Different sowing dates effect on dry matter and nitrogen dynamics for winter wheat: An experimental study based on simulation

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Background: Timely sowing is an important agronomic measure to ensure normal germination, stable seedling establishment and final yield formation for winter wheat (*Triticum aestivum L.*). Under the current multi-cropping system and mechanized production level, the delayed sowing has frequently occurred. However, the effect of different sowing dates on yield change and its potential mechanism are still unclear in the middle-lower Yangtze River Basin.

Methods: Here, through a 2-year field study, the Logistic Curve Model which was used to simulate the dry matter accumulation (DMA) and N accumulation (NA) dynamics of wheat for single stem under different sowing dates was established, and the changes in grain yield and related traits in different sowing dates were studied.

Results: It showed that grain yield declined by (0.97±0.22) % with each one-day early or delay in sowing beyond the normal sowing date. The above yield loss could be explained by the inhibition of crop growth, yield components, biomass and N production. Meanwhile, these negative effects of delayed sowing are mainly caused by key environmental limitations including adverse weather factors such as low temperature during vegetative growth, shortened duration of various phases of crop development and increased temperature during grain filling period. However, owing to a compensation effect between the highest average rates (V_t) and the fast accumulation period (T) of DMA and NA for single stem, grain yield gap decreased between late and normal sowing. Under these conditions, if the ratio of DMA at mature to jointing stage (M_D/J_D) and the ratio of NA at mature to jointing stage (M_N/J_N) could reach 4.06 ($P < 0.01$) and 2.49 ($P < 0.05$) respectively, the grain yield could be maintained at the level of 6000 kg ha^{-1} or more. But this compensation effect still cannot avoid the impact caused by delayed sowing. Thus the final manifestation was delayed in sowing, and biomass and nitrogen production decreased. Meanwhile, the accumulation of physiological development time reached maximal accumulation rate (T_m) of NA was earlier than that of DMA.

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Abstract

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adverse weather factors such as low temperature during vegetative growth, shortened duration of various phases of crop development and increased temperature during grain filling period. However, owing to a compensation effect between the highest average rates (V_t) and the fast accumulation period (T) of DMA and NA for single stem, grain yield gap decreased between late and normal sowing. Under these conditions, if the ratio of DMA at mature to jointing stage (M_D/J_D) and the ratio of NA at mature to jointing stage (M_N/J_N) could reach 4.06 ($P < 0.01$) and 2.49 ($P < 0.05$) respectively, the grain yield could be maintained at the level of 6000 kg ha^{-1} or more. But this compensation effect still cannot avoid the impact caused by delayed sowing. Thus the final manifestation was delayed in sowing, and biomass and nitrogen production decreased. Meanwhile, the accumulation of physiological development time reached maximal accumulation rate (T_m) of NA was earlier than that of DMA.

Keywords Different sowing dates, Dry matter accumulation, Nitrogen accumulation, Grain yield, Simulation model

Introduction

Wheat is one of the most widely cultivated crops worldwide, and wheat growers in China are the largest in the world, producing 17% of the world´s total wheat (Food and Agricultural of the United Nation, 2020). Winter wheat accounts for approximately 95% of the total (winter and spring) wheat production in China (Lu et al., 2013; Wu et al., 2014; Geng et al., 2019). The middle-lower Yangtze River Basin is one of the main winter wheat growing areas in China, in which the photothermal resources are abundant and can meet the needs of rice-wheat rotation system (Zhang et al., 2013). Hence, the rice-wheat rotation is the dominant practice in this region (Liu et al., 2016). Meanwhile, this region´s grain output plays an important role in ensuring food security in China.

Sowing date is one of the most important management factor affecting grain production and quality (Ferrise et al., 2010). In a certain area, the optimum sowing date mainly depends upon the timing of rainfall and temperature (Jackson et al., 2000), which can maintain high grain yield. Rice-wheat rotation system is one of the world´s largest agricultural production systems (Gupta et al., 2003). However, there are also limitations to this planting pattern. In recent years, simple cultivation methods such as mechanical transplanting and direct seeding of rice have shortened the limitation of seedling age. At the same time, the yield benefit of late sowing rice is remarkable, and the extension area is expanding, which leads to late sowing and late harvest of rice. Wheat as the succeeding crop of rice, its traditional sowing date also needs to be adjusted accordingly (Xu et al., 2013).

As an important sign of climate change, global warming has significantly impacted agricultural production and has been the focus of considerable attention of many researchers (Sun et al., 2015; Ding et al., 2015). However, both simulation studies and observed data have showed that a significant decrease in the grown duration of winter wheat appears accompanied by a significant reduction in grain yield due to the evident warming trend (He et al., 2014, 2015; Xiao et al., 2015). Global warming over recent decades has provided extended growing periods prior to wheat wintering that encourage farmers to delay the winter wheat sowing date (Xiao et al., 2013, 2015). Studies have shown that this delay in sowing may increase, maintain or decrease the grain yield of winter wheat (Jalota et al., 2013; Ding et al., 2015; Yin et al., 2018).

Previous research has indirectly suggested that late sowing of wheat usually leads to poor crop conditions, even in the year with optimal weather (Tester and Langriridge, 2010). Delayed sowing of winter wheat will lead to adverse conditions such as low temperature in the process of crop vegetative growth, resulting in low germination rate, poor tillering ability and low plant population (Borràsgelonch et al., 2012; Fernanda et al., 2013). Meanwhile, late sowing would delay flowering and expose crops to the high temperature during grain filling stage, thus accelerating reproductive development and reducing grain filling (Bailey-Serrees et al., 2019; Dubey et al., 2019). In addition, late sowing also reduces dry matter and N accumulation in wheat crops (Ehdaie and Waines, 2001). Therefore, the delay of sowing in wheat often has a negative impact on seed germination process, tiller development, overall crop growth and final yield (Hussain et al., 2017; Kaur, 2017). It is important to note that a delay sowing in the optimal range does not have a serious negative impact on yield performance, as it usually improves the assimilate allocation and nitrogen utilization efficiency for winter wheat (Yin et al., 2018, 2019).

The formation of crop yield is determined by the accumulation and distribution of dry matter, which is the material basis for the formation of crop yield (Zheng et al., 2013). Natural and human factors such as climate, soil, and field management practices all affect the DMA process and ultimately lead to yield differences. At the same time, NA is also the main nutrient factor that affects the grain yield and protein concentration (Ehdaie and Waines, 2001). There are two main methods to describe the process of DMA and NA: one is mechanism model, and the other is empirical model (Whisler et al., 1986). In the empirical model, the Logistic (Royo et al., 1999) and Richards (Richards, 1959) growth equations have certain biological significance and are now widely used.

Some scholars used Logistic equation to describe the dry matter accumulation process of winter wheat and summer maize, as well as the NA process of cotton (Zhao et al., 2013; Xiao et al., 2014; Du et al., 2016). The accumulation of dry matter and N is a continuous process changing with time, which is closely related to yield formation, and has great differences in different years and research sites. At present, there are few studies on the effects of sowing date factors on wheat growth and yield in Jianghan Plain of the middle-lower Yangtze River Basin from the perspective of DMA, NA and yield. Therefore the objectives of this study were to (ⅰ) quantify the effect of different sowing dates on grain yield, yield components, tillers and other agronomic traits of winter wheat, and (ⅱ) clarify the Logistic model was used to fit the DMA and NA process of winter wheat in different sowing dates, and the growth process of wheat was quantitatively analyzed according to the derived characteristic quantity.

Materials and methods

Experimental site

Field experiments were conducted at the experimental farm station of Yangtze University (30˚36’N, 112˚08’E), Jinzhou City, Hubei Province, China, during two growing seasons in 2018/2019 and 2019/2020. This station is located in the Jianghan Plain, which is characterized as a typical subtropical monsoon climate zone in the middle-lower Yangtze River Basin of China. Two-year field experiments were performed in the nearby fields. The farm field chosen for this study was previously managed as a summer-rice/winter-wheat double-cropping system. The daily average temperature and precipitation during the two-year growing seasons are shown in Fig. 1. Soil samples were collected at the start of the experiments. The soil was classified as sandy loam, and the main physicochemical properties were as follows: 17.9 and 14.8 g kg^{-1} organic matter, 60.5 and 42.8 g kg^{-1} total N, 21.9 and 7.3 mg kg^{-1} available phosphorus, 116.6 and 75.7 mg kg^{-1} available potassium before sowing wheat in 2018 and 2019, respectively.

Experimental design and crop management

A widely planted winter wheat cultivar, Zhengmai 9023 was used in field experiments. Seeds were sown by broadcasting at a rate of 15 g m^{-2} in 2018 and 2019 on 28 October (early sowing), 5 November (normal sowing), 13 November (late sowing), and 21 November (latest sowing) using manual ditching drill with 25-cm row spacing. The plots were arranged according to sowing dates with four replicates. Each plot included 25 rows with 25-cm in row spacing (2 m wide) and 6 m in length. Basal fertilization of each subplot included N as urea, phosphorus as calcium superphosphate, and potassium as potassium chloride at rates of 90 kg ha^{-1} N, 105 kg ha^{-1} P_2O_5, and 105 kg ha^{-1} K_2O, respectively. An additional 90 kg ha^{-1} of N was applied at the beginning of the jointing growing stage. Fields were managed following the local cultural practices. Pests, weeds and diseases were controlled chemically.

Measurement items and methods

At three-leaf stage, two lines of 0.5 m with uniform emergence were randomly selected for fixed points in each plot. Tillers were counted before wintering and at the jointing, booting, flowering and maturity stages in each plot with three repeats, respectively.

Sampling for dry matter was carried out before wintering and at the jointing, booting, flowering and maturity stages in each plot with three repeats at ground level. These samples were subsequently separated into flag leaves, other leaves, stem sheathes, and ear tissues (glumes and grains at maturity). All samples were dried at 105 ℃ for 30 min and then at 80 ℃ in a fan-forced oven to constant weight to determine the biomass. The N concentration during each growing stage was determined using the Kjeldahl method (KDY-9820 Auto Distillation Unit, Beijing, China). N accumulation was calculated by multiplying N concentration (%) by dry weight. NA was calculated as the sum of the N uptake of the different measured organs at each growing stage. This process was repeated three times, as well.

Plants used to measure yield were harvested from a sampling area of 2.0 m × 1.0 m (row length × row width) in each plot. The grain was air-dried, weighted, and adjusted to standard 12% moisture content. This was considered as the grain dry matter yield. Effective panicle per unit area was measured from a sampling area of 1.0 m × 1.0 m (row length × row width). 30 panicles were taken continuously to determine the grain number of panicle. The 1000-grain weight was air-dried, weighted, and adjusted to standard 12% moisture content. All the above measurement items were repeated three times per treatment.

According to Zadoks growth scale (Zadoks, 1974), the corresponding accurate date of the main growth period of wheat was observed and recorded in the field, and more than 50% seedling situation in the plot was taken as the basis. The daily maximum, minimum and average temperature, light hours, daily rainfall and other meteorological datum during the two-year wheat growth period were collected from Jingzhou Meteorological Bureau of Hubei Province.

Calculations and data analysis

In order to model the accumulation pattern, a Logistic Model used to quantitatively describe the dynamic changes of accumulation in winter wheat shoot is as follows (Du et al., 2016):

$$W = \frac{W_{max}}{1 + ae^{-kT}} \quad (1)$$

where, W (g stem^{-1}) is the accumulation in wheat, W_{max} (g stem^{-1}) is the theoretical maximum accumulation, T (d) is days after emergence, a and k are the constants to be found.

The following functions can be obtained by calculating the first, second and third derivative of formula (1), respectively.

$$T_1 = \frac{1}{k} ln \frac{2 + \sqrt{3}}{a} \quad (2)$$

$$T_2 = \frac{1}{k} ln \frac{2 - \sqrt{3}}{a} \quad (3)$$

$$T_m = \frac{lna}{k} \quad (4)$$

$$V_m = \frac{kW_{max}}{4} \quad (5)$$

where, T_1 (d) is the accumulated growth time at the fastest beginning date of growth curve, T_2 (d) is the accumulated growth time at the termination date, maximum relative growth rate V_m (g stem^{-1} d^{-1}) and its cumulative growth time T_m (d).

When the fast accumulation phase was begin at T_1 and end at T_2, W is linear correlation with the days after emergence and the average growth rate (V_t).

$$V_t = \frac{W_2 - W_1}{T_2 - T_1} \quad (6)$$

Yield loss (%) due to the early or late sowing was calculated as follows:

$$Yield\ loss\ (\%) = \frac{Y_{ns} - Y}{Y_{ns}} \times 100 \quad (7)$$

where Y_{ns} and Y are the grain yields of normal and early or late sowing dates, respectively.

Statistical analysis

Data preparation was performed with Microsoft Excel software, and the final data plots were produced with Origin 8.0 software. Multiple comparisons were performed after a preliminary F-test. Means were tested based on the least significant difference at $P < 0.05$, by using Data Processing System (DPS) v.7.05 software.

Results

Weather conditions and crop phenology

Mean daily temperatures of two wheat growing seasons decreased first and then increased (Fig.

1). In the first year of wheat growing season, the duration of mean daily temperatures below 10 ℃ were 89 days (continuous 3 days and above, lower than 10 ℃), while in the second year they were shortened to 77 days. Thermal time from sowing to wintering stage decreased greatly when sowing was delayed by more than 8 days across two experimental years. Averaged across two experimental years, thermal time was reduced by 21 %, 37 %, and 51% for 8–, 16–, and 24–days delay in sowing compared with the first sowing date (28-Oct).

Mean daily temperatures from flowering to the end of grain filling increased gradually when sowing was delayed by more than 8 days across two experimental years. It ranged from 20.08 ℃ for 28-Oct to 20.71 ℃ for 21-Nov in 2018-2019, and 17.93 ℃ for 28-Oct to 20.25 ℃ for 21-Nov in 2019-2020. In the second year, there was a significant negative correlation (r = -0.94, $P < 0.05$) between the grain filling days of each sowing date and the mean daily temperatures during the filling stage.

With the delay of sowing date in 2018-2019 and 2019-2020 growing seasons, the crop growth cycle (from seeding to the end of grain filling) of each sowing date were significantly shortened. Compared with the first sowing date (28-Oct), the whole growth duration of 8–, 16–and 24–days delay in sowing decreased by 7, 12 and 18 days on average over two growing seasons. This difference was mainly due to the flowering period moved up and the compression of grain filling period for the late sowing date. Averaged across two years, the flowering date was moved up by 4.0, 7.5, and 11.5 days for 8–, 16–, and 24–days delay in sowing compared with the first sowing date (28-Oct). The duration of filling period of the four sowing dates in the first year was not significantly shortened. In the second year the latest sowing (21-Nov) and early sowing (28-Oct) shortened the filling period by 11 days under the condition of delaying 24 days.

Morphological traits

There were differences in the number of tillers at jointing and maturity. The tiller number at jointing stage of the latest sowing date (21-Nov) was higher than other sowing dates over two growing seasons, and the tiller number of sowing date on 21-Nov was significantly different from that of other sowing dates during the second year. The peak tillers appeared before or after the jointing stage. The peak tillers appeared before jointing stage for the early sowing date (28-Oct) and the normal sowing date (5-Nov), while the late sowing date (13- Nov) and the latest sowing date (21-Nov) appeared after jointing stage, which was the same for two years. The results of two year experiments showed that the tiller number of sowing date on 5-Nov was significantly higher than that of other sowing dates at maturity stage. The percentage of productive tillers on 13-Nov in two years was significantly higher than other sowing dates.

Under the condition of delayed sowing, except for the latest sowing date (21-Nov), the percentage of productive tillers increased significantly each 8-days of delay in sowing.

Yield formation

Wheat grain yield varied by both year and sowing date, and there was significant interaction between these two main factors (Table 3). The grain yield among different sowing dates ranged from 5569.7 to 6578.9 kg ha^{-1} in 2018-2019 and from 5625.0 to 7241.7 kg ha^{-1} in 2019-2020. Grain yield for each sowing date in 2019-2020 was 1.0 %~10.1 % greater than that in 2018-2019. Grain yield of 5-Nov sowing date was greater than those of the other treatments during both years. Grain yield of 5-Nov was 3.2 %, 18.7 % and 23.4 % averaged two year greater than the yields of 28-Oct, 13-Nov and 21-Nov, respectively. The results of two-year experiments showed that the sowing date was delayed for 8 and 16 days after 5-Nov, and the yield decreased significantly. After 5-Nov sowing date a consistent declining trend was observed for grain yield until the last sowing date during both years, showing that the longer the delay in sowing date, the greater the yield reduction (Table 3 and Fig. 2). Regression analysis revealed that with each one-day early or delay in sowing date on the basis of normal sowing, the grain yield declined by (0.97±0.22) % across two years (Fig. 2).

It showed that spike number was affected ($P < 0.01$) by year and sowing date, and the interaction term was extremely significant as well (Table 3). Kernel number per spike reached a very significant level ($P < 0.01$) in year and sowing date, but the interaction term was not significant. 1,000-kernel weight was only affected ($P < 0.01$) by year, and there was no significant between the sowing date and these two main factors. Among all the yield components, spike number was positive correlated with wheat grain yield ($r = 0.73$, $P < 0.05$), whereas kernel number and 1,000-kernel weight were not. The spike number per ha for 5-Nov was 9.1 %~30.3 % in 2018-2019 and 8.0 %~19.3 % in 2019-2020 greater than that for 28-Oct, 13-Nov and 21-Nov, respectively. The kernel per spike for 21-Nov was 0.5 %, 8.5 % and 8.2 % in 2018-2019, and 2.7 %, 8.0 % and 3.7 % in 2019-2020 greater than that for 28-Oct, 5-Nov and 13-Nov, respectively.

Dynamics simulation of DMA

It showed that the dynamic changes of DMA for single stem with the days after sowing conforms to the Logistic Curve Model (Fig. 3). The logistic function was followed by DMA as a sigmoidal growth pattern since all P values were < 0.01 (Table 4), although they differed in equation coefficients among the treatments. The simulated value of DMA for single stem was evaluated by Formula (1), and the characteristic value of dynamic of DMA for single stem was obtained (Table 5).

Calculation by Formulas (2)-(4) based on Table 4 showed that the beginning and termination day at the fast accumulation period of winter wheat DMA for single stem under all sowing dates during both years. The beginning day at the fast accumulation period was after jointing stage and the termination day was after flowering stage. The value of the fastest accumulation period over two years was shorter in early sowing (27.0 ~ 30.6 d) and normal sowing (19.7 ~ 31.5 d) than in late sowing (35.9 ~ 37.5 d) and the latest sowing (36.5 ~ 38.1 d). The differences existed among the treatments in progress of DMA for single stem under different sowing dates in both years. The maximum relative growth rates (V_m) and highest average rates (V_t) of early sowing and normal sowing were slightly higher than those of late sowing and the latest sowing. The fastest DMA point of single stem was during booting and flowering stage.

The results showed that V_m and V_t of early sowing and normal sowing was higher than that of late sowing and the latest sowing, and the coordination of dynamic accumulation characteristic parameters of DMA for single stem was better, which was conducive to biomass accumulation and yield formation.

Dynamics simulation of NA

The dynamic changes of NA for single stem with the days after sowing were consistent with the changes of DMA. With the advance of growth process, the dynamic changes of NA for single stem conformed to the Logistic Curve Model as well. It can be seen from the Figure 4 that delayed sowing can promote the absorption of N for single stem of winter wheat, and NA for single stem also increased with the delay of sowing date.

According to the Formulas (2)-(4) based on Table 6 the fast accumulation period beginning and termination day of NA for single stem were before jointing stage and after booting stage, respectively. The fastest NA point was from jointing to booting stage for different sowing dates in both years. With the delay of sowing date, the duration of fast NA for single stem was gradually shortened. The normal sowing (5-Nov) was postponed by 8 and 16 days, and the fast accumulation period was shortened by 0.8 days and 5.2 days averaged two years. The later the sowing date was delayed, the shorter the fast accumulation period was (Table 7). The maximum relative growth rates (V_m) and highest average rates (V_t) of NA for single stem were different in two years, which showed an increasing trend with the delay of sowing date. The maximum relative growth rates (V_m) and highest average rates (V_t) reached the peak at the latest sowing.

The results showed that with the delay of sowing date, the coordination of dynamic accumulation characteristic parameters for single stem NA of late sowing wheat was better than that of other treatments, and the beginning day of fast accumulation period was earlier than that of DMA, indicating that the growth of biomass was based on adequate nutrient absorption.

Relationships among grain yield, M_D/J_D and M_N/J_N

Since 5-Nov, the aboveground biomass and N production were significantly reduced with an increase in number of days sowing was delayed (Fig. 5). The average DMA of two years decreased by 8.50 % and 13.32 % after 8 and16 days delayed of normal sowing. The rule of NA was basically the same. It decreased by 9.40 % and 12.95 % after 8 and16 days delayed of normal sowing.

To identify the grain yield associated with the law of DMA and NA, correlation analyses were performed. The ratio of DMA at mature to jointing stage was recorded as M_D/J_D and the ratio of NA at mature to jointing stage was recorded as M_N/J_N. Correlations were observed between the grain yield and M_D/J_D, and both years showed a very significant positive correlation (Fig. 6a and b). Furthermore, there was a significant positive correlation between yield and M_N/J_N (Fig. 6c and d). This suggests that the two ratios have an important influence on the grain yield of winter wheat under different sowing dates.

The linear relationship was found between the grain yield and M_D/J_D (Y=306.03X+4511.69 in 2018-2019 and Y=636.93X+3924.05 in 2019-2020) and M_N/J_N (Y=698.98X+3904.74 in 2018-2019 and Y=1273.29X+3485.91 in 2019-2020) (Fig. 6). With the increase in M_D/J_D and M_N/J_N, the grain yield increased. When the two years average DMA and NA reached 4.06 ($P < 0.01$) and 2.49 ($P < 0.05$) respectively, the grain yield could be maintained at the level of 6000 kg ha^{-1} or above.

Discussion

The present experiment has provided new data on the common perception that sowing date is the crucial agronomic decisions for improving, growth, grain yield and nutrient acquisition of winter wheat. Advancing or delaying beyond the optimum sowing time can be a major hindrance in realization of full genetic yield potential of winter wheat. This study evaluated the changes of grain yield and its biological characters caused by different sowing dates. Grain yield declined by (0.97±0.22) % with each one-day early or delay in sowing beyond the normal sowing date (Fig. 2). Similarly, several previous studies also evidenced the grain yield declination resulting from delayed sowing with an average yield penalty of approximately (0.37±0.07) % with each one-day delay in sowing beyond the normal sowing date (Yin et al., 2018; Ma et al., 2018; Dwived et al., 2019; Dubey et al., 2019; Zhu et al., 2019; Gandjaeva, 2019), which was comparable with this study. Grain yield reduction under delayed sowing can be mainly explained in terms of suppression of crop growth, decreased spike number, dry matter and N production.

Environmental factors affected grain yield of late sowing wheat significantly. Firstly, under late sowing conditions, plants first face adverse weather factors from sowing to wintering stage, such as low temperature and less thermal time compared with the normal sowing date (Fig. 1). For example, the thermal time from sowing to wintering period decreased from 543.9 (℃ d) in normal sowing date to 333.8 (℃ d) in average two years after 16-days of delayed sowing (Table 1). These adverse points could have negative effects on early crop growth by inhibiting seed emergence, seedling establishment and tiller development (Shah et al., 2019; Zhou et al., 2020). Secondly, a delay in sowing will also lead to earlier flowering, which shortened the duration of each stage of crop development. The results showed that under the condition of the latest sowing, the crop growth duration from sowing to flowering was shortened by 7.5 days, compared to the normal sowing (Table 1). The shortening of critical phenological period (which is a key determinant of crop photoperiod and productivity) can further explain the poor performance under delayed sowing (Ferrise et al., 2010; Sattar et al., 2010). Thirdly, delayed sowing increases the chance of crop exposure to high temperature during the grain filling stage, which is detrimental particularly for leaf photosynthesis, grain filling and final yield formation. These exposures are considered to be the key stressors for wheat production in many environments around the world (Garg et al., 2013).

Due to the limitation of late sowing, inhibition of early growth, shortening vegetative growth period and other environmental conditions, the tillering ability is low and the tiller development is poor, resulting in the reduction of productive tillers. Although late sowing could establish a greater tiller population around the jointing stage, it could not maintain this advantage during the whole growth period. Compared with the normal sowing, the tillers decreased significantly at the mature stage, which led to the decrease of percentage of productive tillers (Table 2). In addition, the increase of seeding rate could make up for the decrease of tillers for the late sowing winter wheat (Wang et al., 2016； Ma et al., 2018). In our study, wheat was planted at a constant density to eliminate the effects of density on wheat growth and grain yield, resulting in the change of spike number with the delayed in sowing because of the decreased tillers (Xu et al., 2018; Zhu et al., 2019). However, the reduced plant population could increase the number of fertile stems per plant and the number of kernels per spike, but the magnitude is less than the grain weight (Whaley et al., 2015). This is consistent with our results that the spike number and kernel number were the main factors influencing grain yield, but there is no correlation between grain yield and 1,000-kernel weight (Table 3).

DMA and NA are two primary factors influencing wheat grain yield and grain quality, as the demand for high-yielding and high-quality wheat is expected to increase dramatically in the near future (Meng et al., 2013; Jin et al., 2018). The reduction of vegetative growth period, tiller number could further explain the significant decrease in DMA and final yield under delayed sowing (Shah et al., 2020). Due to the delay of sowing date, the number of tillers decreased significantly. DMA and NA for single stem played an important role in grain yield and quality. At the fast accumulation period of DMA for single stem, although the maximum relative growth rates (V_m) and highest average rates (V_t) showed that the normal sowing date was slightly higher than the delayed sowing, the longest duration of the delayed sowing were longer than that of normal sowing date to maintain the corresponding accumulation amount. However, NA for single stem showed the opposite change rule. With the delay of sowing date, V_m and V_t increased gradually, and reached the peak at the latest sowing. Concurrently, the compensation effect of the duration of fast accumulation period also showed the sowing date was delayed, and the fast accumulation period was compressed. There was a certain relationship between the growth rate of dry matter and the amount of nutrient absorption, but they were not synchronous. The maximum rate of NA occurs earlier than that of DMA (Song et al., 2003). In this study, the accumulation of physiological development time reached maximal accumulation rate (T_m) of DMA for winter wheat was 6.4~12.2 days later than that of NA (Table 5 and 7). Therefore, it was necessary to apply nitrogen fertilizer at jointing stage to ensure the nutrient absorption of wheat dry matter and nitrogen during fast accumulation period. The results showed that the final biomass and nitrogen production of the treatment with normal sowing date were significantly higher than those with delayed sowing (Fig. 5), which was consistent with the findings of predecessors (Yin et al., 2018 ; Ferrise et al., 2010).

Conclusion

Grain yield declined by (0.97±0.22) % with each one-day early or delay in sowing beyond the normal sowing date. This yield penalty could be explained by the inhibition of crop growth, yield components, biomass and N production. These negative effects of delayed sowing are mainly caused by key environmental limitations including adverse weather factors such as low temperature during vegetative growth, shortened duration of various phases of crop development and increased temperature during grain filling period. In other words, the sowing date determines the weather conditions to which wheat is exposed. However, owing to a compensation effect between the highest average rates (V_t) and the fast accumulation period (T) of DMA and NA for single stem, grain yield gap decreased between late and normal sowing. Under these conditions, if the ratio of M_D/J_D and M_N/J_N could reach 4.06 ($P < 0.01$) and 2.49 ($P < 0.05$) respectively, grain yield could be maintained at the level of 6000 kg ha^{-1} or above. But the final performance was delayed sowing, biomass and N production declined. Meanwhile, the accumulation of physiological development time reached maximal accumulation rate (T_m) of NA was earlier than that of DMA. We conclude that the reasonable sowing date of winter wheat in the middle-lower Yangtze River Basin should be around 5-Nov. Further research is needed to explore the compensation effect of different genotypes of winter wheat on yield under the condition of increasing sowing rate if late sowing is inevitable.

Additional Information and Declarations

Competing Interests

The authors declare that they have no competing interests.

Author Contributions

Kaizhen Liu conceived and designed the experiments, performed the experiments, analyzed the data, contributed reagents/materials/analysis tools, prepared figures and/or tables, authored or reviewed drafts of the paper, and approved the final draft.

Chengxiang Zhang performed the experiments, and approved the final draft.

BeiBei Guan performed the experiments, and approved the final draft.

Rui Yang performed the experiments, and approved the final draft.

Ke Liu performed the experiments, and approved the final draft.

Zhuangzhi Wang performed the experiments, and approved the final draft.

Xiu Li performed the experiments, and approved the final draft.

Keyin Xue performed the experiments, and approved the final draft.

Lijun Yin performed the experiments, analyzed the data, contributed reagents/materials/analysis tools, prepared figures and/or tables, and approved the final draft.

Xiaoyan Wang conceived and designed the experiments, analyzed the data, contributed reagents/materials/analysis tools, prepared figures and/or tables, authored or reviewed drafts of the paper, and approved the final draft.

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Figures

Figure 1 Average temperature and precipitation over two growing seasons. Top panel shows data from the 2018-2019 growing season, while the bottom panel shows data from the 2019-2020 growing season. Black lines indicate average temperatures in 2018.10-2019.5 and 2019.10-2020.5, respectively. Black bars indicate precipitation events during 2018.10-

2019.5 and 2019.10-2020.5, respectively. Date was collected by the local meteorological bureau of Jingzhou.

Figure 2 Grain yield loss of winter wheat due to the early and delayed sowing during 2018-2019 and 2019-2020 growing seasons. Vertical bars indicate standard errors (n=3).

Figure 3 Effects of different sowing dates on DMA for single stem in 2018-2019 and 2019-2020. Values are means of three replicates per treatment. Vertical bars indicate standard error.

Figure 4 Effects of different sowing dates on NA dynamics for single stem in 2018-2019 and 2019-2020. Values are means of three replicates per treatment. Vertical bars indicate standard error.

Figure 5 Biomass production and N production of winter wheat under different sowing date during 2018-2019 and 2019-2020 growing seasons. Vertical bars indicate standard errors (n=3). Means followed by the same letter are not significantly different among sowing dates according to the LSD0.05 test.

Figure 6 Relationships between grain yield and (a) the ratio of DMA at maturity stage to jointing stage (M_D/J_D) in 2018-2019 and (b) the ratio of DMA at maturity stage to jointing stage (M_D/J_D) in 2019-2020 and (c) the ratio of NA at maturity stage to jointing stage (M_N/J_N) in 2018-2019 and (d) the ratio of NA at maturity stage to jointing stage (M_N/J_N). * Correlation coefficients are significant at the 0.05 probability level; ** Correlation coefficients are significant at the 0.01 probability level. The shaded part represents the 95% confidence band.

Tables

Table 1 Distribution of days for sowing to flowering stage, days for filling stage, accumulated temperature during the whole growth period, thermal time from sowing to wintering stage and mean daily temperature during filling stage for different sowing dates in 2018-2019 and 2019-2020 growing seasons.

Table 2 Tiller number at jointing stage, maturity stage, peak tillers and percentage of productive tillers of winter wheat under different sowing dates in 2018-2019 and 2019-2020 growing seasons.

Table 3 Grain yield and yield components for different sowing dates in 2018-2019 and 2019-2020 growing seasons. Significant analysis of year (Y), sowing date (SD) and their interaction on the yield and yield components of winter wheat (ANOVA).

Table 4 Equations of DMA under different sowing dates in 2018-2019 and 2019-2020 growing seasons.

Table 5 Effects of different sowing dates on the eigen values of DMA in 2018-2019 and 2019-2020 growing seasons.

Table 6 Equations of NA under different sowing dates in 2018-2019 and 2019-2020 growing seasons.

Table 7 Effects of different sowing dates on the eigen values of NA in 2018-2019 and 2019-2020 growing seasons.

Figure 1

Average temperature and precipitation over two growing seasons.

Top panel shows data from the 2018-2019 growing season, while the bottom panel shows data from the 2019-2020 growing season. Black lines indicate average temperatures in 2018.10-2019.5 and 2019.10-2020.5, respectively. Black bars indicate precipitation events during 2018.10-2019.5 and 2019.10-2020.5, respectively. Date was collected by the local meteorological bureau of Jingzhou.

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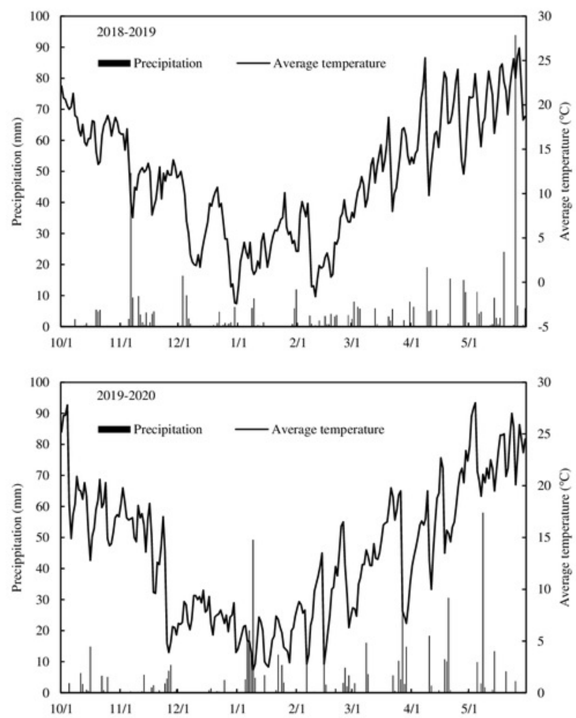

Figure 2

Grain yield loss of winter wheat due to the early and delayed sowing during 2018-2019 and 2019-2020 growing seasons.

Vertical bars indicate standard errors (n=3).

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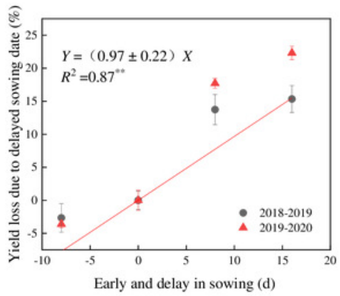

Figure 3

Effects of different sowing dates on DMA for single stem in 2018-2019 and 2019-2020.

Values are means of three replicates per treatment. Vertical bars indicate standard error.

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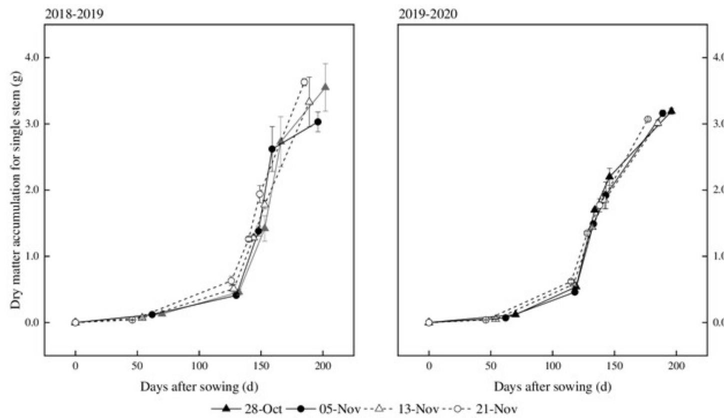

Figure 4

Effects of different sowing dates on NA dynamics for single stem in 2018-2019 and 2019-2020.

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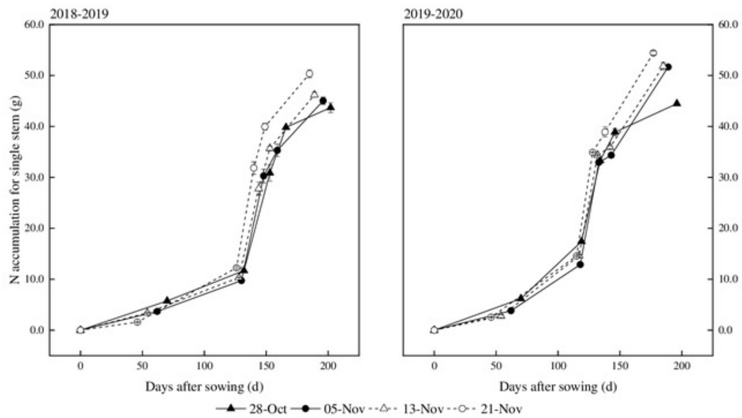

Figure 5

Biomass production and N production of winter wheat under different sowing date during 2018-2019 and 2019-2020 growing seasons.

Vertical bars indicate standard errors (n=3). Means followed by the same letter are not significantly different among sowing dates according to the $LSD_{0.05}$ test.

Figure 5

Figure 5 Biomass production and N production of winter wheat under different sowing date during 2018-2019 and 2019-2020 growing seasons. Vertical bars indicate standard errors (n=3). Means followed by the same letter are not significantly different among sowing dates according to the $LSD_{0.05}$ test.

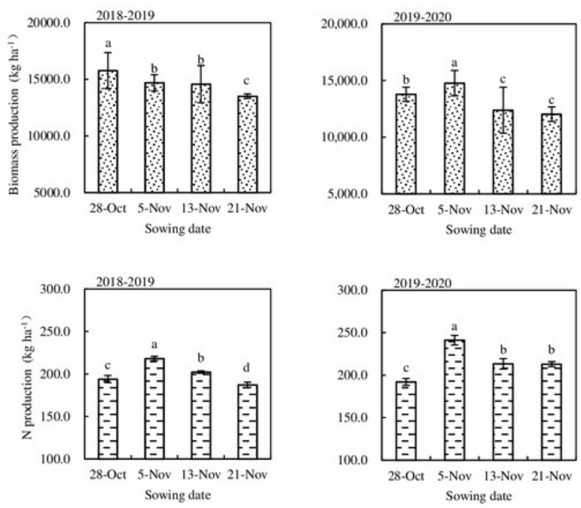

Figure 6

Relationships between grain yield and (a) the ratio of DMA at maturity stage to jointing stage (M_D/J_D) in 2018-2019 and (b) the ratio of DMA at maturity stage to jointing stage (M_D/J_D) in 2019-2020 and (c) the ratio

[*] Correlation coefficients are significant at the 0.05 probability level; [**] Correlation coefficients are significant at the 0.01 probability level. The shaded part represents the 95% confidence band.

Figure 6

Figure 6 Relationships between grain yield and (**a**) the ratio of DMA at maturity stage to jointing stage (M_D/J_D) in 2018-2019 and (**b**) the ratio of DMA at maturity stage to jointing stage (M_D/J_D) in 2019-2020 and (**c**) the ratio of NA at maturity stage to jointing stage (M_N/J_N) in 2018-2019 and (**d**) the ratio of NA at maturity stage to jointing stage (M_N/J_N). * Correlation coefficients are significant at the 0.05 probability level; ** Correlation coefficients are significant at the 0.01 probability level. The shaded part represents the 95% confidence band.

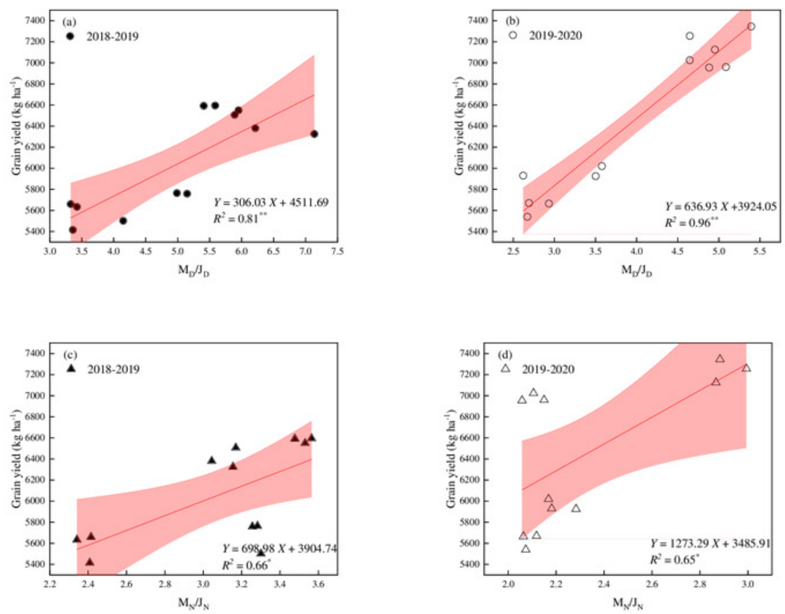

Table 1(on next page)

Distribution of days for sowing to flowering stage, days for filling stage, accumulated temperature during the whole growth period, thermal time from sowing to wintering stage and mean daily temperature during filling stage for different sowing dates in 2

Table 1

Table 1 Distribution of days for sowing to flowering stage, days for filling stage, accumulated temperature during the whole growth period, thermal time from sowing to wintering stage and mean daily temperature during filling stage for different sowing dates in 2018-2019 and 2019-2020 growing seasons.

Season	Sowing date	Days for sowing to flowering stage (d)	Days for filling stage (d)	Accumulated temperature during the whole growth period (℃)	Thermal time from sowing to wintering stage (℃ d)	Mean daily temperature during filling stage (℃)
2018-2019	28-Oct	164	38	2141.2	623.0	20.08
	5-Nov	159	37	2048.6	486.2	20.28
	13-Nov	153	36	1978.9	397.6	20.48
	21-Nov	149	36	1985.2	310.2	20.71
2019-2020	28-Oct	146	50	2304.6	741.6	17.93
	5-Nov	143	46	2187.1	601.6	18.23
	13-Nov	142	43	2140.7	469.3	19.84
	21-Nov	138	39	2028.8	357.4	20.25

Table 2 (on next page)

Tiller number at jointing stage, maturity stage, peak tillers and percentage of productive tillers of winter wheat under different sowing dates in 2018-2019 and 2019-2020 growing seasons.

Values followed by the same letter within a column in the same year are not significantly different at $P < 0.05$ as determined by the LSD test

Table 2

Table 2 Tiller number at jointing stage, maturity stage, peak tillers and percentage of productive tillers of winter wheat under different sowing dates in 2018-2019 and 2019-2020 growing seasons.

Season	Sowing date	Tiller number at jointing stage (no. m^{-2})	Tiller number at maturity stage (no. m^{-2})	Peak tillers (no. m^{-2})	Percentage of productive tillers (%)
2018-2019	28-Oct	530.67b	444.00b	785.33a	56.65c
	5-Nov	636.00a	484.33a	754.67a	64.23b
	13-Nov	596.00ab	437.67b	596.00b	73.45a
	21-Nov	640.00a	371.67c	640.00b	58.33bc
2019-2020	28-Oct	524.00c	432.00b	1078.67a	40.06c
	5-Nov	642.33b	466.67a	876.00b	53.48b
	13-Nov	660.00b	411.67c	660.00c	62.38a
	21-Nov	701.33a	391.33d	701.33c	55.80b

Values followed by the same letter within a column in the same year are not significantly different at $P < 0.05$ as determined by the LSD test

Table 3(on next page)

Grain yield and yield components for different sowing dates in 2018-2019 and 2019-2020 growing seasons. Significant analysis of year (Y), sowing date (SD) and their interaction on the yield and yield components of winter wheat (ANOVA).

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Table 3

Table 3 Grain yield and yield components for different sowing dates in 2018-2019 and 2019-2020 growing seasons. Significant analysis of year (Y), sowing date (SD) and their interaction on the yield and yield components of winter wheat (ANOVA).

Season	Sowing date	Grain yield (kg ha^{-1})	Spike number (10^4 ha^{-1})	Kernel number per spike	1000-kernel weight (g)
2018-2019	28-Oct	6403.8a	444.0b	40.8a	40.5a
	5-Nov	6578.9a	484.3a	37.8b	40.6a
	13-Nov	5674.8b	437.7b	37.9b	40.9a
	21-Nov	5569.7b	371.7c	41.0a	41.1a
2019-2020	28-Oct	6980.0b	432.0b	40.9b	46.9a
	5-Nov	7241.7a	466.7a	38.9c	47.2a
	13-Nov	5958.3c	411.7c	40.5b	47.7a
	21-Nov	5625.0d	391.3d	42.0a	48.1a
Year		.0001	.0002	.0010	.0001
SD		.0001	.0001	.0001	.1425
Y×SD		.0003	.0001	.0627	.8184

Values followed by the same letter within a column in the same year are not significantly different at $P < 0.05$ as determined by the LSD test

Table 4 (on next page)

Equations of DMA under different sowing dates in 2018-2019 and 2019-2020 growing seasons.

**Significant differences at P < 0.01 probability levels (n=6)

Table 4

Table 4 Equations of DMA under different sowing dates in 2018-2019 and 2019-2020 growing seasons.

Season	Sowing date	Regression equations	R^2
2018-2019	28-Oct	$Y=3.6217/(1+4101240.31e^{-0.0976t})$	0.9941**
	5-Nov	$Y=3.0897/(1+420518907.20e^{-0.1339t})$	0.9909**
	13-Nov	$Y=3.5946/(1+45779.88e^{-0.0701t})$	0.9992**
	21-Nov	$Y=3.9149/(1+48761.68e^{-0.0722t})$	0.9995**
2019-2020	28-Oct	$Y=3.1812/(1+109524.11e^{-0.0862t})$	0.9925**
	5-Nov	$Y=3.1866/(1+91308.58e^{-0.0836t})$	0.9949**
	13-Nov	$Y=3.0814/(1+20681.61e^{-0.0734t})$	0.9977**
	21-Nov	$Y=3.2251/(1+10799.99e^{-0.0692t})$	0.9981**

**Significant differences at $P < 0.01$ probability levels (n=6)

Table 5(on next page)

Effects of different sowing dates on the eigen values of DMA in 2018-2019 and 2019-2020 growing seasons.

T_1 and T_2: Beginning and termination days of the duration of fast accumulation phase; $T= T_2- T_1$: Duration of the physiological development time in rapid accumulation period; V_t: Average accumulation rate during the duration of fast accumulation phase; T_m: Accumulation of physiological development time reached maximal accumulation rate; V_m: Maximum accumulation rate during the duration of fast accumulation phase, respectively

Table 5

Table 5 Effects of different sowing dates on the eigen values of DMA in 2018-2019 and 2019-2020 growing seasons.

Season	Sowing date	Fast accumulation period				Fastest accumulation point	
		T_1 (d)	T_2 (d)	T (d)	V_t (g stem^{-1} d^{-1})	T_m (d)	V_m (g stem^{-1} d^{-1})
2018-2019	28-Oct	142.5	169.5	27.0	0.08	156.0	0.09
	5-Nov	138.5	158.2	19.7	0.09	148.4	0.10
	13-Nov	134.2	171.8	37.5	0.06	153.0	0.06
	21-Nov	131.4	167.9	36.5	0.06	149.6	0.07
2019-2020	28-Oct	119.4	150.0	30.6	0.06	134.7	0.07
	5-Nov	120.9	152.4	31.5	0.06	136.6	0.07
	13-Nov	117.4	153.3	35.9	0.05	135.4	0.06
	21-Nov	115.3	153.3	38.1	0.05	134.3	0.06

T_1 and T_2: Beginning and termination days of the duration of fast accumulation phase; $T= T_2- T_1$: Duration of the physiological development time in rapid accumulation period; V_t: Average accumulation rate during the duration of fast accumulation phase; T_m: Accumulation of physiological development time reached maximal accumulation rate; V_m: Maximum accumulation rate during the duration of fast accumulation phase, respectively

Table 6(on next page)

Equations of NA under different sowing dates in 2018-2019 and 2019-2020 growing seasons.

**Significant differences at $P < 0.01$ probability levels (n=6)

Table 6

Table 6 Equations of NA under different sowing dates in 2018-2019 and 2019-2020 growing seasons.

Season	Sowing date	Regression equations	R^2
2018-2019	28-Oct	Y=44.2207/(1+436306.39e$^{-0.0906t}$)	0.9808**
	5-Nov	Y=44.6148(1+839280.29e$^{-0.0960t}$)	0.9874**
	13-Nov	Y=46.4937/(1+1030959.01e$^{-0.0986t}$)	0.9932*
	21-Nov	Y=50.2932/(1+3464573.17e$^{-0.1109t}$)	0.9980*
2019-2020	28-Oct	Y=44.8498/(1+28575.36e$^{-0.0834t}$)	0.9787**
	5-Nov	Y=51.9671/(1+12335.05e$^{-0.0724t}$)	0.9782**
	13-Nov	Y=52.0154/(1+12551.56e$^{-0.0741t}$)	0.9838**
	21-Nov	Y=54.2685/(1+62975.43e$^{-0.0888t}$)	0.9872**

**Significant differences at $P < 0.01$ probability levels (n=6)

Table 7 (on next page)

Effects of different sowing dates on the eigen values of NA in 2018-2019 and 2019-2020 growing seasons.

T_1 and T_2: Beginning and termination days of the duration of fast accumulation phase; $T= T_2-T_1$: Duration of the physiological development time in rapid accumulation period; V_t: Average accumulation rate during the duration of fast accumulation phase; T_m: Accumulation of physiological development time reached maximal accumulation rate; V_m: Maximum accumulation rate during the duration of fast accumulation phase, respectively

Table 7

Table 7 Effects of different sowing dates on the eigen values of NA in 2018-2019 and 2019-2020 growing seasons.

Season	Sowing date	Fast accumulation period				Fastest accumulation point	
		T_1 (d)	T_2 (d)	T (d)	V_t (g stem^{-1} d^{-1})	T_m (d)	V_m (g stem^{-1} d^{-1})
2018-2019	28-Oct	128.8	157.9	29.1	0.88	143.3	1.00
	5-Nov	128.4	155.8	27.4	0.94	142.1	1.07
	13-Nov	127.0	153.7	26.7	1.01	140.4	1.15
	21-Nov	123.9	147.7	23.8	1.22	135.8	1.39
2019-2020	28-Oct	107.3	138.8	31.6	0.82	123.1	0.93
	5-Nov	111.9	148.3	36.4	0.82	130.1	0.94
	13-Nov	109.6	145.1	35.5	0.85	127.3	0.96
	21-Nov	109.6	139.3	29.7	1.06	124.5	1.20

T_1 and T_2: Beginning and termination days of the duration of fast accumulation phase; $T= T_2- T_1$: Duration of the physiological development time in rapid accumulation period; V_t: Average accumulation rate during the duration of fast accumulation phase; T_m: Accumulation of physiological development time reached maximal accumulation rate; V_m: Maximum accumulation rate during the duration of fast accumulation phase, respectively