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Full Length Article

Higher Yields of Rain-Fed Maize Affected by Drought and Sowing Date in a Semi-Humid Region of North-Eastern China

Na Mi, Yushu Zhang*, Fu Cai, Ruipeng Ji, Shujie Zhang and Nina Chen
Institute of Atmospheric Environment, China Meteorological Administration/Key Laboratory of Agrometeorological Disasters, Liaoning Province, Shenyang, 110166 China
*For correspondence: yushuzhang@126.com; mina7921@126.com

Abstract

This field experiment was sown at different dates with 10-day intervals beginning 20 April for two years (2014–2015). Total growth period was significantly ($P < 0.001$) and negatively correlated to the average temperature during the entire growing season and decreased progressively with the extent of delay in sowing. Average above ground dry matter at maturity (235–311 g/plant) for all the five sowing dates in 2015 was lower than in 2014 (312–447 g/plant) due to low soil moisture, especially during the reproductive stage in July and the grain-filling stage in August. In 2014, grain yield decreased progressively with the delay in sowing, whereas in 2015, the pattern was reversed. Grain yield was significantly ($P < 0.001$) and positively correlated to the number of kernels per ear. The date of sowing is crucial in drought years and can lower the yield losses of rain-fed maize by 11–39% in the semi-humid region of North Eastern China, and choosing the right date based on climatic prediction may help in reducing the impact of drought on yield.

Keywords: Anthesis-silking interval (ASI); Drought stress; Grain yield; Kernel number; Spring maize

Introduction

Among the regions that grow rain-fed maize (*Zea mays*) in China, North Eastern China (NEC) is the largest and accounts for more than 30% of China's maize production (Liu *et al*., 2013). Drought is among the main limiting factors for maize production in NEC and drought stress is particularly severe during the seeding and flowering stages of the crop (Yin *et al*., 2016). Within NEC, the dry semi-humid zone, with 450–600 mm of annual rainfall that accounts about 80% of the total yield from the region. As part of the global warming and climate change, droughts are likely to be both more frequent and more severe by 2050 and the dry semi-humid zone in the mid-western part of NEC is expected to suffer the most from drought (Zhao and Luo, 2007; Lu *et al*., 2015), which means that maize production in NEC will be affected since drought often results in marked reductions in crop growth and grain yield (Mi *et al*., 2016). It is therefore important to develop some counter measures to drought.

The date of sowing and the crop's requirements of degree days are two important factors that affect maize yield (Sacks and Kucharik, 2011). Phenological observations on maize from 1990 to 2009 in NEC showed that the date of sowing had been advanced by up to 10 days each decade at 41.5% of the investigated stations (Li *et al*., 2013), compared to 3–8 days per decade in central USA (Kucharik, 2006). Advancing the date of sowing is considered to be an effective measure to adapt to the increasingly warmer climate, and that measure, together with cultivars better suited to a longer growing season, increased maize yields by 17–33% in NEC (Liu *et al*., 2013) and by 19–53% in central USA (Kucharik, 2008). Early sowing not only helps in realizing the full potential of the long-duration cultivars but also makes it more likely that the crop will be physiologically mature before severe frosts that occur in the fall (Sacks and Kucharik, 2011; Liu *et al*., 2013). In the warm plains of southwestern USA, early sowing is crucial to avoid the adverse impacts of extremely high summer temperatures (Myoung *et al*., 2016; Ahmed *et al*., 2017). Another study that simulated global crop yields found that choosing the right date for sowing and the right cultivar can increase yield in temperate regions and cut crop losses by 7–18% (Deryng *et al*., 2011). The right sowing date (SD) can also help in alleviating drought stress around sowing time because yield is highly correlated to soil moisture content at this stage (Lu *et al*., 2017). Above all, it is necessary to realize the importance of taking meteorological variability into account for optimizing crop production (Teasdale and Cavigelli, 2017).

Both computer simulations (Anapalli *et al*., 2005; Soler *et al*., 2007) and field experiments (Kucharik, 2008) have shown that given adequate soil moisture during sowing time and lack of drought stress during the growing season, early sowing increases maize yield markedly. Early-maturing cultivars and earlier sowing are recommended for

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rain-fed maize because delayed sowing generally increases the days to flowering and the anthesis-silking interval (ASI) and lowers yields (Kamara *et al*., 2009). However, it is not known whether the above conclusions would be valid if drought stress occurs during the active growth stage of maize (July–August) and only a few studies have addressed it. This two-year field experiments were undertaken to analyse the above-ground biomass, phenology, development of tassel and silk and yield as affected by different dates of sowing and to evaluate the extent to what the yield of maize in the semi-humid region of NEC can be maximized by adjusting the date of sowing.

Materials and Methods

Site Description

The experiment was conducted in the maize-growing season of 2014 and 2015 at the Jinzhou Agricultural Ecosystem Research Station (41°49′ N, 121°12′ E; elevation 17 m) in southwestern NEC. The region has a continental monsoon climate with four distinct seasons. The mean annual temperature is 9.9°C and the mean annual precipitation is 568 mm (average of 1981–2010). About 60% of the precipitation is received between July and September. The soil is brown and slightly acidic (pH of 6.3), typical of the region, with the following nutritional composition: organic matter, 15.24 g/kg; nitrogen, 1.04 g/kg; phosphorus, 0.50 g/kg and potassium, 22.62 g/kg (Cai *et al*., 2017). The total rainfall during April to September of 2014 and 2015 was only about 60% of the long-term average (Fig. 1a), with the deficit concentrated mostly from July to September (Fig. 1b).

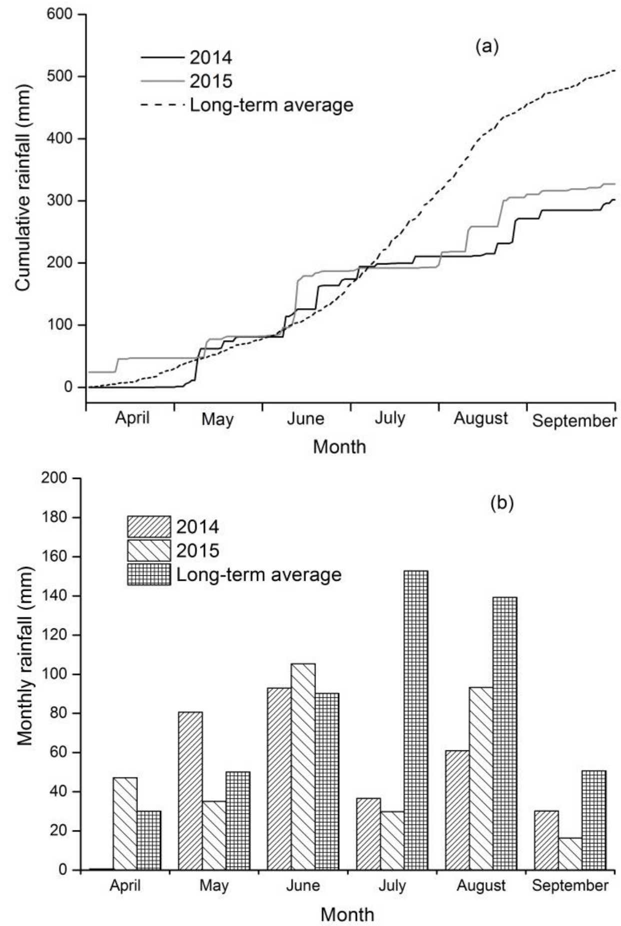

Fig. 1: Cumulative rainfall (**a**) and monthly rainfall (**b**) during April–September of 2014 and 2015 in Jinzhou

Experimental Design

To create contrasting environmental conditions that represent a wide range of situations for maize growth and development, five sowing dates were chosen around the sowing window recommended for Jinzhou (Fig. 2), namely April 20 (A), April 30 (B), May 10 (C), May 20 (D) and May 30 (E). The cultivar was Danyu 39, the most commonly grown cultivar in the area. Each plot was 21.0 m² (3.5 m × 6.0 m) and the planting density was 4.48×10^4 plants per hectare in 2014 and 4.56×10^4 in 2015. The plots were assigned to the five sowing dates at random, using the complete block design with three replicates. A compound fertilizer (28% N, 11% P_2O_5 and 12% K_2O) was applied at the time of sowing at 750 kg/ha. The plots were irrigated only once, on the date of sowing, to ensure proper emergence of seedlings. Diseases, pests, and weeds were kept well under control.

Environmental and Plant Variables

The moisture content of soil to a depth of 50 cm was determined gravimetrically, by weighing, every 10 days from April to September (Fig. 3). The details of the method are given by Song *et al*. (2018). The sampling point was close to the plots in which maize was sown on 10 May in 2014 and 2015. Each measurement was replicated four times. The soil relative water content (SRWC) was calculated using the following equation:

$$\text{SRWC (\%)} = \text{(weight of wet soil - weight of dry soil)/weight of dry soil / F.C.} \times 100$$

Where F.C. (field capacity) is the soil water content measured 24 h after copious watering.

The date of onset of each stage was the date on which 50% of the plants showed the features characteristic of respective stage. The stages were as follows: emergence, 3-leaf, 7-leaf, jointing, tasselling, anthesis, silking, milk and maturity. In 2015, the number of plants showing tasselling and silking was also counted to determine the percentage of plants which reached these two stages.

At each stage after emergence, three plants from each treatment were cut close to the soil surface for leaf measurements. Leaf area of maize was measured at different

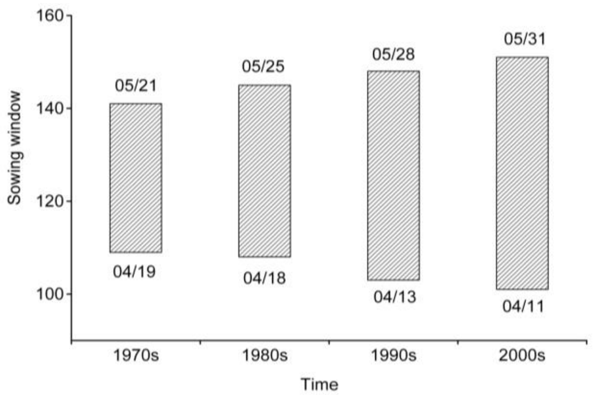

Fig. 2: Calculated sowing window in Jinzhou for the past 40 years. The first day (month/date) for sowing was determined by the day when daily air temperature remained steadily above 10 ℃ and the last day (month/date), by calculating backwards from the earliest frost day (12 Oct.) during the past 30 years (1981–2010) when the accumulated temperature amounted to 3,000℃ d

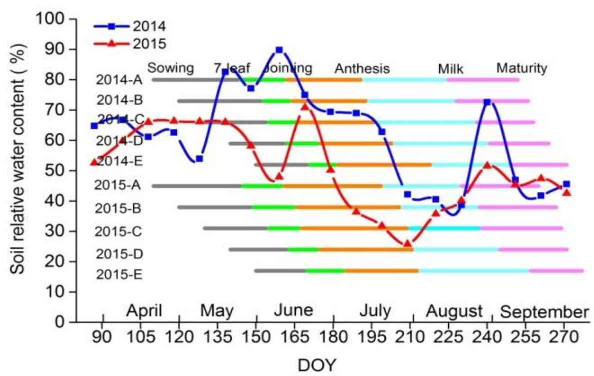

Fig. 3: Soil relative water content (0–50 cm depth) during April to September measured manually every 10 days and corresponding growth stage in plots sown on different dates (A, April 20; B, April 30; C, May 10; D, May 20 and E, May 30)

stages. The maximum length and width of each leaf were measured for every plant in the sample. The conventional formula to calculate the total leaf area per plant was used, as follows (Francis *et al*., 1969):

$$\text{Total leaf area of an entire plant} = \sum_{i=1}^{n}(L_i \times W_i \times 0.75)$$

Where i is the number of the leaf in the order of its appearance on the plant, n is total number of leaves on the plant, L_i is maximum leaf length and W_i is maximum leaf width. The leaf area index (LAI) was calculated using the following equation:

LAI = Total area of all the leaves on one plant × plant stand density

All the samples were then heated at 105°C for 30 min, dried at 70°C to a constant weight.

At maturity, 20 plants selected at random were harvested by hand from each treatment and air-dried. Yield components, namely grain weight per plant, the number of kernels per ear and 100-grain weight, were determined for each plant. Harvest index of each treatment was calculated by the grain yield divided by total dry matter produced above ground. To determine the moisture content of kernels, the collected samples were weighed, dried in an oven, and weighed again. Yield was expressed with 0% moisture. The number of grains per ear was the average of 12 ears from each replication and 100-grain-weight was the average of eight lots of 100 grains each, and corrected to 0% moisture. Grain yield per unit area was calculated by multiplying the weight of grains per plant by the number of effective plants in the unit area.

Statistical Analyses

Linear analyses were carried out on growth period (number of days) and average temperature from sowing to maturity, as well as grain yield and number of kernels per ear, using Origin ver. 9.1.0 (OriginLab, Northampton, Massachusetts, U.S.A.). The data of dry matter per plant, grain yield, 100-grain-weight and no. of kernels per ear were subjected to ANOVA by using SPSS ver. 10.0 (Chicago, U.S.A.). Means were separated by the least significant difference (LSD) test at the probability level of 0.05%.

Results

Growth Stages of Maize

The total growth period (from sowing to maturity) decreased with the delay in sowing (Fig. 4). In fact, the total growth period was significantly ($P < 0.001$) and negatively correlated ($r = 0.93$) to the average temperature during the entire growing season (Fig. 5). In other words, the length of the growing season varied with the SD, which, in turn, affected the average temperature of the entire growing season to a considerable degree: compared to the duration of the crop when the SD was April 20, as compared with the SD of May 30 with shorter by 21–23 days. The shortening of the growth period (by 3–20 days) was mainly due to the shortening of the vegetative stages; the length of the reproductive growth stage (60–63 days) was relatively constant for all the SDs except May 30; in that crop, the reproductive stage lasted only for 53 days in 2014.

Leaf Area Index and Dry Matter Accumulation

The seasonal LAI traced similar shaped curves both in 2014 and 2015 in all the treatments, although the maximum value of the LAI decreased with the delay in sowing (Fig. 6). Compared to the maximum value of the LAI of the crop with SD of April 20, while for the crop with SD of May 30 was smaller by 1.4 in 2014 and by 1.1 in 2015. Except May 30, the greater the delay in sowing, the shorter it took for the crop to reach its peak LAI. When the SD was April 20, the crop took longer compared to SD May 30, to reach its peak LAI; 79 days in 2014 and 82 days in 2015, or 17 days

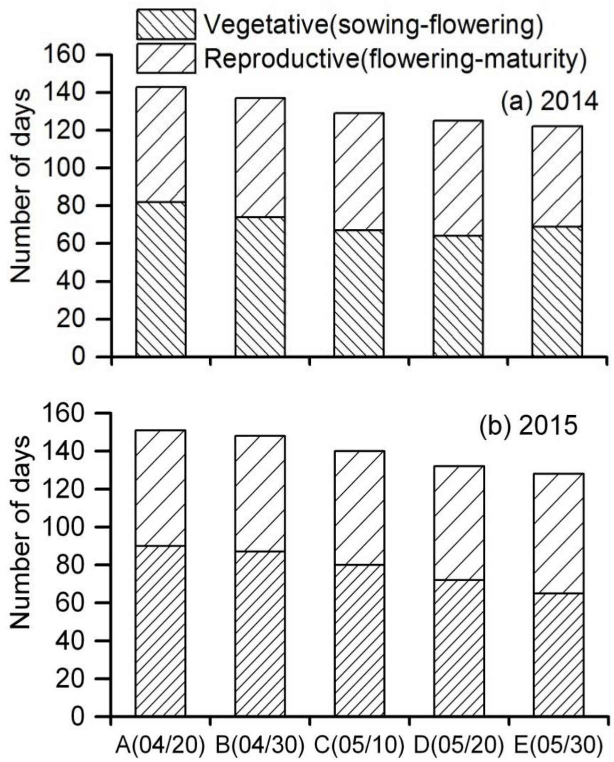

Fig. 4: Length of vegetative and reproductive stages of maize sown on different dates (A, April 20; B, April 30; C, May 10; D, May 20; and E, May 30) of 2014 (**a**) and 2015 (**b**)

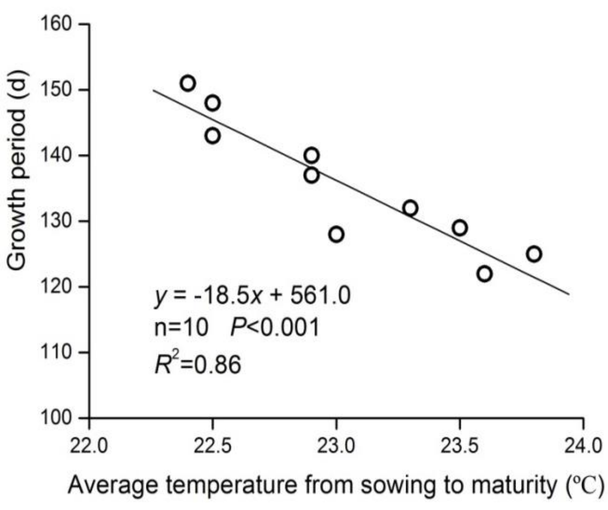

Fig. 5: The relationship between total growth period and average temperature for entire growing season

longer in 2014 and 19 days longer in 2015.

Both in 2014 and 2015, dry matter under different SDs traced the same S-shaped curve, but the results differed between the two years: total above ground dry matter in 2014 was higher than in 2015 irrespective of the SD and at maturity decreased gradually with the delay in sowing in

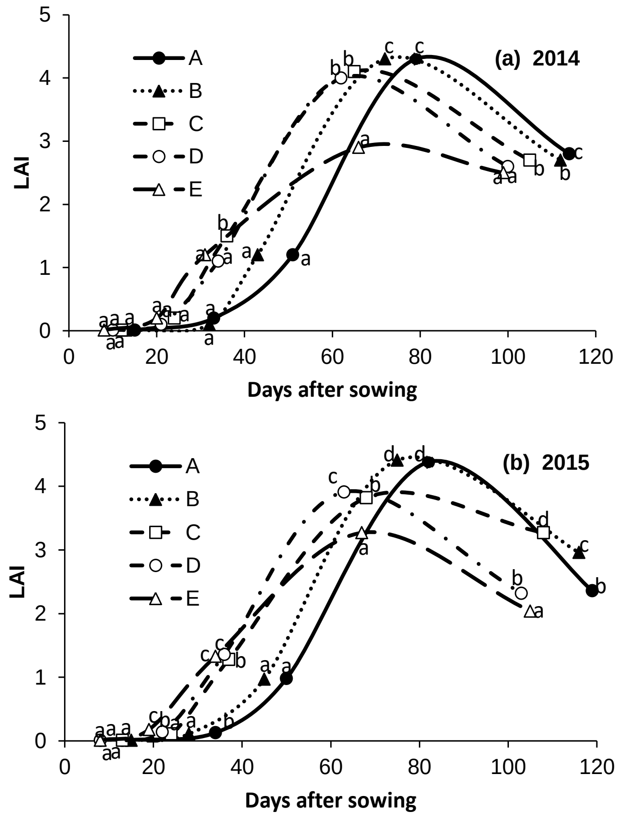

Fig. 6: Leaf area index of crop during 3-leaf, 7-leaf, jointing, tasselling and milk stages under different sowing dates (A, April 20; B, April 30; C, May 10; D, May 20; and E, May 30) of 2014 (**a**) and 2015 (**b**)

Means within the same growth stage followed by differing small letters are significantly different at the 0.05 probability level (LSD)

2014 but increased with the delay in 2015 (Fig. 7a, b). In 2014, dry matter was maximum in the earliest SD (20 April) and minimum in the last SD (30 May); in 2015, the patterns was the exact opposite, with the lowest dry matter production being recorded under the SD of 20 April. After the tasselling stage, the rate of dry matter accumulation in 2015 was slower than in 2014, especially at SDs of 20 April and 30 April, which led to the overall decrease in dry matter at maturity in 2015, the value being 235–311 g per plant in 2015, compared to 312–447 g per plant in 2014.

Tasselling, Silking and Anthesis–silking Interval

The drought in 2015 during the maize-growing season delayed anthesis and silking, especially for SDs 20 April to 20 May (Fig. 8). For the SD of 20 April, the delayed onset of silking led to the longest (15 days) anthesis-silking interval among all the SDs. The delay also affected the development of male and female organs: 12% plants failed to produce tassels and only half of them reached the silking stage. Delayed sowing facilitated tasselling and silking: for the SDs 20 May and 30 May, all the plants produced tassels

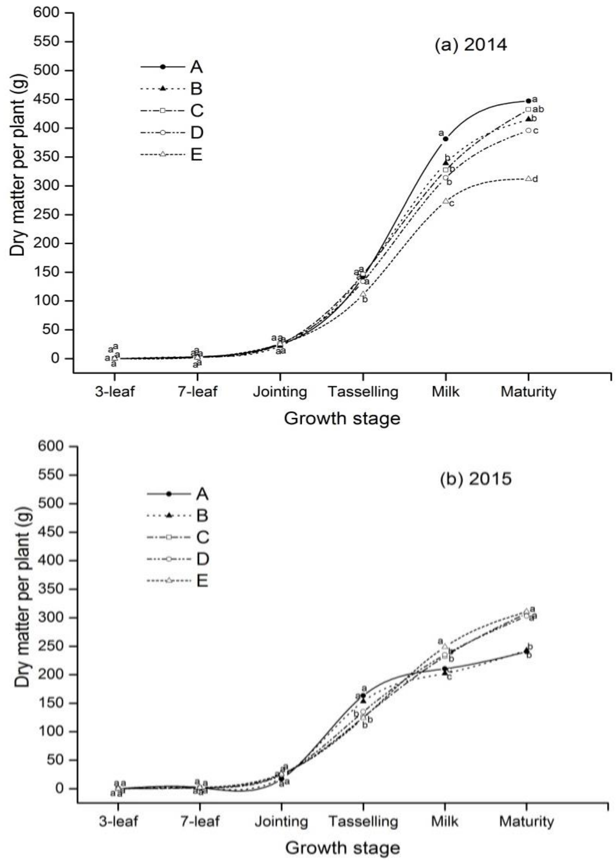

Fig. 7: Dry matter accumulation per plant under different sowing dates (A, April 20; B, April 30; C, May 10; D, May 20; and E, May 30) of 2014 (**a**) and 2015 (**b**)
Means within the same growth stage followed by differing small letters are significantly different at the 0.05 probability level (LSD)

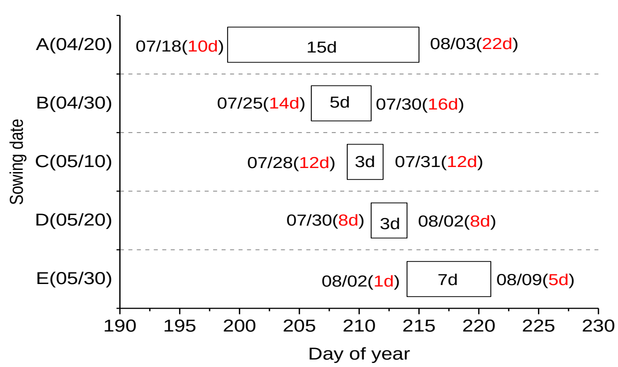

Fig. 8: Dates of anthesis, silking, and anthesis-silking interval under different sowing dates in 2015. Red numerals within brackets show the extent of delay (in days) compared to a normal year

and more than 85% reached the silking stage (Fig. 9).

Grain Yield and its Components

Grain yield showed different patterns during both years but was markedly affected by the SD (Table 1), with the earliest

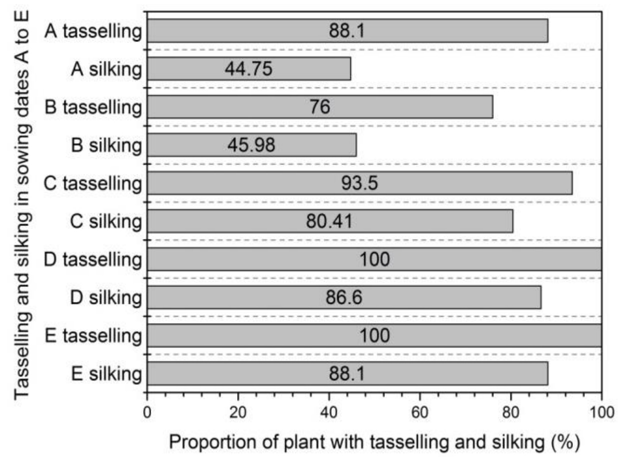

Fig. 9: Proportion (%) of plants producing tassels or silks under different sowing dates (A, April 20; B, April 30; C, May 10; D, May 20; and E, May 30) in 2015

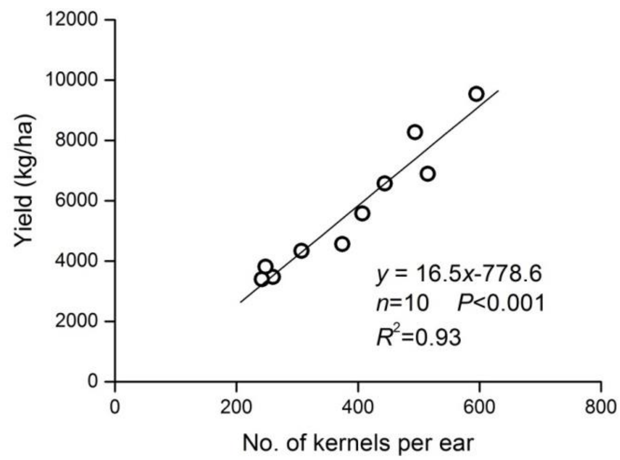

Fig. 10: The relationship between grain yield and number of kernels per ear

date resulting in the highest yield in 2014 and a progressive decrease with the delay, such that the highest yield was 71.0% greater than the lowest yield, resulting from the last SD (May 30). In 2015, maize yields from late sowings (May 20 and May 30) were significantly (P < 0.05) greater than from other sowings by 13.6–34.3%.

Kernel weight per plant is result of number of kernels per ear and the average weight of a kernel; both affected by SD (Table 1). In 2014, greater the delay in sowing, the lower was the number of kernels per ear, whereas in 2015, the pattern was exact opposite, with maximum number of kernels being recorded in the last SD. Both in 2014 and 2015, grain yield was significantly (P < 0.001) and positively correlated to the number of kernels per ear (r = 0.96, Fig. 10), an attribute that explained 93% of the variation in grain yield. As to the average weight of a kernel, in both the years, 100-grain-weight decreased with the delay in sowing. In 2014, the weights from the SDs 10

Table 1: Effects of sowing date on yield, yield components, and harvest index

Plant Date	Yield (kg/ha)		Hundred-grain weight (g)		No. of kernels per ear (grain/ear)		Harvest index	
	2014	2015	2014	2015	2014	2015	2014	2015
A(20 April)	9546a	3476c	37.8b	32.4c	595a	260c	0.55	0.32
B(30 April)	8278b	3403c	40.4a	33.4b	494b	242d	0.49	0.34
C(10 May)	6897c	3817b	31.9d	36.5a	515b	248d	0.53	0.32
D(20 May)	6572c	4337a	34.5c	33.5b	444c	307b	0.54	0.43
E(30 May)	5581d	4569a	32.0d	29.0d	407d	374a	0.49	0.39

Note: Means within a column followed by differing small letters are significantly different at the 0.05 probability level (LSD)

May and 30 May were lower than those from the other SDs and in 2015, the lowest 100-grain-weight was recorded at SD of May 30. As a whole, the harvest index (HI) in 2014 was higher than in 2015. However, the earliest SD (April 20) led to the largest HI (0.55) in 2014 and the lowest HI (0.32) in 2015 (Table 1).

Discussion

The effect of drought on maize has been studied extensively but most of these studies consider drought as a single stress factor; few studies focused on crop phenology as affected by drought. Generally, the growth of cereal plants is closely linked to the temperature of the growing parts of the plant: growth and development are faster at high temperatures with corresponding shorter growth season. Consistent with the results of an earlier experiment in NEC (Lu *et al*., 2017), the present study also found the growth period of maize to be shorter as a result of delayed sowing: the earliest date of sowing resulted in the longest growth period. However, by dividing the total growth period into its two phases, namely vegetative and reproductive, and comparing the influence of different SDs on each separately, it was noted that postponing sowing mainly shortened the period of vegetative growth and of reproductive growth being affected only slightly. This difference can be explained by the varied response of the plant to the environment at different growth phases (Tsuji *et al*., 1998). Temperature is the principal environmental factor for vegetative growth, which is more sensitive to water deficit (Tsuji *et al*., 1998). Therefore, anthesis delayed with the SD of May 30 in 2014 and 2015. The time taken for grain filling was determined by temperature, and the process is sensitive to water deficit (Tsuji *et al.*, 1998; Xiao *et al.*, 2017). In 2014, the crop sown on May 30 was exposed to drought stress both before anthesis, which delayed its onset and after anthesis, which shortened the reproductive period as well. Nevertheless, as a whole, the growth period of maize was significantly and negatively correlated to the average temperature during the entire growing season (Fig. 5).

Environmental factors and stress affect the growth of maize during its vegetative stage in terms of cell mass and the number of cells. The delay in sowing of spring maize exposed it to higher temperatures which speeded up growth and shortened the time it takes to attain the maximum LAI (Fig. 6). However, the very late sowing (May 30) markedly lowered the maximum LAI and also extended the time it took to attain the maximum LAI, which can be attributed to the effect of drought stress during the vegetative stage. Song *et al*. (2018) also reported that pre-anthesis drought markedly limited vegetative growth, leading to decreased plant height and leaf area.

In 2015, lower moisture in July delayed crop development in all the treatments (Fig. 8). As mentioned earlier, the time to anthesis is determined by developmental mechanisms governed by the genotype, temperature, photoperiod and specifically depends on the number differentiated leaves in the apical meristem and phylocron (Borrás *et al*., 2007). Whereas time to silk is a function of biomass accumulation in the ear and currently considered to be limited both by the supply of assimilates and the status of water in plant tissue (Oury *et al*., 2016a, b). It was found that drought stress markedly delayed the development of female organs, whereas the male inflorescence affected less, which is consistent with the present knowledge of maize phenology as affected by drought (Barnabás *et al*., 2008). The differential responses of male and female organs to drought led to a longer anthesis-silking interval (Fig. 8). Compared to delayed sowing, earlier sowing increased the number of days to flowering and silking and the ASI and reduced dry matter production, yield, and yield components.

Drought not only increases the days to flowering, silking and ASI but also affects the development of male and female organs. Earlier sowings (April 20 and April 30 in 2015) delayed tasselling and silking but the proportion of plants producing silks was less than plants producing tassels (Fig. 9), probably because the determinants of the development of male and female organs are different. Silking at the level of an individual plant depends on the specific time by which an ear reaches a critical biomass (Borrás and Vitantonio-Mazzini, 2018): if a given ear cannot attain that critical minimum biomass, the ear will not reach the silking stage. Drought stress during July 2015 decreased above ground biomass (Fig. 7b). Thus, ear growth was reduced not only because the entire plant accumulated less biomass but also because the proportion of the total biomass effectively allocated to the ear was reduced even more (Borrás and Vitantonio-Mazzini, 2018). The present study results showed that pre-anthesis drought had markedly limited the growth of ears and some of them failed to reach the silking stage. Compared to silking, anthesis is less affected by plant growth (Yao *et al*., 1991; Farooq *et al*., 2009). Therefore, almost all the plants reached anthesis for all the SDs in May whereas 12–24% of plants from April sowings failed to reach anthesis, probably because the severe drought increased the plant-to-plant variability, and the canopies were less uniform (Maddonni and Otegui, 2004; Rossini *et al*., 2011). However, the key factor that determines whether a maize plant can reach anthesis is yet to be identified definitively and needs more research, although drought was shown to reduce the number of pollen grains per tassel but not pollen viability (Hall *et al*., 1981; Herrero and Johnson, 1981). It was also found that drought affected the development of female organs and some plants failed to reach the silking stage, which decreased the number of kernels and thus grain yield from unit area.

Mass accumulation is governed by the photosynthetically active radiation (PAR), which produces assimilates that eventually form plant biomass. Thus, the growth of biomass is dependent on the amount of PAR and the leaf surface area available to absorb the PAR for photosynthesis (Tsuji *et al*., 1998). In the absence of environmental stress, early sowing contributes to higher biomass in maize by extending the period of vegetative growth. This accounted for the higher above ground biomass at tasselling in the April sowings in 2014 and 2015 (Fig. 7). In 2015, above ground biomass in treatments increased more slowly than in other treatments after tasselling and was significantly lower ($P < 0.05$) at milk and maturity stages (Fig. 7b), resulting in marked deterioration in ear formation and poor grain filling, leading to significantly fewer kernels per ear (Farooq *et al*., 2009; Ge *et al*., 2012). Water deficit at anthesis also contributed to markedly fewer kernels because of poor receptivity of silk; embryos did form but were aborted later (Zinselmeier *et al*., 1999) and also because of delayed silking, which led to barrenness because the pollen supply had been exhausted before silks appeared (Lu *et al*., 2011). In 2014, above ground biomass at maturity in the last sowing (30 May) was significantly ($P < 0.05$) lower than in any other treatment, because the period available for gain filling had been shortened because of drought (Fig. 4a).

Maize grain yield is closely related to the number of kernels, which is laid down during the flowering period (Borrás and Vitantonio-Mazzini, 2018). Generally, crop productivity in Jinzhou in 2014 was higher than in 2015 because of the differences in distribution of rainfall, particularly during the reproductive stage. Soil moisture content was much lower in 2015 than in 2014, especially during the reproductive stage in July and during the grain-filling period in August 2015 (Fig. 3), which led to fewer kernels and lower grain yield in 2015. Kernel number is a function of the size of the physiological sink of assimilates, a key yield component of the final grain yield in maize (Fischer and Palmer, 1984; Andrade *et al*., 1999). In the present experiment, the number of kernels was responsible for the widest variation in yield (Fig. 10). Grain yield in maize is highly sensitive to drought during the period from tasselling to silking and drought during that period leads to markedly fewer kernels (Barnabás *et al*., 2008; Song *et al*., 2018). Taking 10, 000 kg/ha as the maximum yield for this area (Mi *et al*., 2016), drought decreased maize yield by 5–44% and 54–65% in 2014 and 2015, respectively.

Conclusion

The study concluded that choosing the right sowing date is crucial to yields in drought years. The right choice can lower yield loss in rain-fed maize by 11–39% in the semi-humid region of NEC. Adjusting the sowing date can therefore help in minimizing the impact of drought during flowering and gain filling; (ii) the effects of drought on maize yield are closely related to the date of sowing, because it determines the meteorological factors during anthesis, silking and grain filling. Thus, choosing the sowing date based on climatic prediction can help to lower the adverse impacts of drought.

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References

Ahmed, Z., E.A. Waraich, R. Ahmad and M. Shahbaz, 2017. Morpho-physiological and biochemical responses of *camelina* (*Camelina sativa crantz*) genotypes under drought stress. *Intl. J. Agric. Biol*., 19: 1–7

Anapalli, S.S., L. Ma, D.C. Nielsen, M.F. Vigil and L.R. Ahuja, 2005. Simulating planting date effects on corn production using RZWQM and CERES-Maize model. *Agron. J.*, 97: 58–71

Andrade, F.H., C.R.C. Vega, S. Uhart, A. Cirilo, M. Cantarero and O. Valentinuz, 1999. Kernel number determination in maize. *Crop Sci.*, 39: 453–459

Barnabás, B., K. Jäger and A. Fetér, 2008. The effect of drought and heat stress on reproductive process in cereals. *Plant Cell Environ*., 31: 11–38

Borrás, L. and L.N. Vitantonio-Mazzini, 2018. Maize reproductive development and kernel set under limited plant growth environments. *J. Exp. Bot*., 69: 3235–3243

Borrás, L., M.E. Westgate, J.P. Astini and L. Echarte, 2007. Coupling time to silking with plant growth rate in maize. *Field Crops Res.*, 102: 73–85

Cai, F., H. Ming, N. Mi and Y. Xie, 2017. Comparison of effects of root water uptake functions for simulating surface water and heat fluxes within a corn farmland ecosystem in Northeast China. *J. Irrig. Drain. Eng*., 143: 04017040

Deryng, D., W.J. Sacks, C.C. Barford and N. Ramankutty, 2011. Simulating the effects of climate and agricultural management practices on global crop yield. *Glob. Biogeochem. Cycl*., 25: 1-18Fischer, K.S. and A.F.E. Palmer, 1984. Tropical maize. *In: The Physiology of Tropical Field Crops*. Goldsworthy, P.R. (Ed.). John WileySons, Chichester, England

Farooq, M., A. Wahid, N. Kobayashi, D. Fujita and S.M.A. Basra, 2009. Plant drought stress: Effects, mechanisms and management. *Agron. Sustain. Dev*., 29: 185-212.

Francis, C.A., J.N. Rutger and A.F.E. Palmer, 1969. A Rapid method for plant leaf area estimation in maize (*Zea mays* L.). *Crop Sci.*, 9: 537–539

Ge, T.D., F.G. Sui, L.P. Bai, C.L. Tong and N.B. Sun, 2012. Effects of water stress on growth, biomass partitioning, and water-use efficiency in summer maize (*Zea mays* L.) throughout the growth cycle. *Acta Physiol. Plant*., 34: 1043–1053

Hall, A.J., J.H. Lemcoff and N. Trápani, 1981. Water stress before and during flowering in maize and its effects on yield, its components, and their determinants. *Maydica*, 26: 19–38

Herrero, M.P. and R.R. Johnson, 1981. Drought stress and its effect on maize reproductive systems. *Crop Sci*., 21: 105–110

Kamara, A.Y., F. Ekeleme, D. Chikoye and L.O. Omoigui, 2009. Planting date and cultivar effects on grain yield in dryland corn production. *Agron. J.*, 101: 91–98

Kucharik, C.J., 2008. Contribution of planting date trends to increased maize yields in the central United States. *Agron. J.*, 100: 328–336

Kucharik, C.J., 2006. A multidecadal trend of earlier corn planting in the central U.S.A. *Agron. J*., 98: 1544–1550

Li, Z., P. Yang, H. Tang, W. Wu, H. Yin, Z. Liu and L. Zhang, 2013. Response of maize phenology to climate warming in Northeast China between 1990 and 2012. *Reg. Environ. Change*, 14: 39–48

Liu, Z.J., K.G. Hubbard, X.M. Lin and X.G. Yang, 2013. Negative effects of climate warming on maize yield are reversed by the changing of sowing date and cultivar selection in Northeast China. *Glob. Change Biol*., 19: 3481–3492

Lu, H.D., J.Q. Xue and D.W. Guo, 2017. Efficacy of planting date adjustment as a cultivation strategy to cope with drought stress and increase rainfed maize yield and water-use efficiency. *Agric. Water Manage*., 179: 227–235

Lu, H.J., X.G. Mo and D.J. Meng, 2015. Analyzing Spatiotemporal Patterns of Meteorological Drought and Its Responses to Climate Change Across Northeast China. *Sci. Geogr. Sin.*, 35: 1051–1059

Lu, Y., Z. Hao, C. Xie, J. Crossa, J.L. Araus, S. Gao, B.S. Vivek, C. Magorokosho, S. Mugo and D. Makumbi, 2011. Large-scale screening for maize drought resistance using multiple selection criteria evaluated under water-stressed and well-watered environments. *Field Crop Res*., 124: 37–45

Maddonni, G.A. and M.E. Otegui, 2004. Intra-specific competition in maize: early establishment of hierarchies among plants affects final kernel set. *Field Crops Res*., 85: 1–13

Mi, N., Y.S. Zhang, R.P. Ji, F. Cai, W.Y. Yu and S.J. Zhang, 2016. Analysis on optimum sowing date of maize in Jinzhou using crop growth model and optimum season method. *Chin. J. Agrometeorol.*, 37: 67–75

Myoung, B., S.H. Kim, J. Kim and M. Kafatos, 2016. Regional variations of optimal sowing dates of maize for the southwestern US *Trans. ASABE*, 59: 1759–1769

Oury, V., C.F. Caldeira, D. Prodhomme, J.P. Pichon, Y. Gibon, F. Tardieu and O. Turc, 2016a. Is change in ovary carbon status a cause or a consequence of maize ovary abortion in water deficit during flowering? *Plant Physiol*., 171: 997–1008

Oury, V., F. Tardieu and O. Turc, 2016b. Ovary apical abortion under water deficit is caused by changes in sequential development of ovaries and in silk growth rate in maize. *Plant Physiol.*, 171: 986–996

Rossini, M.A., G.A. Maddonni and M.E. Otegui, 2011. Inter-plant competition for resources in maize crops grown under contrasting nitrogen supply and density: Variability in plant and ear growth. *Field Crops Res*., 121: 373–380

Sacks, W.J. and C.J. Kucharik, 2011. Crop management and phenology trends in the U.S. Corn Belt: impacts on yields, evapotranspiration and energy balance. *Agric. For. Meteorol*., 151: 882–894

Soler, C.M.T., P.C. Sentelhas and G. Hoogenboom, 2007. Application of the CSM-CERES-Maize model for planting date evaluation and yield forecasting for maize grown off-season in a subtropical environment. *Eur. J. Agron.*, 27: 165–177

Song, H., Y.B. Li, L. Zhou, Z.Z. Xu and G.S. Zhou, 2018. Maize leaf functional response to drought episode and rewatering. *Agric. For. Meteorol*., 249: 57–70

Teasdale, J.R. and M.A. Cavigelli, 2017. Meteorological fluctuations define long-term crop yield patterns in conventional and organic production systems. *Sci. Rep*., 7: 1-10Tsuji, G.Y., G. Hoogenboom and P.K. Thornton, 1998. *Understanding options for agricultural production*. Kluwer Academic Publishers, Wageningen, Netherlands

Xiao, D., J. Cao, H. Bai, Y. Qi and Y. Shen, 2017. Assessing the impacts of climate variables and sowing date on spring wheat yield in the northern China. *Intl. J. Agric. Biol*., 19: 1551–1558

Yao, N.R., K. Yeboua and A. Kafrouma, 1991. Effects of intensity and timing of defoliation and growth, yield components and grain yield in maize. *Exp. Agric*., 27: 137–144

Yin, X.G., M. Jabloun, J.E. Olesen, I. Öztürk, M. Wang and F. Chen, 2016. Effects of climatic factors, drought risk and irrigation requirement on maize yield in the Northeast farming region of China. *J. Agric. Sci.*, 154: 1171–1189

Zhao, Z. and Y. Luo, 2007. Projections of climate change over Northeastern China for 21st century. *J. Meteorol. Environ.*, 23: 1–4

Zinselmeier, C., B. Jeong and J.S. Boye, 1999. Starch and the control of kernel number in maize at low water potentials. *Plant Physiol*., 121: 25–36

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