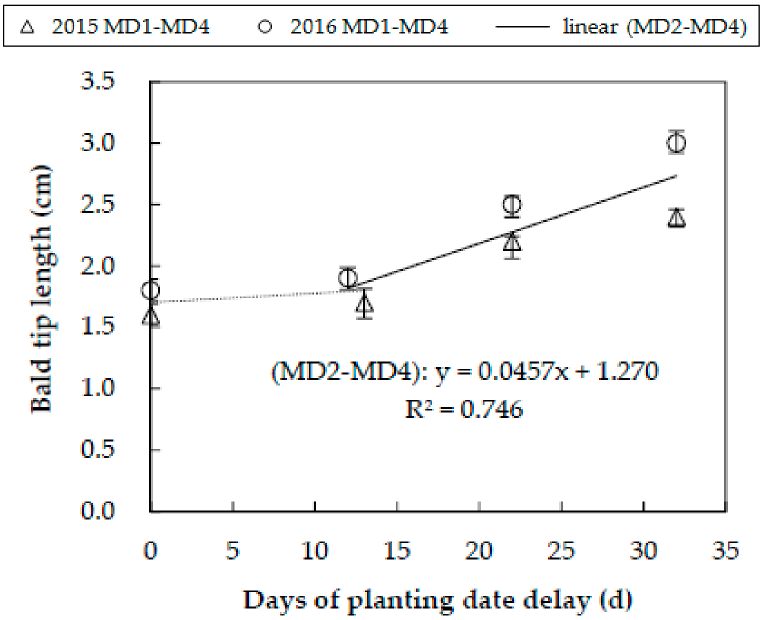

Figure 6. Effect of planting date on Bald tip length.

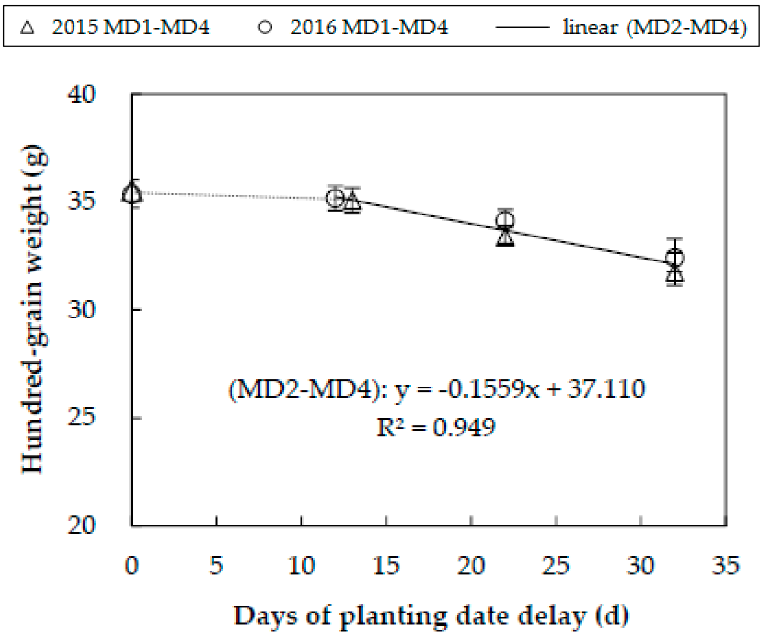

Figure 7. Effect of planting date on hundred-grain weight.

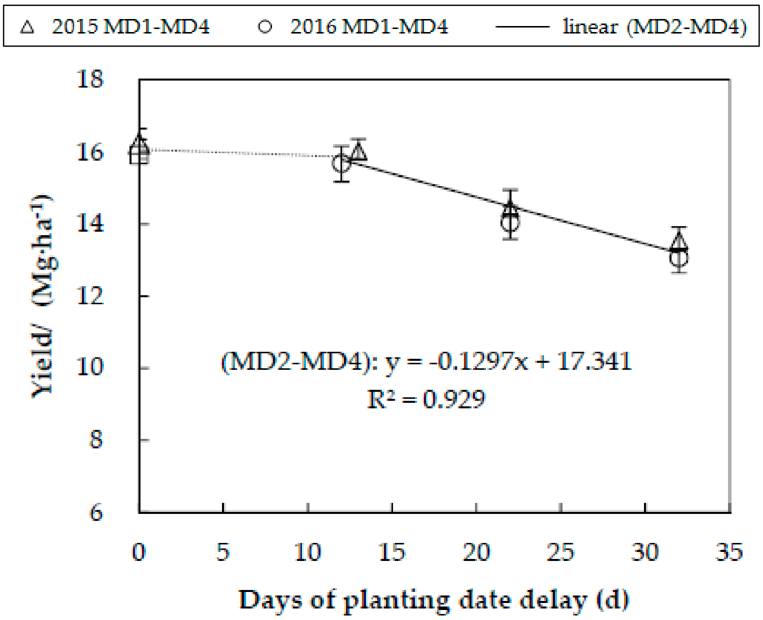

Figure 8. Effect of planting date on maize yield.

4. Discussion

The selection of an appropriate planting time for maize belongs to the category of ecological climate adaptability with regards to the degree of interaction between growth habit and climate condition [36]. Water stress is a key factor that restricts grain yield in areas with limited irrigation, and PD mainly affects yield formation by regulating the reasonable correspondence between rainfall and GP [11]. However, in areas where chilling injury frequently occurs, the selected PD should fully use photo-thermal resources for the limited accumulated temperature [13]. The test was conducted in a cold middle-latitude region with general occurrence of late spring cold from the end of April to early May, along with the regularity of spring drought. Generally, farmers tend to delay maize planting with temperature and soil moisture under consideration. Whereas, the probability of experiencing early autumn freezing (at the end of September) was increased in the later GP of maize, hence resulting in irregular grain yields. In this study, the application of mulched drip irrigation technology provided an environment with appropriate water and fertilizer levels for maize during the entire GP. Therefore, the study mainly analyzed the effects of chilling injury from certain growth stages and AAT differences caused by various PDs on maize growth.

Maize is highly sensitive to chilling injury, which mainly affects crop growth by changing crop root activity, enzyme activity, and photosynthetic rate [37,38]. The chilling injury at the seedling (MD_1) or sowing–VE (MD_2) stages delayed maize jointing or emergence, but the GP (>150 days) met the growth demand and ensured grain physiological maturity. Nevertheless, the maize sowed after May 12 (MD_3 and MD_4) suffered from early autumn freezing at latter growth stages, resulting in significant shortening in GP duration and increase in grain moisture content with failing to reach physiological maturity. The results verified the previous viewpoint that early autumn freezing is detrimental to maize growth [2,39]. On the basis of the maize growth and yield indexes with different PDs, a delay in PD was found to cause weak individual growth and reduced proportion of dry matter in ears (Table 4), which were not conducive to the formation of economic output (Table 5). The results coincided with Dong's viewpoints [40].

Planting date significantly affected the AAT distribution. The AATs in maize's entire GP decreased with the delay in PD under MD_1–MD_4, and the difference mainly manifested during the reproductive growth stage. At this stage, AATs decreased by an average of 96.6 °C for every 10 days of PD delay (Table 3). Whether the AATs in maize reproductive growth stage could meet the growth demand is a key factor in yield formation for the significant effects on grain filling and dehydration process [13,41]. The relationship between maize yield and AATs in this stage is analyzed in Figure 9, which shows that when sowing was performed before May 3 (MD_1 and MD_2), AATs were sufficient to ensure grain physiological maturity with high yield. But with continuous delay in PD (MD_2–MD_4), grain yield exhibited a negative correlation with AATs at this stage, and the amplitude of yield penalty reached 6.14–7.74% for every 100 °C of AAT decrease. Confirming the key measure to guarantee high yield is to ensure grain maturity before early autumn freezing with the maximum use of accumulated temperature [42]. Moreover, the decreasing solar radiation and light interception together with low temperature in latter growth stages exerted adverse effect on yield formation for the late sowing maize [18,43].

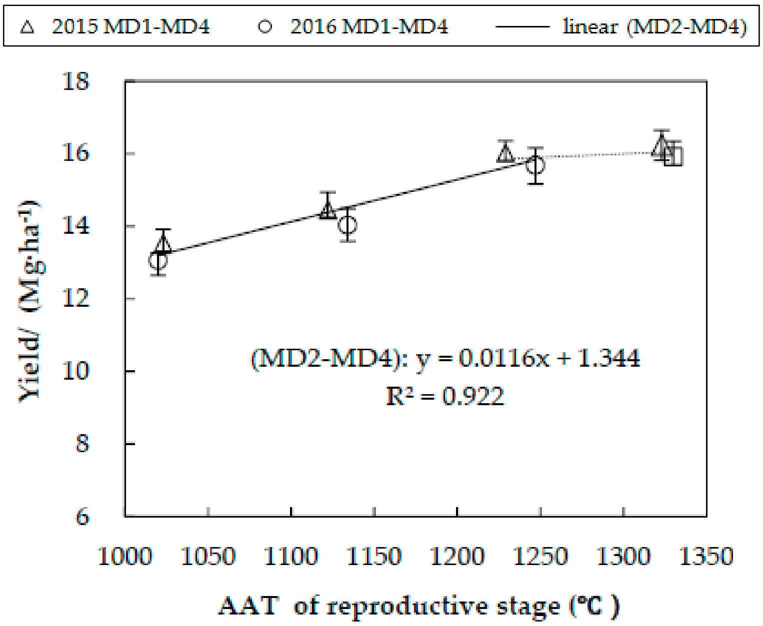

Figure 9. Effect of active accumulated temperature for reproductive stage on maize yield. AAT–active accumulated temperature.

Numerous studies have assumed that chilling injury at each growth stage will lead to varying degrees of yield reduction [13,44,45]. For the early sowing treatments in this study, the late spring cold slowed down maize early growth, but exerted no evident adverse effects on yield benefit. Reasons may be as following: the warming effect of film mulching could partly compensate for the lack of heat during the early stage of maize, thereby guaranteeing high emergence rate and nonfatal hurt from low temperature to seedlings; moreover, sufficient active accumulated temperature and solar radiation during maize growing season promoted the potential productivity. In the test, the yield from NM-D_2 treatment appears to be about the same as the yield from MD_3 treatment but less than that from MD_2 treatment, which showed an evident yield benefit from film mulching. However, early autumn freezing during the reproductive stage led to considerable yield reduction. Therefore, maize should be sown in advance with film mulching in cold middle-latitude regions to avoid early autumn freezing and ensure that GP duration and AATs can meet growth requirements.

In the test region, we suggest that the medium-mature variety of maize is sown from April 20 to May 8 with available irrigation. Compared with the conclusions of Yu et al and Cao et al. (maize cultivation without film mulching) [18,19], appropriate sowing intervals exhibited an increasing trend and were 5–7 days in advance, with 8.3–80.5% increase in grain yield. Appropriate advanced sowing gained a super-high yield in this study, also due to the technology of drip irrigation, which provided in-season supply of water and fertilizers for maize [30,46]. For the same latitude areas with similar ecological environments, it's potential to obtain high yield when the maize sowing date is in range of 10 days before or after the late spring cold, for a medium-mature variety of maize under mulched drip irrigation.

5. Conclusions

Mulched drip irrigation has shown a broad development prospect in middle-latitude spring maize planting area with low temperature and chilling injury. In this study, the effects of environment difference caused by varying PDs on maize growth under mulched drip irrigation were analyzed. The conclusions were as follows:

(1) Film mulching could significantly improve soil temperature, and the warming effect was more evident in maize early growth stages and gradually decreased with the postponement of PDs (based on MD_1). The warming effect of mulching was effective in compensating for the lack of heat caused by the low-temperature environment at the early growth stages of maize, which was beneficial to the improvement of maize emergence rate and economic yield.

(2) Planting date markedly affects AATs and maize growth process. Both AATs and maize GP duration decreased with the delay in PD (based on MD_1). When the PD was within April 20–May 2, the GP and AATs could meet the growth demand, whereas a delay of the PD until May 12 or later failed to guarantee grain physiological maturity.

(3) The effect of PD on maize growth was closely related to chilling injury (the late spring cold and early autumn freezing). The late spring cold slowed down maize early growth process (MD_1 and MD_2), but no significant adverse effect existed on later growth. As to MD_3 and MD_4, the occurrence of early autumn freezing at maize later stages led to significant decrease in AATs during the reproductive stage with adverse effect on grain filing and dehydration, and subsequently resulted in evident yield penalty (11.3–16.8%).

(4) Taking the date (May 1) of late spring cold generally occurring as the starting point, there was a significant positive correlation in maize bald tip length and the days of PD delay, while the changing tendency of hundred-grain weight and grain yield with the days of PD delay showed a linear decreasing trend; the AATs of maize reproductive stage gradually decreased with the postponement of PD, and the grain yield decreased linearly with the decrease in AATs of this stage.

Based on the threat of chilling injury in the middle-latitude area, it seems more reasonable to plant medium-mature maize varieties with close-planting in range of 10 days before and after the late spring cold to obtain a potential high yield (>15 $Mg \cdot ha^{-1}$) under mulched drip irrigation.

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