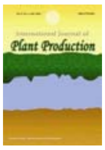

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Effects of sowing time and rate on crop growth and radiation use efficiency of winter wheat in the North China Plain

H. Sun, L. Shao, S. Chen, Y. Wang, X. Zhang*

Key Laboratory of Agricultural Water Resources, Centre for Agricultural Resources Research, Institute of Genetics and Developmental Biology, Hebei 050021.
*Corresponding author. E-mail: xyzhang@sjziam.ac.cn

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Abstract

Crop depends on its canopy to intercept solar radiation to drive both assimilation and water, nutrient absorption for its growth. Field experiments, involving three sowing time and three sowing rate, were conducted at Luancheng Station to investigate the effects of canopy size and development on crop growth and radiation use efficiency (RUE) of winter wheat during 2009/2010 and 2010/2011 growing seasons. The results showed that the maximum effects of sowing time on the phenological development occurred between emergence and elongation, and which was 186.0 and 162.3 d^{o}C thermal time difference during 2009/2010 and 2010/2011, respectively. Sowing time and sowing rate significantly affected above-ground biomass accumulation and RUE. Results showed that optimized sowing time and sowing rate has the potential to improve yield of winter wheat and radiation use efficiency. RUE during pre-anthesis was lower than that during post-anthesis, especially for the delayed sowing treatments which was mainly caused by the lower dry matter mobilization (DMM) and dry matter mobilization efficiency (DMME). Compared with the normal sowing time treatment, the delayed sowing time treatments had the lower DMM and DMME which indicated that the different sowing date would affect the duration of growth and then the RUE.

Keywords: Radiation use efficiency; Winter wheat; Temperature; Sowing time; Sowing rate.

Introduction

In the North China Plain (NCP), rotation of winter wheat and summer maize is the dominant double-cropping system. Winter wheat in this region provided more than 50% of the national winter wheat production (China Statistics Bureau, 2009). Therefore, it is very important to keep the stable yield of this crop. In order to produce more grain yield in this double cropping system, a “double-delayed” technique i.e. delayed sowing time for winter wheat and delayed harvest time for summer maize was applied in the NCP. This technique can significantly improve the annual total grain yield which is mainly dependent on the improvement of maize yield (Sun et al., 2007; Fu et al., 2009). Generally, with the sowing time delayed the grain yield of winter wheat was reduced. Therefore, the sowing rate of winter wheat was increased accordingly to counteract the effects of delayed sowing time.

In the NCP, previous studies have been conducted to determine the influence of sowing date or rate on wheat grain yield and water use efficiency (Sun et al., 2007; Li et al., 2009). Wheat planted at an intermediate date has greater yield potential than late planted wheat because of increased tillers, spikes, and seed weight. Some researchers have studied the effects of sowing time on the phenological development (Sun et al., 2007; Han et al., 2011). They found that the delayed sowing mainly shortened the duration from germination to flowering and had a slightly reduction for the duration for grain filling. These results indicated that the delayed sowing mainly shortened growth period in vegetative stage and a slightly reduction for the reproductive stage. However, most of these studies didn’t consider the growth proceeding which was affected by the solar radiation at the different combined sowing times and rates.

Crop growth depends on the ability of the canopy to capture incoming photosynthesis active radiation (PAR), water and nutrients (Albrizio et al., 2005), which is affected by the leaf area index (LAI) and canopy characters, and the conversion coefficient to biomass (Gifford et al., 1984). Crop dry matter accumulation is determined by the quantity of solar radiation absorbed by the canopy (Sinclair and Muchow, 1999; Giunta et al., 2009). The relationship between crop dry matter and radiation intercepted has been termed as the radiation use efficiency (RUE, Monteith, 1977). RUE plays a critical role in the process of crop productivity and is widely used in the quantification of crop growth. The sowing time and sowing rate affect crop growth and the size of the canopy, then the RUE (Giunta and Motzo, 2004).

A few studies reported RUE for wheat, the locations and experimental conditions were widely distributed in different era and regions (Green, 1987; Fischer, 1993; Gregory and Eastham, 1996; Calderini et al., 1997; Sabine and Jeuffroy, 2004; Singer et al., 2007; Li et al., 2011; Miranzadeh, 2011) and the reported RUE values for wheat based on PAR measurements in non-stress conditions ranged from 1.46 to 3.50 g MJ^{-1}. RUE variation was associated with the stage of wheat development and the different water and fertilizer supply level (Li et al., 2008; Mishra et al., 2009; Li et al., 2011; Miranzadeh, 2011). RUE was higher during the middle and late stages of vegetative growth than that during early vegetative growth and reproductive growth (Green, 1987; Fischer, 1993; Calderini et al., 1997). Foulkes et al. (2001) found that RUE of winter wheat was lower before booting than that after booting. The effects of temperature on the photosynthetic activity of leaves had the potential to alter RUE in some species (Sinclair and Muchow, 1999; Brown et al., 2006). However, some researchers reported the constant value of RUE in all stage of plant life. Therefore, the effect of temperature on RUE has some arguments.

The RUE in cereals was different between pre- and post-anthesis period. Calderini et al. (1997) indicated that there were no differences between wheat varieties based on pre-anthesis periods, but only during the post-anthesis phase. Though RUE value during the pre-anthesis period was usually under-estimated due to exclusion of increased root mass (Acreche et al., 2009), pre-anthesis RUE was often higher than post-anthesis RUE due to leaf senescence occurred and plant organs other than leaves that intercepted radiation lowered the photosynthetic capacity during post-anthesis period. However, Lindquist et al. (2005) found no difference between the RUE before and after flowering for maize.

In the NCP, several researchers (Fu et al., 2009; Li et al., 2009) calculated the RUE on the basis of incident radiation rather than the intercepted radiation. However, the limitation for this method in relating daily matter productivity to incident solar radiation was that only a proportion of incoming radiation was intercepted by crops through their entire growing seasons and available for photosynthesis (Squire, 1990). Li et al. (2008) investigated the effects of irrigation and planting patterns on RUE and yield of winter wheat in the NCP and found there was no significant difference for the amount of intercept PAR between four kinds of planting patterns under different irrigation regimes. These studies, however, have not reported the integrated effects of the sowing time and sowing rate on crop growth and RUE of winter wheat in the NCP. So, the objective of this study was to investigate the effects of sowing time and rate on crop growth and RUE. The better knowledge of the impacts of different factors on RUE would improve the performance of crop growth models under a changing climatic condition and provide references for yield improvement for winter wheat.

Materials and Methods

Climate, site and experiment design

Field experiments were conducted at Luancheng Agro-ecological station (37° 53' N, 114° 40' E, 50.1 m above sea level) in the NCP during 2009/2010 and 2010/2011, two growing seasons of winter wheat. The area is in a monsoon climatic zone with 70% annual rainfall falling in the summer season. Mean rainfall during the growing season of winter wheat was about 132 mm. Soil is a moderately well drained loamy soil with a deep profile.

The experiment was randomised complete block design with 4 replicates of 3 sowing time treatments and 3 sowing rate treatments (Table 1). The size of each plot was 5×6 m. Winter wheat (cultivar: KN199) was sowed manually with 15 cm of row spacing for the 3 different sowing time and 3 different rates during 2009/2010 and 2010/2011 wheat season. Chemical fertilizer was applied at a rate of 100 kg N ha^{-1} and 50 kg P ha^{-1} before tillage as base fertilizers. The tillage to a depth of 15 cm using a mouldboard plow before sowing was conducted. An after manuring was applied at 100 kg N ha^{-1} (Urea) around jointing stage accompanied by irrigation or rainfall. To avoid water stress, two to three irrigations were applied depending on the rainfall condition (Table 1). Weed and pest controlling were similar to the management by the local farmers.

Table 1. Sowing time and sowing rate of winter wheat from 2009 to 2011.

Experiments	Treatments	Sowing date	Sowing rate (kg/ha^{-1})	Irrigation amount (mm)	Seasonal precipitation (mm)
2009/10	T_1N_1	Oct. 6	180	160	65.3
	T_1N_2	Oct. 6	225		
	T_1N_3	Oct. 6	270		
	T_2N_1	Oct. 13	180	160	65.3
	T_2N_2	Oct. 13	225		
	T_2N_3	Oct. 13	270		
	T_3N_1	Oct. 20	180	160	65.3
	T_3N_2	Oct. 20	225		
	T_3N_3	Oct. 20	270		
2010/11	T_1N_1	Oct. 10	180	240	64.4
	T_1N_2	Oct. 10	225		
	T_1N_3	Oct. 10	270		
	T_2N_1	Oct. 17	180	240	64.4
	T_2N_2	Oct. 17	225		
	T_2N_3	Oct. 17	270		
	T_3N_1	Oct. 24	180	240	60.3
	T_3N_2	Oct. 24	225		
	T_3N_3	Oct. 24	270		

Measurements

Soil volumetric water contents

Soil volumetric water contents were monitored every one or two weeks in 20 cm increments to a depth of 2 m using the neutron meter (IH-II, Cambridge) with access tubes installed in the centre of the plots. When soil water content was lower than 65% of field capacity, irrigation was applied by surface irrigation to ensure no water stress occurrence. Irrigation amount was recorded using the water meter in the outlet connected with a pipe.

Biomass, LAI, and phenological development

The main stages of phenological development including emergence (EM), elongation (E), heading (H), anthesis (AN) and physiological maturity (PM) were record when 50% of the plant population reached the corresponding conditions.

Above-ground biomass accumulation was monitored at 2-3 weeks interval during the growing seasons. At the same time, plant density was recorded. At each measuring, 40 stems were sampled randomly in each plot and oven dried at 80 ^{o}C to constant weight before weighting. Prior to dry, green leaf area was measured using a plant meter (model LI3100, LI-COR Ioc., Lincoln, NE).

Radiation and other climatic factors

Hourly solar radiation, air temperature, relative humidity (RH) and wind speed were recorded at a standard automatic weather station which is about 500 m away from the experimental field during the two growing seasons of winter wheat.

Calculations

RUE calculation

There was a debate on how to calculate RUE using the measured biomass and interception solar radiation data. One method for calculating

RUE is to determine the crop growth rate (CGR) between two consecutive harvests divided by the quantity of intercepted solar radiation. Sinclair and Muchow (1999) suggested that the linear relationship between accumulated biomass and cumulative intercepted solar radiation was a more appropriate method to estimate RUE. The former has the least bias because CGR values are independent. Though the later has been widely used to estimate RUE.

The well known relationship (Monteith, 1977) between the amount of aboveground dry matter and solar radiation is:

$$DM_d = RUE \times Q \tag{1}$$

Where DM_d is the daily above-ground total dry matter; Q, is the time-integrated product of intercepted radiation fraction by daily radiation above the canopy. The amount of Q declines exponentially with the leaf area index (LAI). Following Varlet-Grancher et al. (1989), Q could be calculated as:

$$Q = Q_0 \times (1 - e^{-k \times LAI}) \tag{2}$$

Where Q_0 is daily total incoming solar radiation (MJ m^{-2} d^{-1}); *K* is an extinction coefficient that depends on canopy geometry. Averaged *K* was estimated using the model proposed by Liu et al. (2002) in this region.

Daily green leaf area index (GLAI) was estimated assuming a linear increase (or decrease) between the measured values at two consecutive dates. Daily values of RUE were interpolated by third-order polynomial functions (Rinaldi and Alessandro, 2006).

Dry matter mobilization (DMM)

Dry matter mobilization (DMM) and dry matter mobilization efficiency (DMME) during grain-filling stage were calculated according to the equation described by Arduini et al. (2006):

DMM= dry matter of the above ground biomass at heading - (dry matter of leaves + culms + chaff at maturity) (3)

DMME= DMM / (dry matter of the above ground biomass at heading) (4)

Thermal time

Duration of growth stages was different among the different sowing time, especially for the stages before the recovering. Using thermal time to express the duration of the growth stages, the difference could be normalized.

Accumulated temperature above a base temperature is commonly used to compare the length of a phenological period. Thermal times (TT) for the different growing periods were calculated by the daily temperature minus a base temperature. A base temperature of 0 ^{o}C has been largely accepted in most agronomic conditions for winter wheat, although the base temperatures may vary even within species (Slafer and Savin, 1991). So in this study, a common base temperature of 0 ^{o}C was used. The thermal time was calculated following Kirby et al. (1999):

$$T_t = \frac{T_{\max} + T_{\min}}{2} - T_b \qquad \mathrm{T_{max}\ and\ T_{min} > T_b} \tag{5}$$

$$T_t = \left(\frac{T_{\max} + T_{\min}}{2 - T_b - T_{\min}} \right)^{-4} \qquad \mathrm{T_{max} > T_b,\ T_{min} < T_b,\ (T_{max}+T_{min})/2 > T_b} \tag{6}$$

$$T_t = \frac{T_{\max} - T_b}{4} \qquad \mathrm{T_{max} > T_b,\ T_{min} < T_b,\ (T_{max}+T_{min})/2 < T_b} \tag{7}$$

Where T_t is the thermal time, T_{max} and T_{min} are the maximum and minimum temperature, respectively and T_b is the base temperature and it was 0 ^{o}C in this study.

Statistical analysis

Analysis of variance (ANOVA) was used to test the difference in accumulation of thermal time (ATT) calculated using the different temperatures between different treatments. Mean comparisons were made by the LSD (the least significant difference) method with $P<0.05$. The regression analysis was conducted to make the relationship between RUE and thermal time. The analyses were conducted using the SPSS program.

Results

Climatic conditions

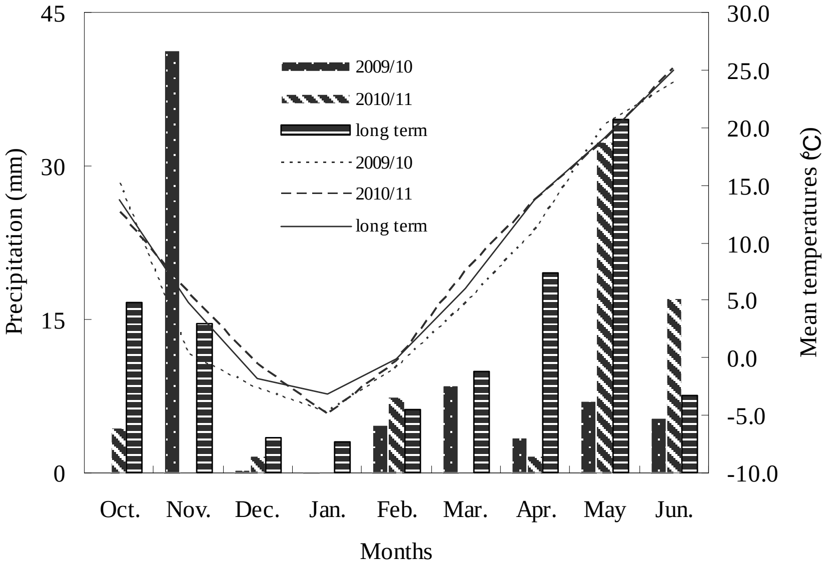


Figure 1. Values of monthly precipitation (bars) and temperatures (lines) during 2009/2010, 2010/2011 and long term average for winter wheat growing season at Luancheng station.

Monthly mean temperature and monthly precipitation for the 2009/2010 and 2010/2011 seasons and their long-term average are presented in Figure 1. There was more rain in November 2009 and June 2011, less rain in April of both seasons compared with the long-term average. Total monthly rainfall in the growing season was 70.7 mm in 2009/2010 and 64.4 mm in 2010/2011, which was far less than the normal seasonal rainfall of 115 mm (Sun et al., 2010). The two seasons were dry season and winter wheat was irrigated to sustain adequate water supply. As for the temperature, the lowest mean temperature occurred in January with average value of -5.0 ^{o}C and the highest temperature occurred in June with average value of 25.1 ^{o}C. 2009/2010 season was cooler than a normal season, especially from November to December.

The heavy snow in earlier winter of 2009/2010 season resulted in significant temperature drop, which lasted into the end of winter dormancy of winter wheat. Temperature in 2010/2011 season was close to the average pattern during much of the season.

Crop growth

Growing stage

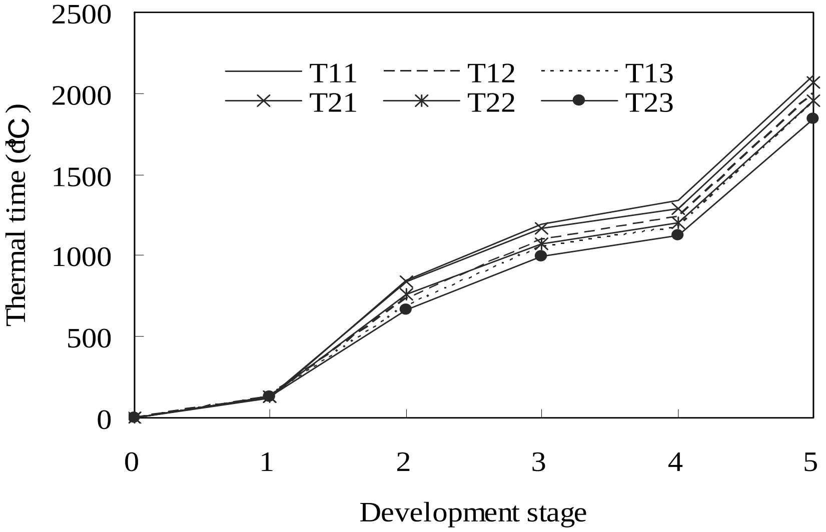


Figure 2. Thermal time changes in relation to phenological development stage (0, sowing; 1, emergence; 2, elongation; 3, heading; 4, anthesis; 5, physiological maturity).

Note: T_{11}, T_{12} and T_{13} represent the treatments sowing at Oct. 6, 13 and 20 during 2009/2010 growing season, respectively. T_{21}, T_{22} and T_{23} represent the treatments sowing at Oct. 10, 17 and 24 during 2010/2011 growing season, respectively.

Figure 2 shows the thermal time changes in relation to phenological development for winter wheat during the two growing seasons. Except for the stage from emergence to elongation, values of thermal time for T_{11} and T_{21}, T_{12} and T_{22}, T_{13} and T_{23} were all close. Therefore, the differences were mainly caused by the different thermal time from emergence to elongation. The difference between the first sowing time treatment (T_1) and the last sowing treatments (T_3) is 186.0 and 162.3 d^{o}C during 2009/2010 and 2010/2011 growing seasons, respectively. The high variation of thermal time might be caused by the shortened vernalization which only needs 40-50 days under lower temperature conditions (Ritchie, 1991), while in this region the vernalization days is more than 60 days. From sowing to emergence, the requirement of thermal time were similar and there wasn't significantly difference (LSD, $P<0.05$) among different treatments, with values ranged from 122.2 to 130.1 d^{o}C in 2009/2010, from 127.2 to 134 d^{o}C in 2010/2011. The requirement of thermal time from elongation to heading was 323.9±6.2 d^{o}C and 358.8±9.9 d^{o}C, for the two seasons, respectively. They were 125.3±5.6 d^{o}C and 136.3±10.0 d^{o}C from heading to anthesis, 751.9±31.3 d^{o}C and 766.4±2.1 d^{o}C from anthesis to maturity, respectively.

Above-ground biomass and GLAI

Comparisons of total above-ground biomass and GLAI are shown in Figure 3 and Figure 4. The results showed that there were similar trends among all the treatments during 2009/2010 and 2010/2011 growing seasons. The difference for the above-ground biomass between sowing time treatments was due to their difference in growing duration. The difference in 2009/2010 was greater than that in 2010/2011 season, which might be caused by the lower temperature in 2009/2010. Earlier sowing treatment had higher above-ground biomass than the later sowing treatment. Sowing rate had small effects on the above-ground biomass. The GLAI followed the trend of unimodal curve. The peak value for the GLAI occurred around anthesis and it was 4.33 and 3.6 for T_1N_3 treatment during 2009/2010 and 2010/2011 growing seasons, respectively. The largest difference for LAI was about 1.2 between the T_1N_3 and T_3N_1 treatments during the two seasons. This indicated that the effect of sowing time on LAI was greater than that of sowing rate.

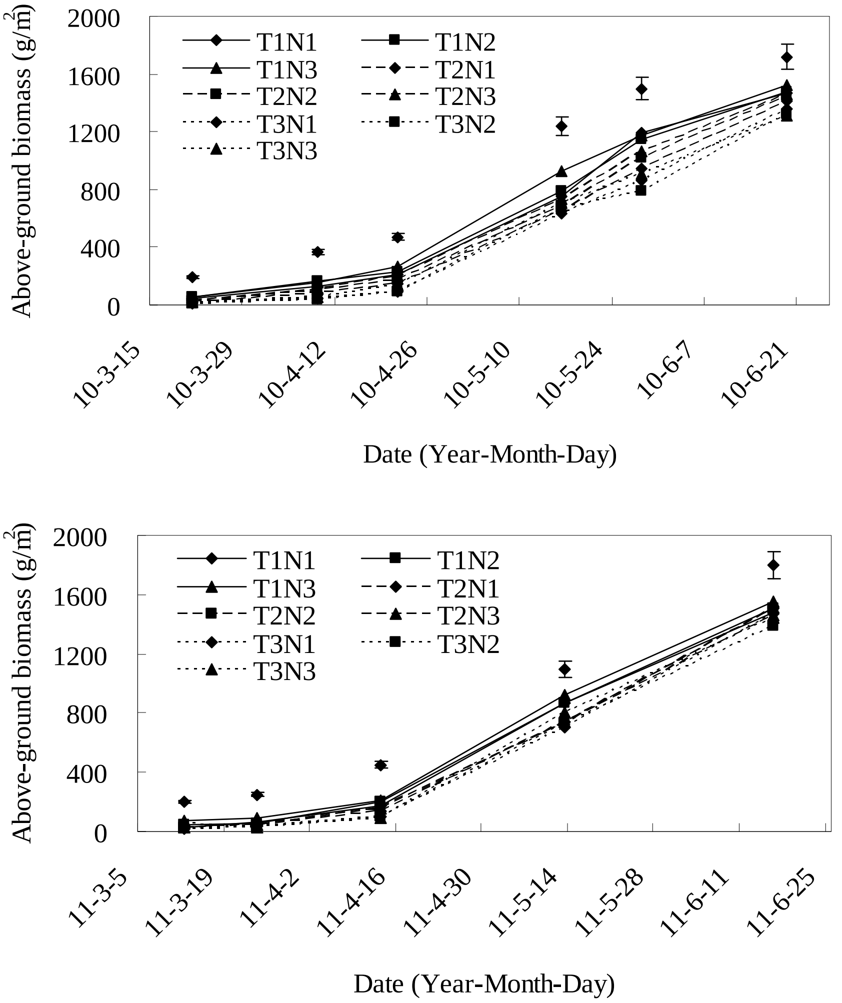
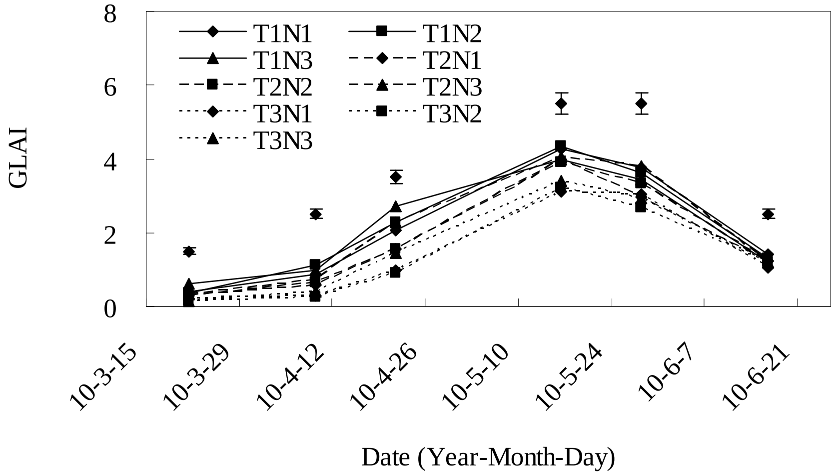


Figure 3. The dynamic variation of above-ground biomass during 2009/2010 and 2010/2011 winter wheat growing seasons.

Note: Bars represent the standard error.



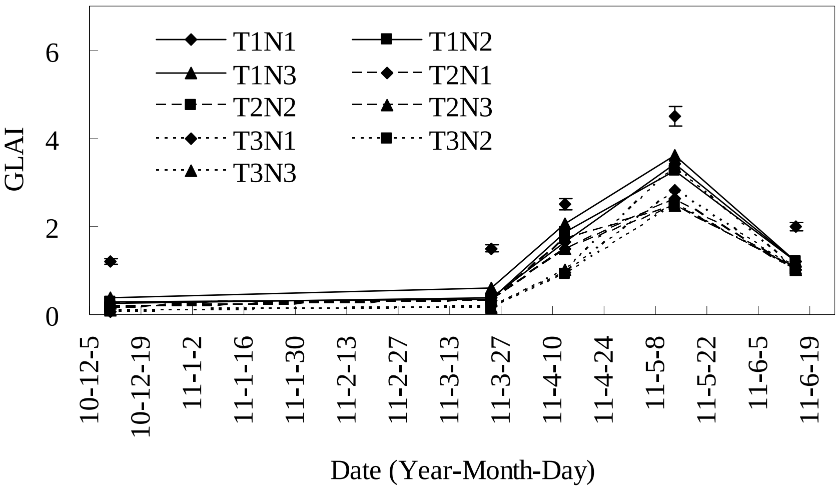


Figure 4. The dynamic variation of GLAI during 2009/2010 and 2010/2011 winter wheat growing seasons.

Note: Bars represent the standard error.

RUE

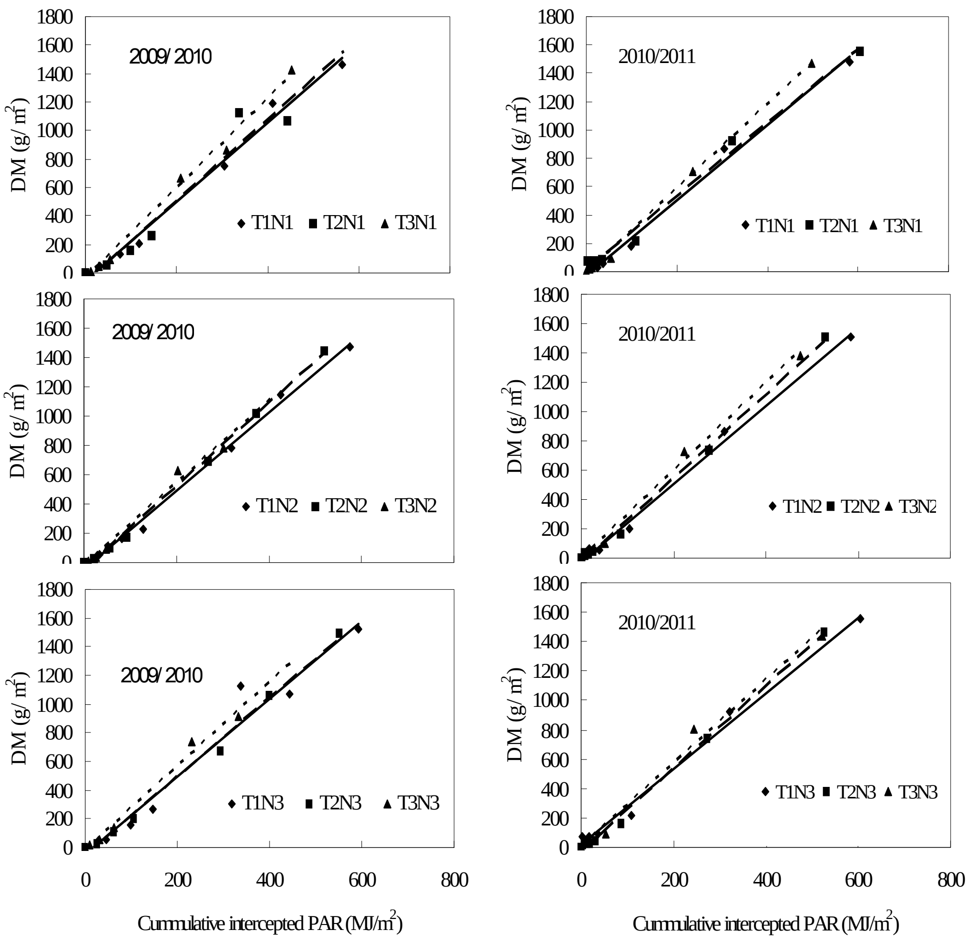


Figure 5. The relationships between cumulative intercepted PAR and above-ground biomass for the different sowing time and sowing rate treatments during 2009/2010 and 2010/2011 winter wheat growing seasons.

There were similar trend during the two seasons for RUE (Figure 5). There was no significant difference for the RUE among the different sowing time and sowing rate treatments (Table 2). RUE values ranged from 2.67 to 3.14 g MJ^{-1} and from 2.59 to 2.98 g MJ^{-1} in the 2009/2010 and 2010/2011 winter wheat seasons, respectively. RUE was decreased with the increase in sowing rate and increased with the delay in sowing. RUE was similar for the different sowing rates at the normal sowing time. However, RUE was not increased with the increase in sowing rate at delayed sowing time. RUE was similar for the low and medium sowing rate treatments, but lower at the high sowing rate which was consistent with the findings by Singer et al. (2007). With the sowing date delayed, RUE was increased through the entire growing season. These results agreed with the pattern of crop growth. Crops would have different duration under different growing environment which mainly caused by the different photoperiod and vernalization. This indicated that the winter wheat had the capacity of self-adjustment according to the environmental factors. The fact that late sowing treatment produced more dry matter at flowering using less time than the normal sowing treatment indicated a more pronounced effect of delaying planting date on crop growth than on crop development.

RUE for pre-and post-anthesis

Table 2. The RUE, RUE during pre-anthesis and post anthesis under different sowing time and sowing rate treatments.

Growing seasons	Treatments	RUE pre-anthesis	RUE Post-anthesis	RUE
2009/2010	T_1N_1	1.763^{bc}	2.682^{b}	2.761^{bc}
	T_1N_2	1.837^{b}	2.655^{b}	2.674^{c}
	T_1N_3	1.834^{b}	2.400^{c}	2.655^{c}
	T_2N_1	1.674^{c}	3.235^{a}	2.811^{b}
	T_2N_2	1.932^{ab}	3.007^{a}	2.839^{b}
	T_2N_3	1.926^{ab}	3.138^{a}	2.742^{bc}
	T_3N_1	1.784^{b}	3.146^{a}	3.140^{a}
	T_3N_2	1.955^{ab}	2.964^{ab}	2.958^{ab}
	T_3N_3	2.191^{a}	2.395^{c}	2.831^{b}
2010/2011	T_1N_1	1.716^{ab}	2.201^{b}	2.627^{b}
	T_1N_2	1.840^{a}	2.336^{b}	2.645^{b}
	T_1N_3	1.611^{b}	2.244^{b}	2.589^{b}
	T_2N_1	1.579^{b}	2.965^{a}	2.865^{ab}
	T_2N_2	1.791^{ab}	3.055^{a}	2.847^{ab}
	T_2N_3	1.722^{ab}	2.857^{a}	2.808^{ab}
	T_3N_1	1.652^{b}	2.898^{a}	2.977^{a}
	T_3N_2	1.872^{a}	2.575^{ab}	2.977^{a}
	T_3N_3	1.488^{c}	2.303^{b}	2.831^{ab}

Within column under the same season values with the same letter were not significant at $P<0.05$.

The duration of grain-filling is very important to the grain yield. So the analysis about the RUE pre-and post-anthesis for different sowing time and sowing rate is necessary. RUE during pre-anthesis period varied between 1.67 and 2.19 g MJ^{-1}, between 1.49 and 1.84 g MJ^{-1} in the 2009/2010 and 2010/2011 seasons, respectively (Table 2). RUE during post-anthesis period varied between 1.66 and 3.15 g MJ^{-1}, between 2.20 and 3.06 g MJ^{-1} in the 2009/2010 and 2010/2011 seasons, respectively. There was no significant difference among the different sowing time and sowing rate treatments. RUE was less during pre-anthesis period than that during post-anthesis period which was not consistent with the findings by Calderini et al. (1997) and Fisher (1993). This might be caused by the growth rate which was constrained by the weather factors, such as the dry-hot wind in the later of May and beginning of June which accelerated the maturity of winter wheat.

The relationship between thermal time and RUE

Figure 6 shows the curves of functions interpolating RUE data during the crop cycle under different sowing treatments. There are greater RUE values in T_3 treatments than that of other treatments before they reached the maximum RUE during the two growing seasons. As for the T_2 treatment, RUE value was slightly greater than that of T_1 treatment and less than that of T_3 treatment. All these greater RUE values occurred between 1000 and 1500 d^{o}C. These periods for the maximum RUE located around the 80% of soil cover by the crop canopy and before the reaching of maximum GLAI.

RUE and the temperature

The biggest difference for the RUE and biomass occurred from sowing to stem elongation for the different sowing times. Therefore, the relationship between RUE and the daily average temperature from sowing to stem elongation was analysed (shown in Figure 7). Meanwhile, the growth of winter wheat would stop when the temperature was lower than 0 ^{o}C, so the temperatures lower than 0 ^{o}C wasn’t considered in this study. The regression analysis showed that there was linear relations and which indicated that RUE was increased with the daily average temperature in this period.

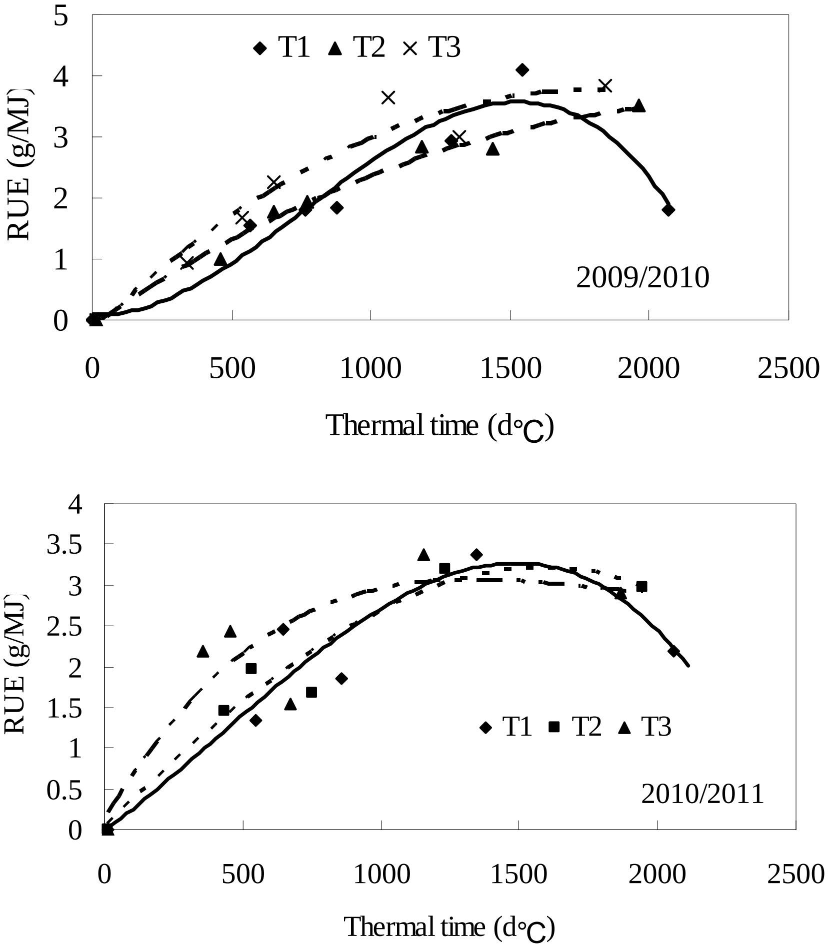


Figure 6. Radiation use efficiency in winter wheat during crop cycle expressed as thermal time. The lines represent the third-order polynomial functions of daily values at sampling date (6-8 for each season).

During 2009/2010 season:
T_1: y= -2E-09x^3+5E-06X^2-0.0001X+0.0815, R^2=0.92;
T_2: y= -3E-11x^3-7E-07X^2+0.0032X-0.09686, R^2=0.98;
T_3: y= -1E-10x^3-8E-07X^2+0.0041X-0.1622, R^2=0.95.

During 2010/2011 season:
T_1: y= -9E-10x^3+1E-06X^2+0.0025X-0.016, R^2=0.88;
T_2: y= -3E-10x^3-4E-07X^2+0.0033X+0.0218, R^2=0.94;
T_3: y= 7E-10x^3-3E-06X^2+0.0056X+0.132, R^2=0.78

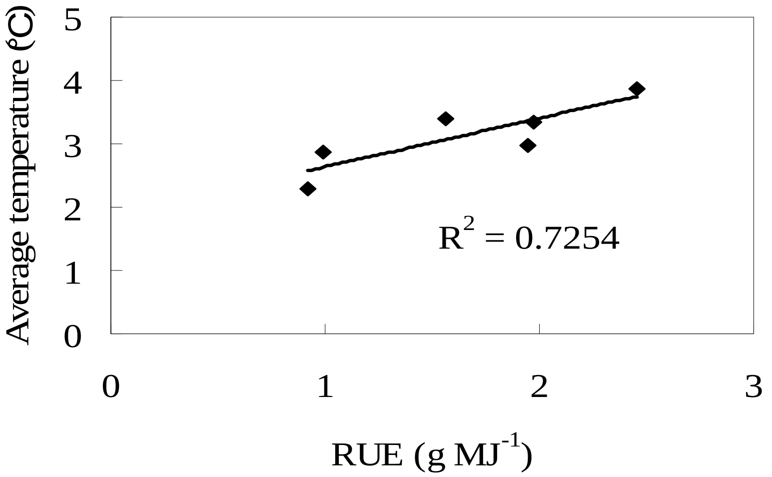


Figure 7. The relationship between RUE and the temperature from sowing to stem elongation.

Grain yield

Table 3 shows that with the sowing rate increase, biomass at heading increased during the two winter wheat growing seasons. Grain yield (GY) ranged from 592.0 to 655.2 gm^{-2} during 2009/2010, and from 645.9 to 693.6 during 2010/2011. With the delayed sowing time, GY was slightly reduced under the same sowing rate for both seasons. There was also an improvement for the GY when the sowing rate was increased. Biomass at heading (BH) was declined with the delaying in sowing time. However, biomass at maturity was similar for all the treatments. This indicated that the variation of RUE after heading among the treatments was different.

HI was between 0.46 and 0.49 during the two growing seasons. There was no significant difference for the different sowing time and sowing date treatments. In the normal sowing time treatments, HI was decreased with the increase in sowing rate. It was similar among the medium delayed sowing time treatments. However, it was increased with the increase in sowing rate for the most delayed sowing time treatments.

Generally, the DMM and DMME increased with the increase in sowing rate. The maximum DMM and DMME occurred for T_1N_3 treatment for the two seasons. Compared with the sowing time, values of DMM and DMME for normal sowing treatments were greater than that of the delayed sowing treatments. This might be attributed to phenological development. The delayed sowing treatments tended to delay its heading and anthesis date by 2-5 days compared with the normal sowing treatments. Generally, in the NCP the duration of grain-filling is about one month due to the high temperature and dry hot wind in the late of May and early June. Thus, the duration of grain-filling for the normal sowing treatments was longer than that of delayed sowing treatments, resulting higher DMM and DMME. This result was consistent with Zhang et al. (2008). So the biomass and grain yield for the delayed sowing treatments were reduced under this condition.

Table 3. Harvest index (HI), grain yield (g/m^2), Aerial biomass at heading (BH) and maturity (BM) (g/m^2) and dry matter mobilization and dry matter mobilization efficiency for all the treatments during the 2 winter wheat growing seasons.

Seasons	Treatments	HI	GY	BH	BM	DMM	DMME
2009/2010	T_1N_1	0.47^{ns}	641.7^{ab}	759.7^{abc}	1370.1^{ns}	31.3^{b}	4.12^{b}
	T_1N_2	0.46^{ns}	649.9^{a}	796.4^{ab}	1408.9^{ns}	37.4^{ab}	4.69^{ab}
	T_1N_3	0.46^{ns}	655.2^{a}	821.6^{a}	1425.7^{ns}	51.1^{a}	6.22^{a}
	T_2N_1	0.47^{ns}	619.2^{ab}	712.7^{b}	1330.7^{ns}	1.1^{b}	0.16^{b}
	T_2N_2	0.46^{ns}	630.8^{ab}	738.7^{abc}	1362.4^{ns}	7.1^{b}	0.97^{b}
	T_2N_3	0.46^{ns}	638.7^{ab}	762.5^{abc}	1390.2^{ns}	11.0^{b}	1.44^{b}
	T_3N_1	0.47^{ns}	592.0^{b}	685.0^{c}	1270.7^{ns}	6.2^{b}	0.91^{b}
	T_3N_2	0.47^{ns}	603.5^{ab}	696.8^{c}	1282.8^{ns}	17.5^{b}	2.51^{b}
	T_3N_3	0.47^{ns}	612.4^{ab}	725.5^{ab}	1305.9^{ns}	32.1^{ab}	4.42^{ab}
2010/2011	T_1N_1	0.49^{ns}	676.1^{ns}	828.2^{ab}	1381.0^{ns}	123.3^{a}	14.89^{a}
	T_1N_2	0.48^{ns}	672.1^{ns}	869.6^{ab}	1408.6^{ns}	133.0^{a}	15.30^{a}
	T_1N_3	0.48^{ns}	693.6^{ns}	934.0^{a}	1461.7^{ns}	166.0^{a}	17.77^{a}
	T_2N_1	0.47^{ns}	664.9^{ns}	760.3^{bc}	1412.6^{ns}	12.5^{b}	1.65^{b}
	T_2N_2	0.47^{ns}	666.9^{ns}	786.1^{ab}	1435.3^{ns}	17.7^{b}	2.26^{b}
	T_2N_3	0.47^{ns}	673.7^{ns}	799.0^{ab}	1446.5^{ns}	26.2^{b}	3.28^{b}
	T_3N_1	0.47^{ns}	645.9^{ns}	733.8^{bc}	1365.2^{ns}	14.5^{b}	1.97^{b}
	T_3N_2	0.48^{ns}	650.8^{ns}	730.7^{bc}	1363.9^{ns}	17.5^{b}	2.40^{b}
	T_3N_3	0.48^{ns}	662.8^{ns}	765.8^{bc}	1390.5^{ns}	38.1^{b}	4.97^{b}

Within column under the same season values with the same letter were not significant at $P<0.05$.

Discussion

The coupling effects of sowing time and rate on winter wheat in the NCP was apparent in this study. Although some researchers studied the effect of different sowing times and rates on the grain yield, they didn't show how the different sowing times and rates affected the growth proceeding for winter wheat (Gao et al., 2002; Sun et al., 2007). In this study, RUE based on the biomass and incepted radiation was showed for the different sowing times and rates and which indicated that the grain yield was not only affected by the RUE but also by the DMM. The study should be combined with the canopy structure, fertilizer use and yield components and so on. Averagely, the delayed sowing time reduced grain yield of winter wheat by 2.7 kg/ha per day, while the increased sowing rate resulted in smaller yield penalties in delayed sowing time by 0.7 kg/ha per day. The results from this research also showed that winter wheat has a strong ability to adjust its growing duration to replenish the lost time in growth and development. The difference in development was gradually reduced among the sowing time treatments. Mohammad et al. (2011) found that in Pakistan there are significant different seed and biomass production for the four wheat varieties and different sowing time and the crop growth rate and its duration are also difference. Han et al. (2011) found that with delaying sowing date, the number of developed small spike and born small spike and number of head were reduced significantly and then caused the yield reduction. These findings showed that the delayed sowing time caused the reduction for the biomass and yield production which could be compensated by the increase in the sowing rates.

Conclusions

Results from this study showed that there were significant effects of sowing time on phenological development, accumulated above-ground biomass and LAI which then affected RUE. RUE was increased with the increase in sowing rate and it was decreased with the delay in sowing time. The reduction was mainly caused by the shortened duration from emergence to stem-elongation for the delayed sowing time treatments.

RUE during pre-anthesis was less than that during post-anthesis, especially for the delayed sowing treatments which was mainly caused by the lower DMM and DMME. Compared with the normal sowing time treatment, the delayed sowing time treatments had the lower DMM and DMME which indicated that the different sowing date would affect the duration of growth and then the RUE.

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