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Abstract 23 Background: Timely sowing is an important agronomic measure to ensure normal germination, 24 stable seedling establishment and final yield formation for winter wheat (Triticum aestivum L.). 25 Under the current multi-cropping system and mechanized production level, the delayed sowing 26 has frequently occurred. However, the effect of different sowing dates on yield change and its 27 potential mechanism are still unclear in the middle-lower Yangtze River Basin.

28 Methods: Here, through a 2-year field study, the Logistic Curve Model which was used to 29 simulate the dry matter accumulation (DMA) and N accumulation (NA) dynamics of wheat for 30 single stem under different sowing dates was established, and the changes in grain yield and 31 related traits in different sowing dates were studied. 32 Results: It showed that grain yield declined by (0.97±0.22) % with each one-day early or delay 33 in sowing beyond the normal sowing date.

The above yield loss could be explained by the 34 inhibition of crop growth, yield components, biomass and N production. Meanwhile, these 35 negative effects of delayed sowing are mainly caused by key environmental limitations including PeerJ reviewing PDF | (2021:01:57230:0:1:NEW 20 Jan 2021) Manuscript to be reviewed 36 adverse weather factors such as low temperature during vegetative growth, shortened duration of 37 various phases of crop development and increased temperature during grain filling period.

38 However, owing to a compensation effect between the highest average rates (Vt) and the fast 39 accumulation period (T) of DMA and NA for single stem, grain yield gap decreased between late 40 and normal sowing. Under these conditions, if the ratio of DMA at mature to jointing stage 41 (MD/JD) and the ratio of NA at mature to jointing

stage (MN/JN) could reach 4.06 (P < 0.01) and 42 2.49 (P < 0.05) respectively, the grain yield could be maintained at the level of 6000 kg ha-1 or 43 more.

But this compensation effect still cannot avoid the impact caused by delayed sowing. Thus 44 the final manifestation was delayed in sowing, and biomass and nitrogen production decreased. 45 Meanwhile, the accumulation of physiological development time reached maximal accumulation 46 rate (Tm) of NA was earlier than that of DMA.

47 Keywords Different sowing dates, Dry matter accumulation, Nitrogen accumulation, Grain 48 yield, Simulation model 49 50 Introduction 51 Wheat is one of the most widely cultivated crops worldwide, and wheat growers in China are the 52 largest in the world, producing 17% of the world´s total wheat (Food and Agricultural of the 53 United Nation, 2020). Winter wheat accounts for approximately 95% of the total (winter and 54 spring) wheat production in China (Lu et al., 2013; Wu et al.,

2014; Geng et al., 2019). The 55 middle-lower Yangtze River Basin is one of the main winter wheat growing areas in China, in 56 which the photothermal resources are abundant and can meet the needs of rice-wheat rotation 57 system (Zhang et al., 2013). Hence, the rice-wheat rotation is the dominant practice in this region 58 (Liu et al., 2016).

Meanwhile, this region´s grain output plays an important role in ensuring food 59 security in China. 60 61 Sowing date is one of the most important management factor affecting grain production and 62 quality (Ferrise et al., 2010). In a certain area, the optimum sowing date mainly depends upon the 63 timing of rainfall and temperature (Jackson et al., 2000), which can maintain high grain yield.

64 Rice-wheat rotation system is one of the world´s largest agricultural production systems (Gupta 65 et al., 2003). However, there are also limitations to this planting pattern. In recent years, simple 66 cultivation methods such as mechanical transplanting and direct seeding of rice have shortened 67 the limitation of seedling age.

At the same time, the yield benefit of late sowing rice is 68 remarkable, and the extension area is expanding, which leads to late sowing and late harvest of 69 rice. Wheat as the succeeding crop of rice, its traditional sowing date also needs to be adjusted PeerJ reviewing PDF | (2021:01:57230:0:1:NEW 20 Jan 2021) Manuscript to be reviewed 70 accordingly (Xu et al., 2013).

71 72 As an important sign of climate change, global warming has significantly impacted agricultural 73 production and has been the focus of considerable attention of many

researchers (Sun et al., 2015; 74 Ding et al., 2015). However, both simulation studies and observed data have showed that a 75 significant decrease in the grown duration of winter wheat appears accompanied by a significant 76 reduction in grain yield due to the evident warming trend (He et al., 2014, 2015; Xiao et al., 77 2015).

Global warming over recent decades has provided extended growing periods prior to 78 wheat wintering that encourage farmers to delay the winter wheat sowing date (Xiao et al., 2013, 79 2015). Studies have shown that this delay in sowing may increase, maintain or decrease the grain 80 yield of winter wheat (Jalota et al., 2013; Ding et al., 2015; Yin et al., 2018).

81 82 Previous research has indirectly suggested that late sowing of wheat usually leads to poor crop 83 conditions, even in the year with optimal weather (Tester and Langriridge, 2010). Delayed 84 sowing of winter wheat will lead to adverse conditions such as low temperature in the process of 85 crop vegetative growth, resulting in low germination rate, poor tillering ability and low plant 86 population (Borràsgelonch et al., 2012; Fernanda et al., 2013).

Meanwhile, late sowing would 87 delay flowering and expose crops to the high temperature during grain filling stage, thus 88 accelerating reproductive development and reducing grain filling (Bailey-Serrees et al., 2019; 89 Dubey et al., 2019). In addition, late sowing also reduces dry matter and N accumulation in 90 wheat crops (Ehdaie and Waines, 2001).

Therefore, the delay of sowing in wheat often has a 91 negative impact on seed germination process, tiller development, overall crop growth and final 92 yield (Hussain et al., 2017; Kaur, 2017). It is important to note that a delay sowing in the optimal 93 range does not have a serious negative impact on yield performance, as it usually improves the 94 assimilate allocation and nitrogen utilization efficiency for winter wheat (Yin et al., 2018, 2019).

95 96 The formation of crop yield is determined by the accumulation and distribution of dry matter, 97 which is the material basis for the formation of crop yield (Zheng et al., 2013). Natural and 98 human factors such as climate, soil, and field management practices all affect the DMA process 99 and ultimately lead to yield differences.

At the same time, NA is also the main nutrient factor 100 that affects the grain yield and protein concentration (Ehdaie and Waines, 2001). There are two 101 main methods to describe the process of DMA and NA: one is mechanism model, and the other 102 is empirical model (Whisler et al., 1986). In the empirical model, the Logistic (Royo et al.,

1999) 103 and Richards (Richards, 1959) growth equations have certain biological significance and are now 104 widely used. 105 PeerJ reviewing PDF | (2021:01:57230:0:1:NEW 20 Jan 2021) Manuscript to be reviewed 106 Some scholars used Logistic equation to describe the dry matter accumulation process of winter 107 wheat and summer maize, as well as the NA process of cotton (Zhao et al., 2013; Xiao et al., 108 2014; Du et al., 2016).

The accumulation of dry matter and N is a continuous process changing 109 with time, which is closely related to yield formation, and has great differences in different years 110 and research sites. At present, there are few studies on the effects of sowing date factors on 111 wheat growth and yield in Jianghan Plain of the middle-lower Yangtze River Basin from the 112 perspective of DMA, NA and yield.

Therefore the objectives of this study were to (?) quantify 113 the effect of different sowing dates on grain yield, yield components, tillers and other agronomic 114 traits of winter wheat, and (?) clarify the Logistic model was used to fit the DMA and NA 115 process of winter wheat in different sowing dates, and the growth process of wheat was 116 quantitatively analyzed according to the derived characteristic quantity.

117 118 Materials and methods 119 Experimental site 120 Field experiments were conducted at the experimental farm station of Yangtze University 121 (30?36’N, 112?08’E), Jinzhou City, Hubei Province, China, during two growing seasons in 122 2018/2019 and 2019/2020. This station is located in the Jianghan Plain, which is characterized as 123 a typical subtropical monsoon climate zone in the middle-lower Yangtze River Basin of China. 124 Two-year field experiments were performed in the nearby fields.

The farm field chosen for this 125 study was previously managed as a summer-rice/winter-wheat double-cropping system. The 126 daily average temperature and precipitation during the two-year growing seasons are shown in 127 Fig. 1. Soil samples were collected at the start of the experiments.

The soil was classified as 128 sandy loam, and the main physicochemical properties were as follows: 17.9 and 14.8 g kg-1 129 organic matter, 60.5 and 42.8 g kg-1 total N, 21.9 and 7.3 mg kg-1 available phosphorus, 116.6 130 and 75.7 mg kg-1 available potassium before sowing wheat in 2018 and 2019, respectively. 131 132 Experimental design and crop management 133 A widely planted winter wheat cultivar, Zhengmai 9023 was used in field experiments.

Seeds 134 were sown by broadcasting at a rate of 15 g m-2 in 2018 and 2019 on 28 October (early sowing), 135 5 November (normal sowing), 13 November (late sowing), and 21 November (latest sowing) 136 using manual ditching drill with 25-cm row spacing. The plots were arranged according to 137 sowing dates with four replicates. Each plot included 25 rows with 25-cm in row spacing (2 m 138 wide) and 6 m in length.

Basal fertilization of each subplot included N as urea, phosphorus as PeerJ reviewing PDF | (2021:01:57230:0:1:NEW 20 Jan 2021) Manuscript to be reviewed 139 calcium superphosphate, and potassium as potassium chloride at rates of 90 kg ha-1 N, 105 kg ha- 140 1 P2O5, and 105 kg ha-1 K2O, respectively. An additional 90 kg ha-1 of N was applied at the 141 beginning of the jointing growing stage. Fields were managed following the local cultural 142 practices.

Pests, weeds and diseases were controlled chemically. 143 144 Measurement items and methods 145 At three-leaf stage, two lines of 0.5 m with uniform emergence were randomly selected for fixed 146 points in each plot. Tillers were counted before wintering and at the jointing, booting, flowering 147 and maturity stages in each plot with three repeats, respectively.

148 149 Sampling for dry matter was carried out before wintering and at the jointing, booting, flowering 150 and maturity stages in each plot with three repeats at ground level. These samples were 151 subsequently separated into flag leaves, other leaves, stem sheathes, and ear tissues (glumes and 152 grains at maturity). All samples were dried at 105 ? for 30 min and then at 80 ? in a fan-forced 153 oven to constant weight to determine the biomass.

The N concentration during each growing 154 stage was determined using the Kjeldahl method (KDY-9820 Auto Distillation Unit, Beijing, 155 China). N accumulation was calculated by multiplying N concentration (%) by dry weight. NA 156 was calculated as the sum of the N uptake of the different measured organs at each growing stage. 157 This process was repeated three times, as well.

158 159 Plants used to measure yield were harvested from a sampling area of 2.0 m × 1.0 m (row length 160 × row width) in each plot. The grain was air-dried, weighted, and adjusted to standard 12% 161 moisture content. This was considered as the grain dry matter yield. Effective panicle per unit 162 area was measured from a sampling area of 1.0 m × 1.0 m (row length × row width).

30 panicles 163 were taken continuously to determine the grain number of panicle. The 1000-grain weight was 164 air-dried, weighted, and adjusted to standard 12% moisture

content. All the above measurement 165 items were repeated three times per treatment.

166 167 According to Zadoks growth scale (Zadoks, 1974), the corresponding accurate date of the main 168 growth period of wheat was observed and recorded in the field, and more than 50% seedling 169 situation in the plot was taken as the basis. The daily maximum, minimum and average 170 temperature, light hours, daily rainfall and other meteorological datum during the two-year wheat 171 growth period were collected from Jingzhou Meteorological Bureau of Hubei Province.

172 173 Calculations and data analysis 174 In order to model the accumulation pattern, a Logistic Model used to quantitatively describe the PeerJ reviewing PDF | (2021:01:57230:0:1:NEW 20 Jan 2021) Manuscript to be reviewed 175 dynamic changes of accumulation in winter wheat shoot is as follows (Du et al., 2016): 176 ??= (1) ???????? 1 + ???? ? ???? 177 where, W (g stem-1) is the accumulation in wheat, Wmax (g stem-1) is the theoretical maximum 178 accumulation, T (d) is days after emergence, a and k are the constants to be found.

179 The following functions can be obtained by calculating the first, second and third derivative of 180 formula (1), respectively. 181 ?? (2) 1 = 1 ??????2 + 3 ?? 182 ?? (3) 2 = 1 ??????2 ? 3 ?? 183 ???? = (4) ?????? ?? 184 ???? = (5) ?????????? 4 185 where, T1 (d) is the accumulated growth time at the fastest beginning date of growth curve, T2 (d) 186 is the accumulated growth time at the termination date, maximum relative growth rate Vm (g 187 stem-1 d-1) and its cumulative growth time Tm (d).

188 When the fast accumulation phase was begin at T1 and end at T2, W is linear correlation with the 189 days after emergence and the average growth rate (Vt). 190 ???? = (6) ??2 ? ??1 ??2 ? ??1 191 Yield loss (%) due to the early or late sowing was calculated as follows: 192 ?????????? ???????? (%) = (7) ?????? ? ?? ?????? × 100 193 where Yns and Y are the grain yields of normal and early or late sowing dates, respectively.

194 195 Statistical analysis 196 Data preparation was performed with Microsoft Excel software, and the final data plots were 197 produced with Origin 8.0 software. Multiple comparisons were performed after a preliminary F- 198 test. Means were tested based on the least significant difference at P < 0.05, by using Data 199 Processing System (DPS) v.7.05 software.

200 201 Results 202 Weather conditions and crop phenology 203 Mean daily temperatures of two wheat growing seasons decreased first and then increased (Fig. PeerJ reviewing PDF | (2021:01:57230:0:1:NEW 20 Jan 2021) Manuscript to be reviewed

204 1). In the first year of wheat growing season, the duration of mean daily temperatures below 10 ? 205 were 89 days (continuous 3 days and above, lower than 10 ?), while in the second year they 206 were shortened to 77 days.

Thermal time from sowing to wintering stage decreased greatly when 207 sowing was delayed by more than 8 days across two experimental years. Averaged across two 208 experimental years, thermal time was reduced by 21 %, 37 %, and 51% for 8–, 16–, and 24–days 209 delay in sowing compared with the first sowing date (28-Oct).

210 211 Mean daily temperatures from flowering to the end of grain filling increased gradually when 212 sowing was delayed by more than 8 days across two experimental years. It ranged from 20.08 ? 213 for 28-Oct to 20.71 ? for 21-Nov in 2018-2019, and 17.93 ? for 28-Oct to 20.25 ? for 21-Nov 214 in 2019-2020. In the second year, there was a significant negative correlation (r = -0.94, P < 0.05) 215 between the grain filling days of each sowing date and the mean daily temperatures during the 216 filling stage.

217 218 With the delay of sowing date in 2018-2019 and 2019-2020 growing seasons, the crop growth 219 cycle (from seeding to the end of grain filling) of each sowing date were significantly shortened. 220 Compared with the first sowing date (28-Oct), the whole growth duration of 8–, 16–and 24–days 221 delay in sowing decreased by 7, 12 and 18 days on average over two growing seasons. This 222 difference was mainly due to the flowering period moved up and the compression of grain filling 223 period for the late sowing date.

Averaged across two years, the flowering date was moved up by 224 4.0, 7.5, and 11.5 days for 8–, 16–, and 24–days delay in sowing compared with the first sowing 225 date (28-Oct). The duration of filling period of the four sowing dates in the first year was not 226 significantly shortened.

In the second year the latest sowing (21-Nov) and early sowing (28-Oct) 227 shortened the filling period by 11 days under the condition of delaying 24 days. 228 229 Morphological traits 230 There were differences in the number of tillers at jointing and maturity. The tiller number at 231 jointing stage of the latest sowing date (21-Nov) was higher than other sowing dates over two 232 growing seasons, and the tiller number of sowing date on 21-Nov was significantly different 233 from that of other sowing dates during the second year.

The peak tillers appeared before or after 234 the jointing stage. The peak tillers appeared before jointing stage for the early sowing date (28- 235 Oct) and the normal sowing date (5-Nov), while the late sowing date (13- Nov) and the latest 236 sowing date (21-Nov) appeared after jointing stage, which was the same for two years.

The 237 results of two year experiments showed that the tiller number of sowing date on 5-Nov was 238 significantly higher than that of other sowing dates at maturity stage. The percentage of 239 productive tillers on 13-Nov in two years was significantly higher than other sowing dates. PeerJ reviewing PDF | (2021:01:57230:0:1:NEW 20 Jan 2021) Manuscript to be reviewed 240 Under the condition of delayed sowing, except for the latest sowing date (21-Nov), the 241 percentage of productive tillers increased significantly each 8-days of delay in sowing.

242 243 Yield formation 244 Wheat grain yield varied by both year and sowing date, and there was significant interaction 245 between these two main factors (Table 3). The grain yield among different sowing dates ranged 246 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. 247 Grain yield for each sowing date in 2019-2020 was 1.0 %~10.1 % greater than that in 2018-2019.

248 Grain yield of 5-Nov sowing date was greater than those of the other treatments during both 249 years. Grain yield of 5-Nov was 3.2 %, 18.7 % and 23.4 % averaged two year greater than the 250 yields of 28-Oct, 13-Nov and 21-Nov, respectively. The results of two-year experiments showed 251 that the sowing date was delayed for 8 and 16 days after 5-Nov, and the yield decreased 252 significantly.

After 5-Nov sowing date a consistent declining trend was observed for grain yield 253 until the last sowing date during both years, showing that the longer the delay in sowing date, the 254 greater the yield reduction (Table 3 and Fig. 2). Regression analysis revealed that with each one- 255 day early or delay in sowing date on the basis of normal sowing, the grain yield declined by 256 (0.97±0.22) % across two years (Fig. 2). 257 258 It showed that spike number was affected ($P < 0.01$) by year and sowing date, and the interaction 259 term was extremely significant as well (Table 3).

Kernel number per spike reached a very 260 significant level ($P < 0.01$) in year and sowing date, but the interaction term was not significant. 261 1,000-kernel weight was only affected ($P < 0.01$) by year, and there was no significant between 262 the sowing date and these two main factors. Among all the yield components, spike number was 263 positive correlated with wheat grain yield ($r = 0.73$, $P < 0.05$), whereas kernel number and 264 1,000-kernel weight were not. The spike number per ha for 5-Nov was 9.1 %~30.3 % in 2018- 265 2019 and 8.0 %~19.3

% in 2019-2020 greater than that for 28-Oct, 13-Nov and 21-Nov, 266 respectively. The kernel per spike for 21-Nov was 0.5 %, 8.5 % and 8.2 % in 2018-2019, and 2.7 267 %, 8.0

% and 3.7 % in 2019-2020 greater than that for 28-Oct, 5-Nov and 13-Nov, respectively. 268 269 Dynamics simulation of DMA 270 It showed that the dynamic changes of DMA for single stem with the days after sowing conforms 271 to the Logistic Curve Model (Fig. 3). The logistic function was followed by DMA as a sigmoidal 272 growth pattern since all P values were < 0.01 (Table 4), although they differed in equation 273 coefficients among the treatments.

The simulated value of DMA for single stem was evaluated 274 by Formula (1), and the characteristic value of dynamic of DMA for single stem was obtained 275 (Table 5). PeerJ reviewing PDF | (2021:01:57230:0:1:NEW 20 Jan 2021) Manuscript to be reviewed 276 277 Calculation by Formulas (2)-(4) based on Table 4 showed that the beginning and termination day 278 at the fast accumulation period of winter wheat DMA for single stem under all sowing dates 279 during both years.

The beginning day at the fast accumulation period was after jointing stage and 280 the termination day was after flowering stage. The value of the fastest accumulation period over 281 two years was shorter in early sowing (27.0 ~ 30.6 d) and normal sowing (19.7 ~ 31.5 d) than in 282 late sowing (35.9 ~ 37.5 d) and the latest sowing (36.5 ~ 38.1 d).

The differences existed among 283 the treatments in progress of DMA for single stem under different sowing dates in both years. 284 The maximum relative growth rates (Vm) and highest average rates (Vt) of early sowing and 285 normal sowing were slightly higher than those of late sowing and the latest sowing. The fastest 286 DMA point of single stem was during booting and flowering stage.

287 288 The results showed that Vm and Vt of early sowing and normal sowing was higher than that of 289 late sowing and the latest sowing, and the coordination of dynamic accumulation characteristic 290 parameters of DMA for single stem was better, which was conducive to biomass accumulation 291 and yield formation. 292 293 Dynamics simulation of NA 294 The dynamic changes of NA for single stem with the days after sowing were consistent with the 295 changes of DMA.

With the advance of growth process, the dynamic changes of NA for single 296 stem conformed to the Logistic Curve Model as well. It can be seen from the Figure 4 that 297 delayed sowing can promote the absorption of N for single stem of winter wheat, and NA for 298 single stem also increased with the delay of sowing date.

299 300 According to the Formulas (2)-(4) based on Table 6 the fast accumulation period beginning and 301 termination day of NA for single stem were before jointing stage and after booting stage, 302 respectively. The fastest NA point was from jointing

to booting stage for different sowing dates 303 in both years. With the delay of sowing date, the duration of fast NA for single stem was 304 gradually shortened.

The normal sowing (5-Nov) was postponed by 8 and 16 days, and the fast 305 accumulation period was shortened by 0.8 days and 5.2 days averaged two years. The later the 306 sowing date was delayed, the shorter the fast accumulation period was (Table 7). The maximum 307 relative growth rates (Vm) and highest average rates (Vt) of NA for single stem were different in 308 two years, which showed an increasing trend with the delay of sowing date. The maximum 309 relative growth rates (Vm) and highest average rates (Vt) reached the peak at the latest sowing.

310 311 The results showed that with the delay of sowing date, the coordination of dynamic accumulation PeerJ reviewing PDF | (2021:01:57230:0:1:NEW 20 Jan 2021) Manuscript to be reviewed 312 characteristic parameters for single stem NA of late sowing wheat was better than that of other 313 treatments, and the beginning day of fast accumulation period was earlier than that of DMA, 314 indicating that the growth of biomass was based on adequate nutrient absorption.

315 316 Relationships among grain yield, MD/JD and MN/JN 317 Since 5-Nov, the aboveground biomass and N production were significantly reduced with an 318 increase in number of days sowing was delayed (Fig. 5). The average DMA of two years 319 decreased by 8.50 % and 13.32 % after 8 and16 days delayed of normal sowing. The rule of NA 320 was basically the same. It decreased by 9.40 % and 12.95 % after 8 and16 days delayed of 321 normal sowing.

322 323 To identify the grain yield associated with the law of DMA and NA, correlation analyses were 324 performed. The ratio of DMA at mature to jointing stage was recorded as MD/JD and the ratio of 325 NA at mature to jointing stage was recorded as MN/JN. Correlations were observed between the 326 grain yield and MD/JD, and both years showed a very significant positive correlation (Fig. 6a and 327 b).

Furthermore, there was a significant positive correlation between yield and MN/JN (Fig. 6c 328 and d). This suggests that the two ratios have an important influence on the grain yield of winter 329 wheat under different sowing dates. 330 331 The linear relationship was found between the grain yield and MD/JD (Y=306.03X+4511.69 in 332 2018-2019 and Y=636.93X+3924.05 in 2019-2020) and MN/JN (Y=698.98X+3904.74 in 2018- 333 2019 and Y=1273.29X+3485.91 in 2019-2020) (Fig. 6). With the increase in MD/JD and MN/JN, 334 the grain yield increased.

When the two years average DMA and NA reached 4.06 (P < 0.01) and 335 2.49 (P <

0.05) respectively, the grain yield could be maintained at the level of 6000 kg ha-1 or 336 above. 337 338 Discussion 339 The present experiment has provided new data on the common perception that sowing date is the 340 crucial agronomic decisions for improving, growth, grain yield and nutrient acquisition of winter 341 wheat.

Advancing or delaying beyond the optimum sowing time can be a major hindrance in 342 realization of full genetic yield potential of winter wheat. This study evaluated the changes of 343 grain yield and its biological characters caused by different sowing dates. Grain yield declined 344 by (0.97±0.22) % with each one-day early or delay in sowing beyond the normal sowing date 345 (Fig. 2).

Similarly, several previous studies also evidenced the grain yield declination resulting 346 from delayed sowing with an average yield penalty of approximately (0.37±0.07) % with each PeerJ reviewing PDF | (2021:01:57230:0:1:NEW 20 Jan 2021) Manuscript to be reviewed 347 one-day delay in sowing beyond the normal sowing date (Yin et al., 2018; Ma et al., 2018; 348 Dwived et al., 2019; Dubey et al., 2019; Zhu et al., 2019; Gandjaeva, 2019), which was 349 comparable with this study.

Grain yield reduction under delayed sowing can be mainly explained 350 in terms of suppression of crop growth, decreased spike number, dry matter and N production. 351 352 Environmental factors affected grain yield of late sowing wheat significantly. Firstly, under late 353 sowing conditions, plants first face adverse weather factors from sowing to wintering stage, such 354 as low temperature and less thermal time compared with the normal sowing date (Fig. 1). For 355 example, the thermal time from sowing to wintering period decreased from 543.9

(? d) in 356 normal sowing date to 333.8 (? d) in average two years after 16-days of delayed sowing (Table 357 1). These adverse points could have negative effects on early crop growth by inhibiting seed 358 emergence, seedling establishment and tiller development (Shah et al., 2019; Zhou et al., 2020). 359 Secondly, a delay in sowing will also lead to earlier flowering, which shortened the duration of 360 each stage of crop development.

The results showed that under the condition of the latest sowing, 361 the crop growth duration from sowing to flowering was shortened by 7.5 days, compared to the 362 normal sowing (Table 1). The shortening of critical phenological period (which is a key 363 determinant of crop photoperiod and productivity) can further explain the poor performance 364 under delayed sowing (Ferrise et al., 2010; Sattar et al., 2010).

Thirdly, delayed sowing increases 365 the chance of crop exposure to high temperature during the grain filling stage, which is 366 detrimental particularly for leaf photosynthesis, grain filling and final yield formation. These 367 exposures are considered to be the key stressors for wheat production in many environments 368 around the world (Garg et al., 2013).

369 370 Due to the limitation of late sowing, inhibition of early growth, shortening vegetative growth 371 period and other environmental conditions, the tillering ability is low and the tiller development 372 is poor, resulting in the reduction of productive tillers. Although late sowing could establish a 373 greater tiller population around the jointing stage, it could not maintain this advantage during the 374 whole growth period.

Compared with the normal sowing, the tillers decreased significantly at the 375 mature stage, which led to the decrease of percentage of productive tillers (Table 2). In addition, 376 the increase of seeding rate could make up for the decrease of tillers for the late sowing winter 377 wheat (Wang et al., 2016?Ma et al., 2018). In our study, wheat was planted at a constant 378 density to eliminate the effects of density on wheat growth and grain yield, resulting in the 379 change of spike number with the delayed in sowing because of the decreased tillers (Xu et al., 380 2018; Zhu et al., 2019).

However, the reduced plant population could increase the number of 381 fertile stems per plant and the number of kernels per spike, but the magnitude is less than the 382 grain weight (Whaley et al., 2015). This is consistent with our results that the spike number and PeerJ reviewing PDF | (2021:01:57230:0:1:NEW 20 Jan 2021) Manuscript to be reviewed 383 kernel number were the main factors influencing grain yield, but there is no correlation between 384 grain yield and 1,000-kernel weight (Table 3).

385 386 DMA and NA are two primary factors influencing wheat grain yield and grain quality, as the 387 demand for high-yielding and high-quality wheat is expected to increase dramatically in the near 388 future (Meng et al., 2013; Jin et al., 2018). The reduction of vegetative growth period, tiller 389 number could further explain the significant decrease in DMA and final yield under delayed 390 sowing (Shah et al., 2020). Due to the delay of sowing date, the number of tillers decreased 391 significantly.

DMA and NA for single stem played an important role in grain yield and quality. 392 At the fast accumulation period of DMA for single stem, although the maximum relative growth 393 rates (Vm) and highest average rates (Vt) showed that the normal sowing date was slightly higher 394 than the delayed sowing, the longest duration of the delayed sowing were longer than that of 395 normal sowing date to maintain the corresponding accumulation amount. However, NA for 396 single stem showed the opposite change rule.

With the delay of sowing date, Vm and Vt 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 (Tm) 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 (Vt) 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 MD/JD and MN/JN 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 (Tm) of NA was earlier than that of DMA. We conclude that the reasonable sowing date of winter wheat in the middle-lower 425 Yangtze River Basin should be around 5-Nov.

Further research is needed to explore the 426 compensation effect of different genotypes of winter wheat on yield under the condition of 427 increasing sowing rate if late sowing is inevitable.

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