



Measured Phenology Response of Unchanged Crop Varieties to Long-Term Historical Climate Change

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Abstract

Understanding how crop phenology responds to historical climate change is a prerequisite for evaluating crop phenology and future yield responses. Most phenology response investigations are based on the phenology observed under circumstances of varieties changing over time, which then necessitates disentangling the role of climate change from the effect of changing varieties using various models. However, results from such studies are limited by the uncertainties caused by model mechanisms and assumptions and parameter calibration and validation. In this study, phenology observations were made for varieties of winter wheat (*Triticum aestivum* L.), rice (*Oryza sativa* L.), and spring maize (*Zea mays* L.) at 11 agro-meteorological observation sites in north China. The varieties observed for each species did not change over a period of at least 15 years. The observations were used to investigate the measured phenology response to climate. Dates of major wheat phenology stages tended to occur earlier due to warming, but the trend in rice and spring maize was not clear. Growth duration was shortened during the vegetative period of winter wheat, but was prolonged during vegetative period of rice and in the reproductive period of winter wheat and rice. Growing degree days (GDD) were generally increased for both vegetative and reproductive periods for all crops except during the vegetative period for winter wheat. We found that most trends in date of phenology stages, duration of growth phases, and GDD were similar to previous reports in which the varieties observed did not remain constant. This indicates that previous reports are likely to have overestimated the effect of cultivar shifting on crop phenology and underestimated the role of climate. Based on our results, growth duration under future warmer conditions may be longer than previously simulated, and hence yield may also be higher than previously estimated.

Keywords Climate change · Phenology · Temperature sensitivity · Unchanged variety · Field observation

Introduction

Changes in crop phenology play a key role in yield formation through regulation of the duration of biomass accumulation in various organs. Climate warming will shorten crop growth duration, thereby potentially reducing yield and thus threatening future world food security (Anwar et al. 2015). Consequently, climate change impacts on crop phenology have been of much concern, especially during the last two decades.

In recent decades, the response of crop phenology to historical climate change has been extensively investigated in many regions and climates around the world, especially in Germany and China, since those two countries have systematic and complete phenology observations (Chmielewski et al. 2004; Hu et al. 2005; Estrella et al. 2007; García-Mozo et al. 2010; Siebert and Ewert 2012; Sadras and Moran 2013). Reports have shown that phenology has potentially

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changed as a consequence of climate change for many crops, but the changes appear to be crop and location dependent. In Germany, the response of date of phenology stages to temperature ranged between 3.73 and 4.31 day/°C in 78 agronomic and horticultural crops (Estrella et al. 2007). Similarly, dates of oat phenology stages were advanced about 4 day/°C (Siebert and Ewert 2012), and winter rye phenology dates were advanced by 3.8 day/°C (Chmielewski et al. 2004). In China, the length of the wheat growth period was negatively correlated with temperature, with an average rate of -3.8 d and -1.2 day/°C for the period from green-ing to heading and from heading to maturity, respectively (Tao et al. 2012; Xiao et al. 2013, 2014), and -2.71 and -1.07 day/°C for the maize growth period from sowing to maturity and from heading to maturity, respectively (Meng et al. 2015).

However, the above-mentioned responses are not solely caused by climate change. Other non-climatic factors, including varietal differences, can also play an important role in determining crop phenology. Depending on climate characteristics and the need for avoiding local agro-meteorological disasters, variety shifts can shorten or lengthen growing season duration (Estrella et al. 2007; Torrión et al. 2011; Tao et al. 2013; Zhang et al. 2013; He et al. 2015). Hence, there is a need to disentangle the effects of climate change and variety shifts. To separate the effects of climate change from the combined effects of climate change and variety shifts, many computer simulation phenology models have been applied. During the last decade, effects of variety shifts on phenology of major crops including rice (Liu et al. 2012), maize (Liu et al. 2013), and wheat (He et al. 2015; Li et al. 2015) have been investigated using various simulation models, such as CERES (Tao et al. 2014), APSIM (He et al. 2015), and RiceGrow (Liu et al. 2012). These simulations showed that variety shifting generally prolonged growth duration for most crops (Tao et al. 2014; Li et al. 2015).

Theoretically, before applying models to specific situations or to answer specific questions, model parameters should be validated over a wide temperature range to make sure the model can capture phenology responses under various environments (Menzel et al. 2005). However, the actual execution of field experimentation results in varieties being changed after only brief time periods. In China, winter wheat varieties have been changed about every 2 or 3 years (Wu et al. 2018). Thus, there exist two dilemmas in using these computer simulations. The first is that during these limited 2 or 3 years, the temperature range that a crop has been exposed to is unlikely to be varied enough. As a consequence, the obtained parameters are unlikely to fully capture the temperature response. Secondly, if observations are obtained for model calibration over a period of more than 2 or 3 years, then it is difficult to guarantee that the same variety has been used over the entire observation

period. Applying a computer simulation model before it is fully validated can introduce great errors (Bonhomme et al. 1994; Kumudini et al. 2014; Wang et al. 2015; Wu et al. 2018). Therefore, credibility of simulation results from models applied to changing climatic conditions depend heavily on the veracity and reliability of the models and whether they have been adequately calibrated and validated.

A more reliable way to investigate the effects of climate change on phenology is to use long-term observations of varieties that remain unchanged over time and are grown in locations that do not change. The record of observations from such experiments must extend over as long a period as possible to ensure that the observations contain a sufficiently broad range of temperature variation. But conducting such long-term experiments is very difficult since the seed supply of a single chosen variety may be difficult to obtain over an extended period of time (Major et al. 1983). Consequently, these long-term datasets with a single variety, even though they would have great value for investigating the true response of crop phenology to a wide range of climate variation, are very limited in number. These data, if available, could present more accurate information than model simulations, especially in predicting phenology responses to future climate change.

In this study we gathered phenology observations for 12 varieties of the three major food crops (wheat, rice, and maize) from historical records that were at least 15 years in length at fixed stations and under field conditions across North China during the last 30 years in order to investigate phenology responses to historical climate change. The objectives of this study were to: (1) identify changes of the measured date of major phenology stages and the length of major phenology phases of fixed varieties under changing historical climate conditions; (2) analyze changes in GDD of these varieties during major phenology phases; and (3) investigate temperature sensitivity during several growth periods.

Materials and Methods

Study Sites and Observations

In the early 1980s, the Chinese Meteorology Administration (CMA) initiated the national phenology observation plan for major cereal crops using nation-wide agro-meteorological observation stations. Observations were conducted by trained agricultural technicians following standardized observation methods (CMA 1993). More than 600 observation sites were gradually established thereafter, resulting in the accumulation of a large number of phenological observations that continue to the present time. A number of studies provide planting and management details and phenology observation methods (Tao et al. 2014; Wu et al. 2018).

Many reports have been published based these observations (Liu et al. 2012; Tao et al. 2013, 2014; Zhang et al. 2008, 2013; Wang et al. 2013). By chance, 11 of these sites have not changed varieties for more than 15 years. These sites are all located in north China (Fig. 1). In total, 12 crop varieties (seven winter wheat, two rice, and three spring maize) were planted at the 11 sites (Tonghua station had both rice and spring maize). Table 1 shows the name, elevation, and planting information for the 11 sites.

All of the observed phenology data used in this study were obtained from the National Meteorological Information Center (NMIC). Historical daily mean temperatures at the 11 agro-meteorological observation sites during the same years as phenology observations were also obtained from NMIC.

Data Analysis

For simplicity, five major phenology stages (PS) were used for all three crops. Accordingly, four phenology growth phases (GP) were defined. The five stages and four phases are defined in Table 2. PS1, PS4 and PS5 are emergence, anthesis and maturity for the three crops. For winter wheat, PS2 and PS3 are the start of overwintering and turning green, respectively. For rice, PS2 and PS3 are transplanting and turning green, respectively. The definition of rice

turning green is the time when the leaf color turns green after transplanting. At this time, rice roots are actively growing into the soil (CMA, 1993), and the plant has partially recovered from the damage caused by transplanting. For spring maize, PS2 and PS3 are seven leaves and jointing, respectively. Generally, GP1, GP2, GP3 and GP4 correspond to the early vegetative period, the vegetative period, reproductive period and the entire growth period, respectively.

Average dates of PS1–PS5 for each variety were calculated. Linear trends of growth period average temperature (T_{aver}) and dates of PS1–PS5 against years were calculated using the least squares method. The GDD in the four GPs were calculated using previously reported base temperatures for winter wheat, rice, and spring maize of 0, 8, and 8 °C, respectively (Porter and Gawith 1999; Zhang et al. 2008; Kumudini et al. 2014). The trends of GDD against the year were calculated for each GP using the least squares method.

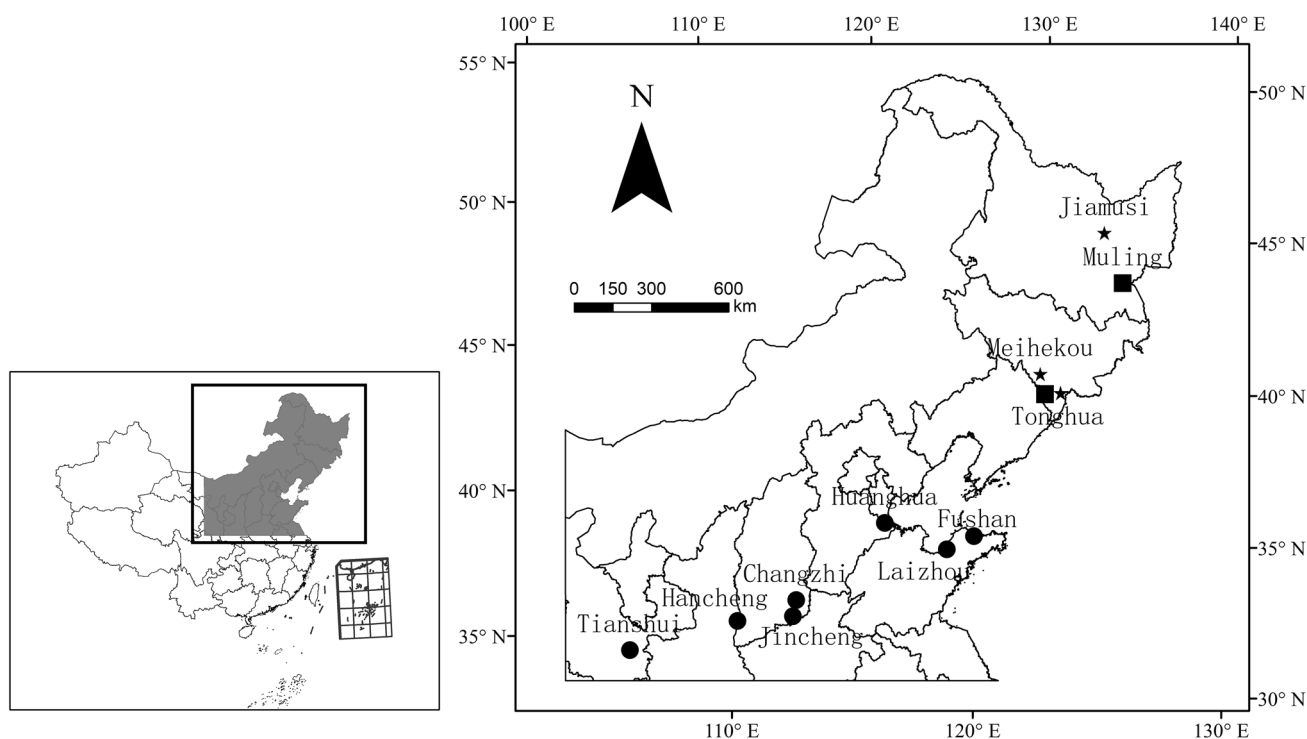


Fig. 1 Study area and locations of 11 agro-meteorological observation stations. Filled circle are winter wheat observation sites, filled square are rice sites, filled star are spring maize sites. Tonghua station has both rice and spring maize observations, with the filled star above

the Tonghua label indicating the actual position for the observations. To show the two crops in the same figure, we show the rice site to the left of the actual position

Table 1 Information for north China sites in which the planted variety remained unchanged for at least 15 years

Site	Elevation (m)	Planted years	Number of years	Variety name
Winter wheat				
Changzhi	992	1988–2004	17	CZ648
Hancheng	458	1991–1994, 1996–2003, 2006–2009	15	XY6
Jincheng	753	1981–1986, 1989–1992, 1994–1998, 2001, 2003–2006	21	5819
Huanghua	7	1989–2011	23	71321
Laizhou	48	1990–2010	21	YN15
Fushan	54	1987–2011	26	YN15
Tianshui	1142	1991–2009	19	7464
Rice				
Tonghua	380	1985–2010	26	QG
Muling	266	1994–1995, 1997–2011	16	SY397
Jiamusi	82	1992–2002, 2004–2010	18	DN248
Spring maize				
Meihekou	341	1986–1993, 1995–2001	15	TD4
Tonghua	380	1983–2002	20	JD101

Table 2 Definitions of the phenology stages (PS) and growth phases (GP) for three crops grown in north China

	Crop	PS1	PS2	PS3	PS4	PS5
Phenology stages	Winter wheat	Emergence	Start overwintering	Turning green	Anthesis	Maturity
	Rice	Emergence	Transplanting	Turning green	Heading	Maturity
	Spring maize	Emergence	Seven leaves	Jointing	Anthesis	Maturity
		GP1	GP2	GP3	GP4	
Phenology phases	Winter wheat	PS1–PS2	PS1–PS4	PS4–PS5	PS1–PS5	
	Rice	PS1–PS2	PS1–PS4	PS4–PS5	PS1–PS5	
	Spring maize	PS1–PS2	PS1–PS4	PS4–PS5	PS1–PS5	

Results

Trends of Average Temperature During Phenology Phases

Over the entire study period for each crop variety, growing season average temperature varied about 2.4 °C (Fig. 2a), ranging from 1.7 to 3.0 °C. In contrast, when considering only the first 3 years of each variety's study period, growing season average temperature varied only about 1/3 of what was observed over the entire period (0.8 °C), ranging from 0.1 to 1.4 °C. Therefore, when model parameters are validated based on only the first 3 years' observations, the parameter values obtained may not represent the response of the crop over a sufficiently wide temperature range.

Generally, warming trends were observed during the four phenology phases, but the trend varied with crops and phases (Fig. 3). For GP1, temperature decreased

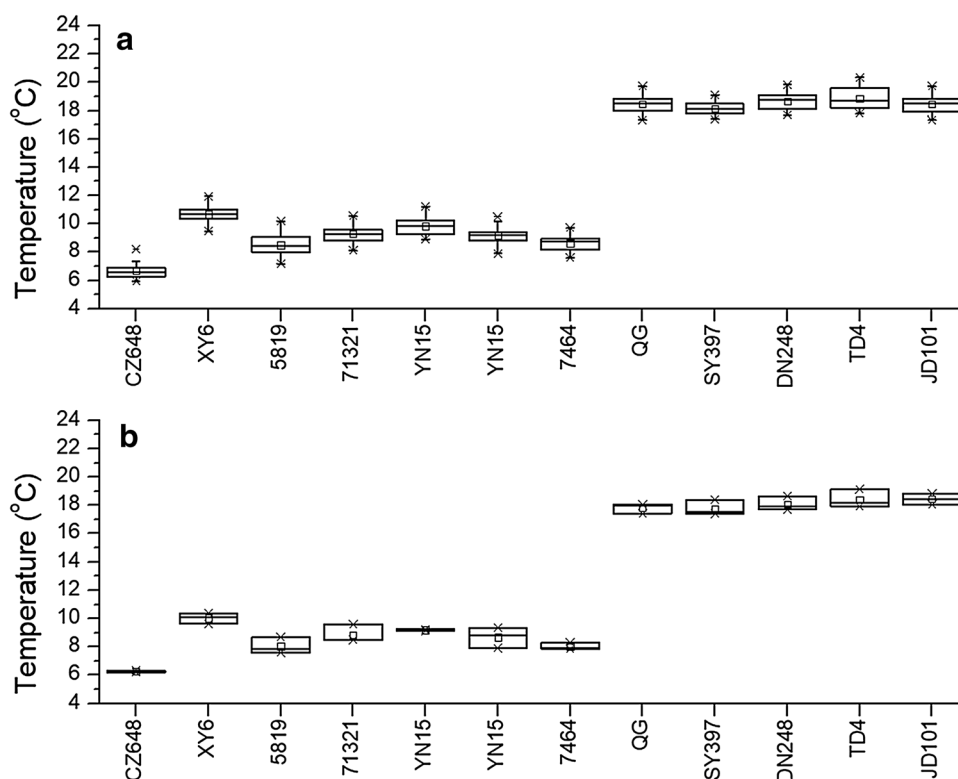
insignificantly at winter wheat sites, but increased insignificantly at all rice sites and two spring maize sites (Fig. 3a). At one spring maize site (Tonghua), the warming trend was significant. For GP2, the warming trend was significant at one winter wheat site, one rice site, and two spring maize sites (Fig. 3b). For GP3, temperature significantly decreased at one rice site and significantly increased at two spring maize sites (Fig. 3c). For GP4, the warming trend was significant at one winter wheat site and one spring maize site (Fig. 3d).

This warming trend was inconsistent with the warming trend during the growing season (Fig. 4). All trends during the measured phases were less than trends during the growing seasons except for two spring maize sites.

Changes of Date of Major Phenology Stages

Winter wheat phenology was delayed before the start of overwintering (PS1, positive values) and was advanced

Fig. 2 Variation in growing season average temperature during the entire study period in north China for each crop variety (a) and in the first three years of each study period for each crop variety (b). The first seven box plots are for winter wheat varieties, in which the growing season was defined as from 1 October to 30 June of the following year. The next two box plots are for rice varieties. The last three box plots are for spring maize varieties. For rice and spring maize, the growing season was defined as from 1 May to 30 September. Solid lines and open squares within boxes indicate medians and means, respectively. Box boundaries indicate upper and lower quartiles, whisker caps indicate 95th and 5th percentiles, and upper and lower crosses indicate maximums and minimums



thereafter (negative values). Average trends for PS1–PS5 were 0.55, -1.06 , -0.17 , -0.26 , and -0.15 day/year, respectively (Table 3). Emergence dates (PS1) in six out of seven sites were delayed significantly. Dates for PS2–PS5 were generally advanced, and the trends were significant at 0, 2, 2, and 2 winter wheat sites, respectively.

Rice in Tonghua showed no significant trend for any of the PSs (Table 3), while in Muling, dates for PS1–PS3 had no significant trends, but were significantly delayed by 0.9 and 1.06 day/year for PS4 and PS5, respectively.

Spring maize in Jiamusi showed no significant trend for any of the PSs (Table 3). In Meihekou, PS1–PS4 showed no significant trend, but the date for PS5 was significantly advanced by 0.75 day/year. In Tonghua, dates for PS2, PS3, and PS5 were significantly delayed by 0.38, 0.43, and 0.36 day/year, respectively.

Changes in Length of Major Phenology Growth Phases

The length of the winter wheat growing season (from emergence to maturity, GP4) was significantly reduced at six out of seven sites by an average of -0.70 day/year (Table 4). For GP1 and GP2, growth durations were significantly reduced in three and five sites, respectively. However, during the important yield-determining GP3 period (the reproductive and grain-filling period), there was no obvious reduction in the length of GP3 (average trend was 0.11 day/year). The

trends in GP3 duration were significantly reduced at one site (-0.20 day/year) and significantly increased at another site ($+0.22$ day/year).

Except for GP1, growth durations in other GPs of rice were increased, but the trend was only significant for GP2 and GP4 for Muling (0.81 and 0.97 day/year), and GP3 for Tonghua (0.19 day/year) (Table 4).

Spring maize in Jiamusi and Meihekou showed no significant trends for any of the growth phase periods, but lengths of GP1 and GP3 in Tonghua were significantly increased by 0.28 and 0.31 day/year (Table 4).

Changes in GDD

GDD requirements for GP1 and GP2 were decreased at six out of seven winter wheat sites, but the trends were significant at only two sites (one negative trend and one positive trend) (Table 5). On the other hand, GDD for GP3 were increased in six out of seven sites by an average of 3.33 °C day/year, ranging from -2.94 to 5.51 °C day/year (significant at four sites). As a result, GDD in GP4 (emergence to maturity) increased by an average of 0.87 °C day/year, ranging from -3.89 to 12.40 °C day/year (significant at one site, Jincheng). Both Laizhou and Fushan stations used the same variety (Table 1). The results show that GDD values at the two stations were very similar, but their trends varied substantially, especially during GP3.

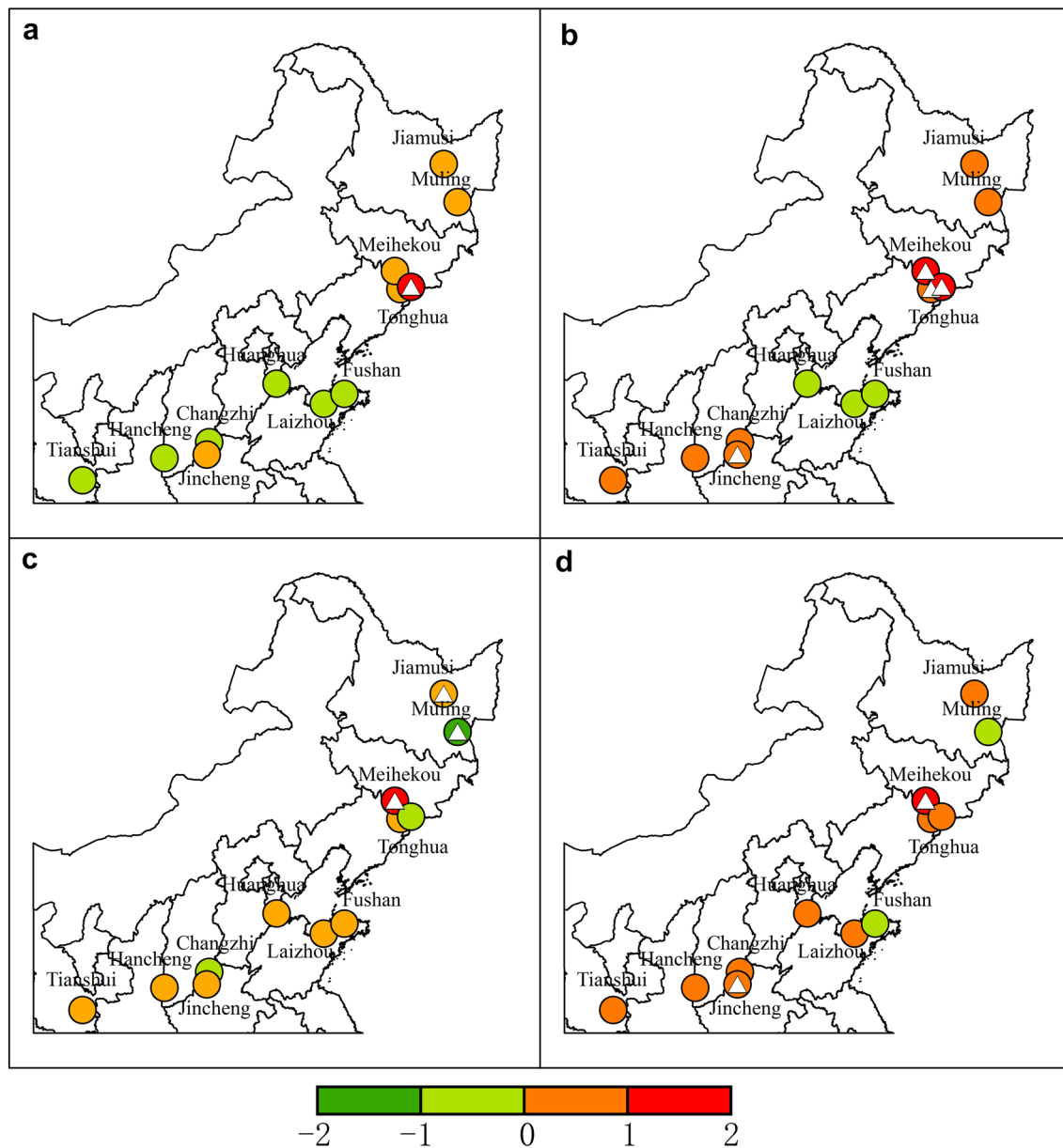


Fig. 3 Trends of growing season average temperature against year for GP1 (a), GP2 (b), GP3 (c) and GP4 (d) for three crops in north China (unit: $^{\circ}\text{C}/10$ year). A white triangle inside a circle indicates that the

trend at this site was statistically significance at $p < 0.05$. GP1, GP2, GP3, and GP4 for each crop are defined in Table 2

For rice, GDD requirements in Muling were significantly increased for GP2 (11.91 $^{\circ}\text{C}$ day/year), but significantly decreased for GP3 (-6.96 $^{\circ}\text{C}$ day/year) (Table 5). As a result, GDD for GP4 were nonsignificantly increased (5.06 $^{\circ}\text{C}$ day/year). At Tonghua, GDD requirements were significantly increased for GP2 (6.29 $^{\circ}\text{C}$ day/year) and insignificantly increased in GP3 (2.79 $^{\circ}\text{C}$ day/year), resulting in a significant increase for GP4 (9.07 $^{\circ}\text{C}$ day/year).

GDD requirements at all spring maize sites and during all GPs were increased (Table 5). For GP1 to GP4, the trends were significant at 2, 2, 0, and 3 sites, respectively.

The average value for the GDD trend for the four GPs were 4.63, 5.72, 4.84, and 10.51 $^{\circ}\text{C}$ day/year, respectively.

Response of Growth Duration to Temperature

Growth duration of winter wheat from emergence to start of overwintering (GP1), emergence to anthesis (GP2), anthesis to maturity (GP3), and emergence to maturity (GP4) was changed by an average of 0.39, 1.24, -1.54 , and -0.39 day/ $^{\circ}\text{C}$, respectively (Fig. 5). The number of wheat sites which had significant trends for GP1 and GP3 (Figs. 5a

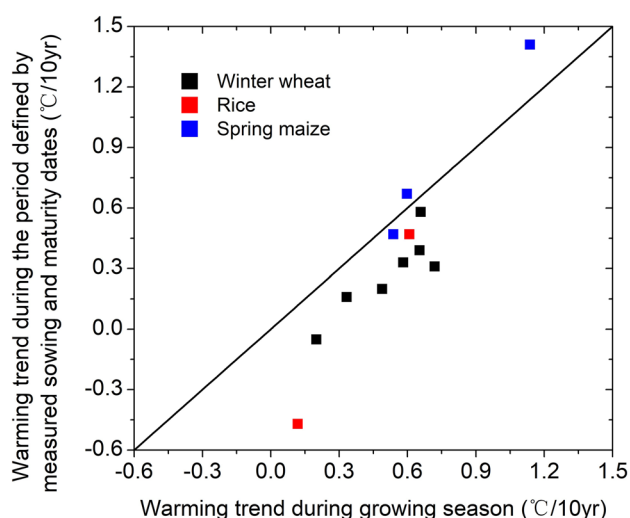


Fig. 4 Warming trend during the growing season compared with the warming trend during the period defined by measured sowing and maturity dates in north China. Definitions of growing seasons for the three crops were the same as in Fig. 2

and 5c) were 1 and 5, respectively. No wheat site in GP2 and GP4 had a significant response of growth duration to average temperature.

Growth duration of rice for the four GPs was changed by an average of -0.26 , -0.96 , -1.02 , and -4.14 day/°C, respectively (Fig. 5). For GP3, trends at both sites were significant. For GP4, the trend at Muling was significant (-5.53 day/°C).

For spring maize, growth duration in the four GPs was changed by an average of -0.73 , -2.58 , -0.31 , and -2.61 day/°C, respectively (Fig. 5). The number of sites which had significant trends in GP1, GP2, and GP3 were 1, 2, and 1, respectively. No maize site had a significant trend for GP4.

Discussion

Climate warming accelerates crop development and shortens growth duration. This acceleration leads to subsequent growth phases shifting to a cooler portion of the growing season and results in an inconsistency between T_{aver} and growing season average temperatures (Siebert and Ewert 2012). Based on observed phenology data when variety remained unchanged over many years, we found this inconsistency to be different with different crops. For winter wheat and rice, T_{aver} was always less than the growing season average temperature, but this was not the case for spring maize (Fig. 4). This may be caused by seasonal differences in warming and the varying responses of different crops to warming.

A general delay in emergence date of winter wheat in north China has been reported in experiments where the variety has not remained the same over the course of the study (Xiao et al. 2013; He et al. 2015). We also found this trend in our analysis where the variety remained the same over the course of the study (Table 3). The reason may be that too much growth prior to the start of overwintering dormancy could decrease the wheat plant's ability to successfully survive winter conditions (He et al. 2015). Since the warming trend provides an increased thermal resource for wheat growth, farmers may be motivated to postpone sowing which then delays the emergence date. A warming trend makes it possible to advance the sowing and emergence dates for rice and spring maize, but freezing risk due to a late frost at subsequent growth stages may be increased (Wang et al. 2017), so farmers may be reluctant to plant earlier. As a result, no significant trend was detected in those two crops. A previous study which reported observations on wheat varieties that changed over time reported that in North China Plain, dates of turning green, anthesis, and maturity were advanced by 0.11, 0.27, and 0.14 day/year, respectively (Xiao et al. 2013). Our study, which is based on fixed varieties over time, showed similar trends (dates advanced by 0.171, 0.258, and 0.153 day/year, respectively). Another previous study with rice in northeast China in which varieties changed with time showed that the dates of PS2 and PS5 were changed by -0.149 and 0.039 day/year, respectively (Zhang et al. 2014), while the corresponding values in our study were -0.075 and 0.604 day/year (Table 3), respectively. Hence, under both situations (i.e., varieties changing over time and varieties remaining the same over time), changes in phenology date due to increasing temperature may trend similarly.

Variable trends in date of phenology stages led to variable trends in duration of phenology phases. The warming trend advanced winter wheat anthesis and maturity dates, but the rate of advancement for anthesis date was greater than the rate of advancement for maturity date. There was no general reduction in the duration of the reproductive period (Table 4). In a previous study where a single variety was not maintained throughout the study, growth duration in North China Plain was prolonged by 0.13 day/year in GP3, and was decreased by 0.31 day/year in GP4 (Xiao et al. 2013). Wang et al. (2013) reported similar results. He et al. (2015) reported that in the Loess Plateau duration of GP3 was prolonged by 0.07 day/year. Our study found similar results of growth periods being prolonged (0.11 day/year for GP3 and 0.70 day/year for GP4). A study of rice in northeast China where varieties changed over time reported that length of GP3 increased by 0.089 day/year (Zhang et al. 2014), while the corresponding value in our study is twice that value (0.18 day/year). Therefore, changes to the length of growth periods delineated by major phenology phases may share similar

Table 3 Average date of major phenology stages and trend of date against year for winter wheat, rice, and spring maize in north China

Site	PS1			PS2			PS3			PS4			PS5		
	Average date (DOY)	Trend (day/year)	Average date (DOY)	Average date (DOY)	Trend (day/year)	Average date (DOY)	Average date (DOY)	Trend (day/year)	Average date (DOY)	Average date (DOY)	Trend (day/year)	Average date (DOY)	Average date (DOY)	Trend (day/year)	Average date (DOY)
Winter wheat															
Changzhi	279	1.08*	335	71	– 0.35	– 0.49*	136	– 0.35	167	– 0.07					
Hancheng	287	0.48*	347	46	0.56	– 0.15	119	– 0.59*	150	– 0.45**					
Jincheng	281	– 0.15	346	61	– 0.13	– 0.75***	130	– 0.19	165	0.03					
Huanghua	282	0.61**	341	62	– 0.14	0.58**	130	0.04	157	0.16					
Laizhou	280	0.72**	317	60	– 5.42	– 0.48	127	– 0.19	162	0.01					
Fushan	281	0.42**	295	61	– 1.71	– 0.34	134	– 0.10	169	– 0.11					
Tianshui	296	0.65**	345	52	– 0.21	0.44	132	– 0.63***	172	– 0.63***					
Rice															
Muling	130	0.10	152	159	– 0.03	– 0.15	213	0.9***	261	1.06***					
Tonghua	119	0.05	148	156	0.00	0.12	220	0.03	261	0.14					
Spring maize															
Jiamusi	150	– 0.32	174	186	0.05	0.4	209	– 0.16	268	– 0.12					
Mehekou	137	– 0.26	162	189	– 0.26	– 0.04	211	– 0.44	270	– 0.75*					
Tonghua	134	0.10	160	178	0.38*	0.43**	205	– 0.05	255	0.36***					

*, **, ***Statistical significance at $p < 0.05$, 0.01 and 0.001, respectively

Table 4 Average length of major phenology growth phases and trend of growth phase duration against year for winter wheat, rice, and spring maize in north China

Station	GP1		GP2		GP3		GP4	
	Average duration (day)	Trend (day/year)	Average duration (day)	Trend (day/year)	Average duration (day)	Trend (day/year)	Average duration (day)	Trend (day/year)
Winter wheat								
Changzhi	57	− 1.44*	223	− 1.43**	33	0.28	255	− 1.15*
Hancheng	61	0.08	198	− 1.08**	33	0.13	230	− 0.94***
Jincheng	66	0.02	216	− 0.04	35	0.22*	250	0.18
Huanghua	60	− 0.75*	214	− 0.58*	28	0.12	241	− 0.45*
Laizhou	73	− 0.42	213	− 0.91*	35	0.19	248	− 0.72*
Fushan	73	− 0.43	219	− 0.33	36	− 0.20*	254	− 0.54*
Tianshui	50	− 0.86*	202	− 1.28*	40	0.00	241	− 1.28*
Rice								
Muling	23	− 0.13	84	0.81***	48	0.16	132	0.97***
Tonghua	30	− 0.07	102	0.01	43	0.19*	143	0.19
Spring maize								
Jiamusi	25	0.37	60	0.16	60	0.04	119	0.20
Meihekou	26	0.00	75	− 0.18	60	− 0.31	134	− 0.49
Tonghua	27	0.28*	72	− 0.05	52	0.31**	122	0.27

*, **, ***Statistical significance at $p < 0.05$, 0.01 and 0.001, respectively

Table 5 Average GDD for major phenology growth phases and the trend of GDD over years for winter wheat, rice, and spring maize in north China

Station	GP1		GP2		GP3		GP4	
	Average (°C day)	Trend (°C day/year)	Average (°C day)	Trend (°C day/year)	Average (°C d)	Trend (°C day/year)	Average (°C day)	Trend (°C day/year)
Winter wheat								
Changzhi	403	− 15.38**	1191	− 8.49*	623	4.67*	1799	− 3.89
Hancheng	480	− 2.62	1374	− 1.26	670	4.05	2026	2.90
Jincheng	494	2.78*	1312	7.54*	710	4.78*	2004	12.40**
Huanghua	507	− 8.81	1380	− 2.78	604	3.93*	1966	1.27
Laizhou	652	− 8.77	1499	− 6.40	740	5.51**	2221	− 0.97
Fushan	630	− 6.29	1480	− 0.90	756	− 2.94	2218	− 3.79
Tianshui	266	− 4.58	1202	− 1.95	795	0.14	1979	− 1.87
Rice								
Muling	156	− 0.08	950	11.91***	537	− 6.96**	1472	5.06
Tonghua	185	0.80	1103	6.29*	470	2.79	1558	9.07**
Spring maize								
Jiamusi	282	6.31*	799	4.24	636	5.93	1420	10.01*
Meihekou	245	2.57	927	6.37*	638	6.31	1550	12.74**
Tonghua	227	5.03***	805	6.56***	657	2.30	1447	8.78**

*, **, ***Statistical significance at $p < 0.05$, 0.01 and 0.001, respectively

trends under situations in which varieties remained the same over time and in which varieties changed over time.

Our results may not be consistent with some reports. For example, Li et al. (2015) reported that the length of time

from winter wheat sowing to maturity at the Huanghua site during 1981–2005 was decreased by 0.40 day/year, and also reported that changing varieties during the study period prolonged the growing period by about 0.1 day/year. Thus, if the

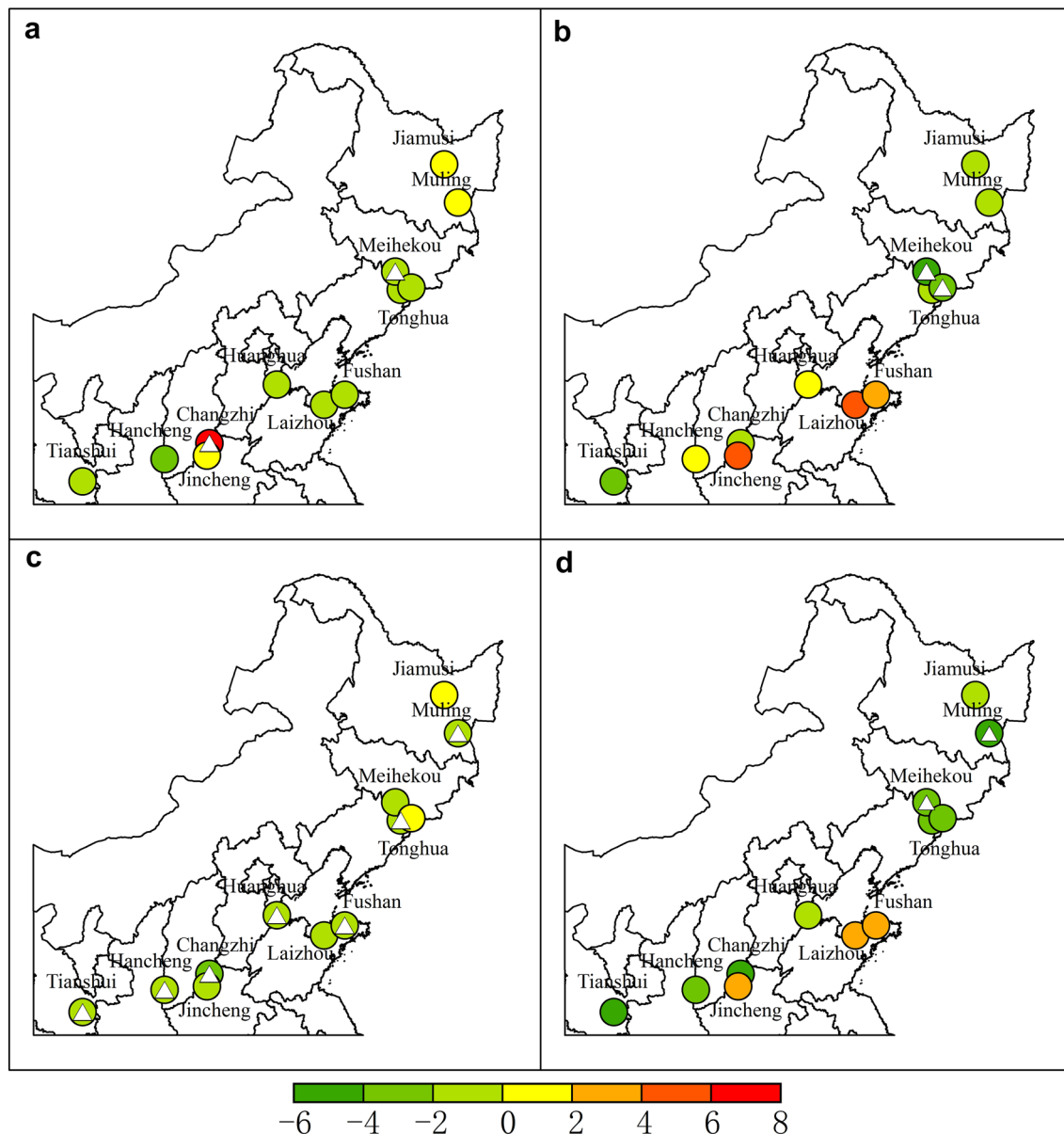


Fig. 5 Observed response of growth durations to average temperature in GP1 (a), GP2 (b), GP3 (c), and GP4 (d) (unit: d/°C) in north China. A white triangle inside a circle indicates statistical significance at $p < 0.05$

variety had remained unchanged, the growth period would likely have decreased by about 0.5 day/year due to warming. In our study we actually did keep the variety unchanged during 1989–2011 at this site (Table 1). After recalculating the trend using sowing date instead of emergence date, we found the growth period duration from sowing to maturity during 1989–2011 was decreased by 0.35 day/year (the value is 0.45 day/year in GP4, see Table 4). So the difference between the two studies was about 0.15 day/year. Since the time period selected by the two studies was not the same (1981–2005 and 1989–2011, respectively), directly comparing their results may be inappropriate. However, the difference still

indicates the large uncertainty that exists in such simulation studies.

Based on model simulations, several reports concluded that variety shifts over time have prolonged crop phenology in China during the last 3 decades (Tao et al. 2012; Li et al. 2016; Wang et al. 2013; Liu et al. 2013; Zhang et al. 2014; He et al. 2015). Based on an experiment using varieties bred in different years at the same site, Wang et al. (2018) affirmed this prolongation effect. However, most of these simulation reports were based on the trend of GDD (or some revised forms of GDD) over the years studied, and attributed the trend of increasing GDD to changing varieties.

In contrast, our study, which used observations of the same varieties of winter wheat, rice, and spring maize over time, showed that GDD for GP4 also changed positively over years (with the trend in 5 out of 12 data sets being significant) (Table 5). For example, He et al. (2015) reported GDD of winter wheat in GP3 was increased by 2.26 °C day/year in Loess Plateau. The corresponding value in our study was 2.88 °C day/year. Zhang et al. (2014) reported that GDD of rice in GP4 was increased by 2.74 °C day/year in northeast China, and our corresponding value was 7.06 °C day/year. Liu et al. (2013) reported that for spring maize in northeast China, GDD in GP3 and GP4 increased by 4.65 and 5.29 °C day/year, respectively, while our corresponding values were 5.72 and 4.84 °C day/year, respectively. We conclude, therefore, that GDD in various growth phases may have similar trends in response to warming conditions whether variety was maintained over the study period or not. This similarity suggests that current studies disentangling the effects of climate change and changing varieties over time on crop phenology may overestimate the role of changing varieties.

The measured responses of the length of phenology phases to mean temperature in GP2, GP3, and GP4 were 1.24, −1.54, and −0.39 day/°C, respectively. However, the simulated responses given by the APSIM model were much larger (−8.28, −0.71, and −8.09 day/°C, respectively) (He et al. 2015). These large differences suggest that the model may not have been parameterized correctly, or that there may be large uncertainty in the results of studies to disentangle climate change effects from variety changing effects. As suggested by our results, the impact of changing varieties over time on phenology may be overestimated by most studies. In other words, under future warming conditions, crop phenology is not likely to be advanced as much as simulated by models. Consequently, growth duration will be longer than simulated by models, and yield will likely be greater than the model-simulated yield.

It should be mentioned that the GDD calculation method used in this study was relatively simple, and using a more complicated model could result in different trends. However, using a more complicated model, Zhang et al. (2008) found that GDD for rice variety QG at Tonghua station were also increased significantly. Lowering the base temperature in the GDD calculation effectively removed the trend (van Oort et al. 2011). Therefore, before applying a phenology model, not only the GDDs required to advance growth stage, but also the three base temperatures used in these models need to be precisely validated. In addition, parameters need to be calibrated using data observed over a wide range of temperature variation (Menzel et al. 2005).

As this current work was based on phenology observations made when variety remained unchanged over time, the results obtained can be treated as the true response of crop phenology to climate change. However, phenology is also

affected by other non-climatic factors, such as soil water availability (Wang and Engel 1998; Liu et al. 2016) and fertilization (Estrella et al. 2007). In the course of long-term observations, these two factors are very likely to be varied. Similar to previous studies, our study assumed water availability and fertilizer conditions had no effect on phenology, since these kinds of information are inconsistently available or incompletely reported. In China, irrigation and chemical fertilizer availability have improved greatly during the last 30 years, and this may have positively affected phenology (McMaster and Wilhelm 2003; Liu et al. 2016). As a result, disregarding this information is likely to overestimate the impact of warming on phenology.

Conclusions

This study investigated the measured crop phenology responses to historical climate change under conditions in which variety remained the same for at least 15 years. Results showed that measured dates of major phenological growth stages for winter wheat, rice, and spring maize have changed. The warming trend has slightly advanced anthesis and maturity dates of winter wheat, but delayed maturity dates of rice. Length of GP4 decreased but length of GP3 increased for winter wheat, and length of GP3 and GP4 increased for rice. GDD was generally increased in GP3 and GP4 for all three crops. Trends in dates of major phenological growth stages, length of time between stages, and GDD of growth phases generally fell within the ranges which had previously been reported for studies in which the varieties changed over time, suggesting that current evaluations based on model simulations may overestimate the effect of variety shifts on phenology. We conclude that growing season length for winter wheat, rice, and spring maize will not likely be shortened due to global warming as much as model simulations predict.

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