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RESEARCH ARTICLE

Observed Climatic Variations in the Growing Season of Field Crops in Northeast China from 1992 to 2012

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Abstract

To determine the potential effects of climate change on crop phenological development and productivity, an integrated analysis was conducted based on the observed climatic and phenological records of Northeast China from 1992 to 2012. A set of quality assurance procedures, including repeated record checks, agro-meteorological station selection, internal consistency checks, temporal outlier checks, spatial outlier checks, and interpolation of missing data, were designed and applied to the phenology datasets of spring maize and paddy rice. Our results indicated that almost all phenological dates of spring maize and paddy rice became increasingly delayed from 1992 to 2012. The duration of the growing season was prolonged, particularly for the grain-filling stage (GS3). The prolonged growing season was beneficial to productivity. For spring maize, the average precipitation during GS3 decreased at a rate of 27.46 mm/decade, and the annual accumulated temperature over 10°C increased at a rate of 31.07°C/decade. Farmers initiatively adjusted crop cultivars and selected drought-resistant crops to cope with the challenges of drought.

Key words: climate change, quality assurance, phenology, growing season, field crop

INTRODUCTION

The global average surface temperature has increased by 0.74°C over the last century (IPCC 2007). Climate warming in China has a slightly higher magnitude of temperature increase than the rest of the world (Ding *et al*. 2006). Northeast China (NEC) is the part of the world that is potentially the most vulnerable to climate change (Piao *et al*. 2010; Ni 2011). Numerous studies have reported climate change in China (Wang *et al*. 2004; Ding *et al*. 2006; Xu *et al*. 2006; Shi *et al*. 2007). Agronomists are also becoming increasingly concerned with the variations of climatic resources during crop-growing seasons (Chen *et al*. 2012). Most studies define crop-growing seasons by using a permanent period that is based on previous experience (Chen *et al*. 2005; Xin *et al*. 2007). Phenology datasets provide an accurate approach to assess such seasons.

Phenology refers to periodic plant life cycle events that are largely driven by climate. Phenological variations not only reflect climate change (Defila and Clot 2001, 2005; Chmielewski and Rotzer 2002; Menzel *et al*. 2006; Stöckli *et al*. 2011) but also affect agricultural production (Chen *et al*. 2005; Xiao *et al*. 2012). However, most papers have focused on phenological changes of natural vegetation such as locust trees (Menzel 2000) and ginkgo trees (Matsumoto *et al*. 2003). Thus far, few papers have reported on phenological changes of field crops despite their importance for agricultural production (Chmielewski *et al*. 2004). Agronomists have attempted

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to use crop models to assess the relationship between climate change and phenological development (van Bussel *et al*. 2011). However, direct evidence based on field observations reflecting crop phenological changes is scarce. In China, the Chinese Academy of Sciences and the China Meteorological Administration (CMA) established phenological stations and networks in the early 1960s, but they terminated almost all observations in the late 1960s and 1970s. Phenological observations were resumed in the early 1980s (Chen *et al*. 2005). To date, phenological stations and continuous phenological records remain scarce and are of poor quality, i.e., they contain duplicated, missing, or erroneous records.

The objectives of this study are as follows: (1) to design quality-control methods for phenological records and to apply them to spring maize and paddy rice in NEC; (2) to investigate the phenological trends of major crops (spring maize and paddy rice) for the last two decades in NEC; and (3) to analyze climatic variations in some critical phenological phases or over the entire growing season.

RESULTS

Phenological trends of field crops

Spring maize For spring maize, we selected 34 stations based on the completeness of records, including the dates and phenological developments of sowing (SW), emergence (EM), 3 leaves unfolded (TL), 7 leaves unfolded (SL), jointing (JT), tasseling (HD), milky maturity (MM), and maturity (MT). Furthermore, we defined 4 phenophases for maize: GP1 (EM-JT), GP2 (JT-HD), GP3 (HD-MT), and GP0 (EM-MT). All data from the phenological events were transformed to values of day of the year (DOY).

The average duration from EM to MT in spring maize ranged from 121 to 131 d (Table 1). The sowing SW and MT dates of spring maize were DOY 121.36 (early May) and DOY 264.15 (late September), respectively.

Fig. 1 shows the long-term trends in phenological events of spring maize across NEC from 1992 to 2012. In this figure, a negative trend indicates advanced phenological events, and a positive trend indicates delayed events. Almost all phenological events were slightly delayed, except SL. The average SW date in NEC was significantly delayed by approximately 2.12 d/decade ($P<0.05$). A total of 26 stations showed a positive trend, whereas 8 stations showed a negative trend. The average EM date, which was mainly affected by SW, also revealed a positive but insignificant ($P<0.05$) trend. The MT dates at 24 stations showed a positive trend, particularly in Liaoning Province. However, only 4 stations showed significance ($P<0.05$). The slope of the MT date across NEC was 1.15 d/decade.

The slope of the duration of the growing season (GS0) at each station ranged from -5.0 to 5.6 d/decade, and the average duration was 0.25 d/decade. A longer growing season was mainly determined by the grain-filling stage

Table 1 Statistical analysis of the average phenological events of field crops in NEC from 1992 to 2012

Phenophase & Phenology[1)]	Unit	X_{avg}	SD	X_{min}	X_{max}	T (per decade)	Phenophase & Phenology	Unit	X_{avg}	SD	X_{min}	X_{max}	T (per decade)
Spring maize							Paddy rice						
GS0	d	126.99	2.60	121.38	131.29	0.26	GS0	d	147.33	2.71	142.46	153.00	2.02**
GS1	d	45.85	1.92	40.71	50.06	-0.02	GS1	d	54.59	2.05	51.31	58.62	0.71
GS2	d	20.97	1.13	18.76	23.35	-0.39	GS2	d	47.55	2.21	42.38	51.77	0.20
GS3	d	60.16	1.18	57.85	62.47	0.67	GS3	d	45.18	1.25	43.23	48.62	1.11***
SW	DOY	121.36	2.69	116.41	129.12	2.12**	SW	DOY	105.14	1.71	102.08	107.77	-1.12*
EM	DOY	137.16	1.95	132.47	142.88	0.90	EM	DOY	115.93	2.04	111.62	119.77	-0.57
TL	DOY	144.97	2.12	139.68	150.38	0.62	TP	DOY	145.60	1.99	141.62	151.77	1.14
SL	DOY	160.62	2.25	153.82	163.74	-0.21	GU	DOY	153.63	2.06	148.31	158.77	1.31*
JT	DOY	183.02	1.54	178.91	185.44	0.88	TR	DOY	170.52	1.45	167.77	173.23	0.15
HD	DOY	203.99	1.55	199.74	206.68	0.49	BT	DOY	208.43	1.37	206.23	211.00	0.70
MM	DOY	235.31	1.65	231.74	238.26	0.42	HD	DOY	218.07	2.04	213.23	220.69	0.35
MT	DOY	264.15	2.18	259.26	267.88	1.15	MM	DOY	235.69	2.27	231.23	238.54	1.59**
							MT	DOY	263.25	2.09	258.62	265.46	1.46**

[1)] GS0, EM-MT; GS1, EM-JT (maize) or EM-TR (rice); GS2, JT-HD (maize) or TR-HD (rice); GS3, HD-MT;SW, sowing; EM, emergence; TL, 3 leaves unfolded; SL, 7 leaves unfolded; JT, jointing; HD, tasseling (maize) or heading (rice); MM, milky maturity; MT, maturity; TP, transplanting; GU, greenup; TR, tillering; BT, booting. X_{avg}, arithmetic average; SD, standard deviation; X_{min}, minimum; X_{max}, maximum; T, trend; DOY, day of year.

*, significance at $P<0.1$; **, significance at $P<0.05$; ***, significance at $P<0.01$. The same as below.

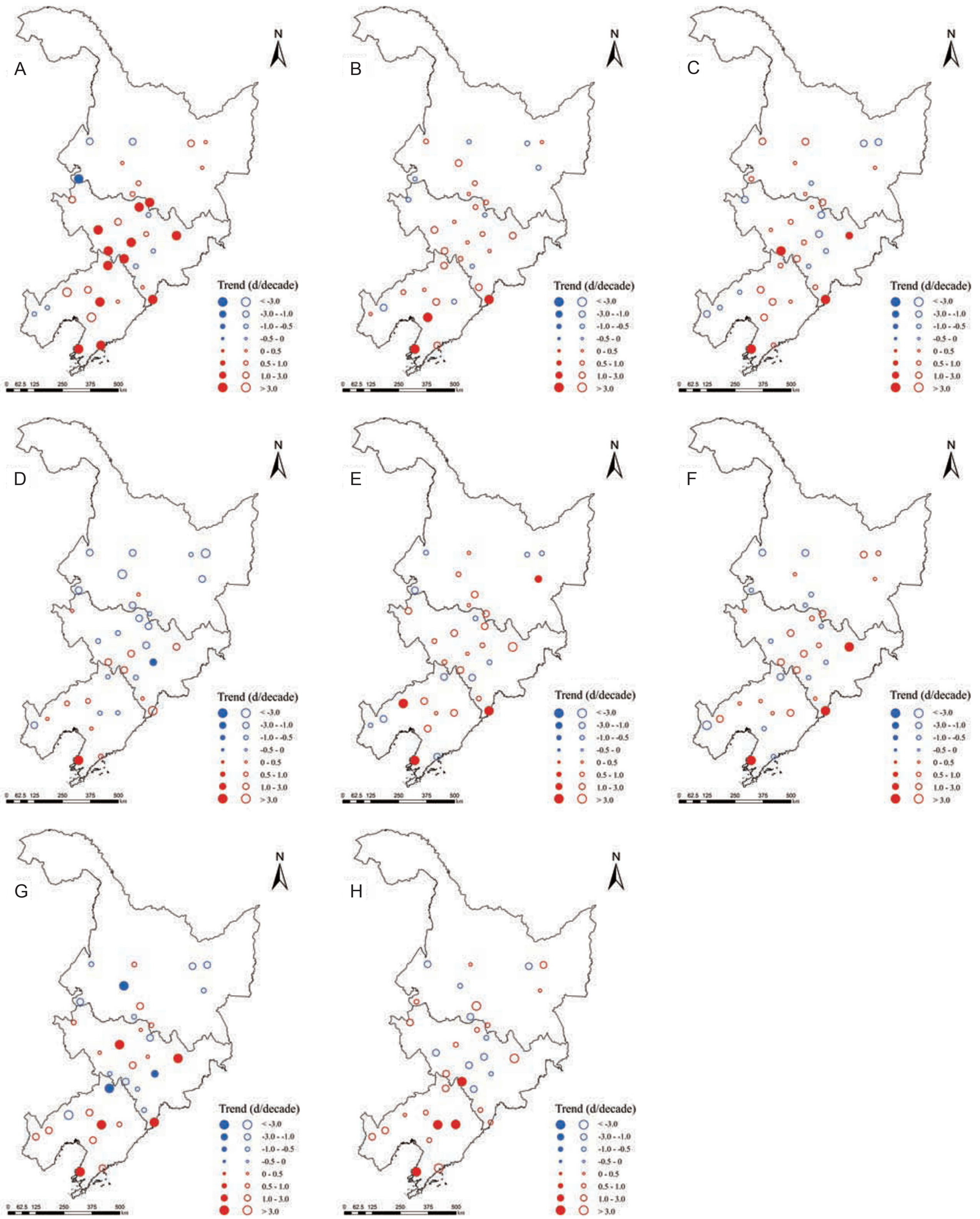

Fig. 1 Trends of the phenological events of spring maize. A, sowing. B, emergence. C, 3 leaves unfolded. D, 7 leaves unfolded. E, jointing. F, tasseling. G, milky maturity. H, maturity. The solid circle represents a significant trend at the 0.05 probability level, and the hollow circle represents an insignificant trend at the 0.05 probability level. The blue and red circles represent upward and downward trends, respectively.

(GS3). Durations in the early stages of maize growth across NEC, such as GS1 and GS2, became shorter at rates of 0.02 and 0.39 d/decade, respectively. Similar to GS0, the average slope of GS3, which was the critical stage for maize yield, was 0.67 d/decade.

Paddy rice For paddy rice, we selected 13 agro-experimental stations based on the completeness of records, including the phenological developments of SW, EM, transplanting (TP), greenup (GU), tillering (TR), booting (BT), heading (HD), MM, and MT. Similarly, the 4 phenophases were defined for paddy rice: GP1 (EM-TR), GP2 (TR-HD), GP3 (HD-MT), and GP0 (EM-MT).

Fig. 2 illustrates the long-term trends of the phenological events of paddy rice across NEC from 1992 to 2012. The SW and EM dates of paddy rice advanced at almost all stations. All phenological events from TP to MT were delayed. In particular, the variations of MM and MT reached statistical significance (P<0.05).

Affected by the earlier EM and the late MT, GS0 lengthened significantly at a rate of 2.02 d/decade (P<0.05). The variations of HD at almost all stations were less than the variations of MT, thus demonstrating that the durations of GS3 (HD-MT) increased. The variation of GS0 was mainly determined by GS3 and accounts for more than half of the extended period.

Climatic trend in the growing season

For the trend analysis of climatic variables in the phenophases, such as precipitation (Pre) and accumulative temperature above 10°C (AAT10°C), we selected 18 plots for spring maize and 5 plots for paddy rice that had complete meteorological and agro-experimental data.

Pre For spring maize, 82.35% of stations showed a decreasing trend in Pre in the GS0 period, with only a few stations showing an increasing trend (mainly in the southeast region). The slopes of average Pre in the GS1 and GS2 periods were less than 6 mm/decade. Pre decreased by 27.46 mm/decade in the GS3 period across NEC. Compared with GS1 and GS2, Pre in period GS3 showed a large negative slope at most stations, which mainly determined the variations in period GS0 (Table 2).

For paddy rice, the average Pre in the GS0, GS1, GS2, and GS3 periods showed an upward trend. Three stations (Qianguo, Yongji, and Ji'an) showed a positive trend in most periods, whereas the other two stations (Meihekou and Yanji) showed a negative trend.

AAT10°C In most stations, we found an upward trend for AAT10°C in the GS0 period of spring maize. Among them, 4 stations significantly (P<0.1) increased by over 75°C/decade. An increase at a rate of 49.38°C/decade was observed in GS0. Similar to GS0, the upward trends in GS1 and GS3 were dominant and maintained an average rate of 28.25 and 31.07°C/decade, respectively. However, the trend in GS2 was unclear. Half of the stations showed an increase of AAT10°C in GS2, mainly in the eastern region, and the other half of the stations showed a decrease of AAT10°C, mainly in the western region.

Similar to spring maize, an increase of AAT10°C in the GS0 period of paddy rice was detected, ranging from 19.50 to 134.79°C/decade. The highest value occurred at Qianguo, and the lowest occurred at Ji'an. Specifically, AAT10°C showed a significant increase in the GS1 period (P<0.01) and was significant at 4 stations. Most stations in GS2 showed a negative slope at a rate of -11.56°C/decade. Assessing the trend in the GS3 period was difficult. Half of the stations showed an increase of AAT10°C, whereas the other half showed a decrease of AAT10°C.

Phenological responses to climate change

Correlation analyses showed the responses of phenology to Pre and temperature. Pre and temperature had different correlation patterns with GS0 (Table 3). During the investigation period, different correlations existed between GS0 length and Pre. Thus, the correlation between them was difficult to determine. Among the 23 stations investigated, the number of positive correlations was almost equal to that of the negative correlations. Unlike Pre, the correlation coefficients between GS0 length and temperature at most stations (82.61%) were negative. In particular, the GS0 length was significantly negatively correlated with temperature at 8 stations (34.78%). Results indicated that the length of the growing season was shortened to some extent by climate warming.

DISCUSSION

In this study, we focused on the variation of phenologi-

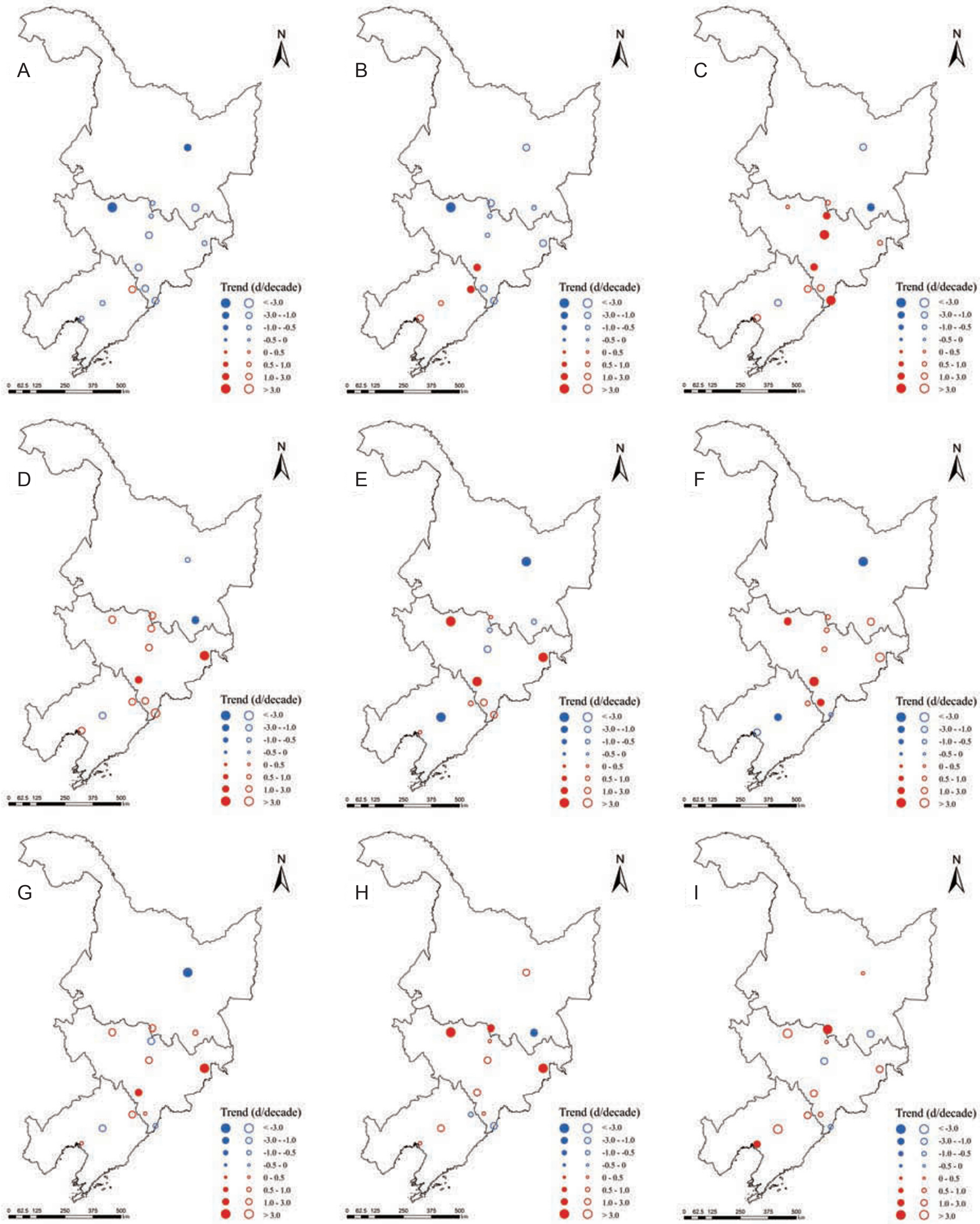

Fig. 2 Trends of the phenological events of paddy rice. A, sowing. B, emergence. C, transplanting. D, greenup. E, tillering. F, booting. G, heading. H, milky maturity. I, maturity.

cal and climatic variables over a relatively short period (1992-2012). World Meteorological Organization (WMO) recommended at least 3 decades for climate change research. In China, a phenology observation network was established in the late 1960s and halted in the 1970s. Phenology observations were gradually resumed after this time and continued until the early 1980s. Therefore, obtaining a long time series of phenology

Table 2 Variations of climatic resources in the growing season of field crops

Station	Pre (mm/decade)				AAT10°C (°C/decade)			
	GS0	GS1	GS2	GS3	GS0	GS1	GS2	GS3
Spring maize								
Fuyu	-17.32	32.19	1.72	-51.23*	62.23	12.52	-18.43	68.14*
Hailun	-54.74	26.71	-30.85	-50.60**	76.39*	44.02	-56.30**	88.67*
Tailai	-30.63	8.54	1.43	-40.60	84.46**	20.61	16.47	47.38
Jiamusi	-45.53	-11.95	-3.39	-30.18	54.43	24.73	49.15	-19.45
Baicheng	-49.39	-0.42	-10.86	-38.10	113.73***	75.55*	-19.61	57.78**
Harbin	-53.91	9.59	-28.66	-34.84	155.13**	101.38*	-82.83*	136.57**
Changling	-76.2**	-10.49	-38.52**	-27.20	18.13	22.34	-16.59	12.38
Yongji	106.34**	45.85**	49.96**	10.54	-3.86	18.04	2.25	-24.15
Dunhua	-60.53**	-13.56	-0.14	-46.83	76.07	68.27	15.33	-7.54
Fuxin	-79.8*	12.90	-27.59	-65.11**	6.32	81.09	-82.18	7.40
Meihekou	-15.08	-1.87	-0.36	-12.85	7.27	-17.93	25.23	-0.03
Huadian	-33.24	0.18	-9.46	-23.96	18.68	5.03	3.27	10.37
Chaoyang	-85.15**	-6.54	-18.90	-59.71**	62.89	-31.50	101.59**	-7.21
Yeboshou	-42.35	0.34	-33.10	-9.59	100.16**	4.05	-86.44	182.55***
Xinming	-40.48	-8.67	-34.60	2.79	6.91	53.40	-43.79	-2.71
Ji'an	22.41	-3.44	29.59	-3.74	-48.77	46.70	-23.83	-71.64**
Wafangdian	19.09	2.61	31.12	-14.65	67.49	39.24	25.94	2.31
Zhuanghe	12.43	-20.31	31.13*	1.61	31.24	-58.99**	11.7	78.53*
Average	-29.12	3.42	-5.08	-27.46	49.38	28.25	-9.95	31.07*
Paddy rice								
Qianguo	20.94	23.15**	-12.36	10.14	134.79***	175.04***	-72.72*	32.47
Yongji	120.97***	37.51**	113.28***	-29.83	45.32	-19.83	98.97**	-33.82
Meihekou	-19.74	-10.8	-8.85	-0.09	31.99	109.97***	-35.13	-42.85
Yanji	-31.69	7.49	-13.55	-25.63	30.92	53.68*	32.38	-55.14
Ji'an	31.81	8.12	-36.05	59.74**	19.50	91.92*	-81.32	8.90
Average	24.46	13.09	8.49	2.87	52.50	82.16***	-11.56	-18.09

Table 3 Correlation coefficients between GS0 length, precipitation (Pre), and mean temperature (Tmp)

Station	Pre	Tmp	Station	Pre	Tmp
Spring maize			Paddy rice		
Fuyu	-0.0315	-0.3760*	Qianguo	0.1222	-0.4452**
Hailun	0.1703	-0.4494**	Yongji	-0.0563	-0.2892
Tailai	-0.2027	0.0234	Meihekou	-0.0418	-0.1163
Jiamusi	-0.1079	-0.1676	Yanji	0.0215	-0.4585**
Baicheng	-0.0598	-0.5282**	Ji'an	-0.0089	-0.4359**
Harbin	-0.0068	-0.2428			
Changling	0.1388	-0.6540***			
Yongji	-0.3564	-0.4534**			
Dunhua	0.3326	0.1992			
Fuxin	0.1896	-0.2275			
Meihekou	0.3224	-0.3656			
Huadian	0.1780	-0.2554			
Chaoyang	-0.0022	-0.1670			
Yeboshou	0.1135	-0.229			
Xinming	0.0058	0.0986			
Ji'an	0.0064	-0.3368			
Wafangdian	0.0555	-0.0331			
Zhuanghe	0.0674	0.0369			

observation data was difficult.

The relationship between the phenology of field crops and climate resources was analyzed. The influences of human activity, such as cultivars, soil, field management, and socioeconomic factors, were not considered. The crop choice of households was deeply affected by social and economic conditions, such as family status, production inputs, and crop price (Shi *et al*. 2013; Xia *et al*. 2013). However, current phenological records did not include crop varieties and cropping systems.

This investigation showed that almost all phenology dates were delayed. This result differs from the assumption that phenology dates would advance with global warming. Tao *et al*. (2006) found that the SW and anthesis dates of field crops became early from 1980 to 2000. This difference might be related to the time during which the research was conducted. Temperature has shown a significant warming trend from 1980 to 2000 ($P<0.01$; Fig. 3), however the temperature over the last 20 years (1992-2012) was statistically decreasing. The lower temperature seems to explain the delay in the phenological events of field crops over the last 20 years. Some researchers have also noted a delayed MT stage and a prolonged growing season of maize and paddy rice in NEC over the last 20 years (Zhang *et al*. 2012; Li *et al*. 2013).

GS3 mainly affects crop yield formation. GS3 durations have extended by an average of 0.67 d/decade

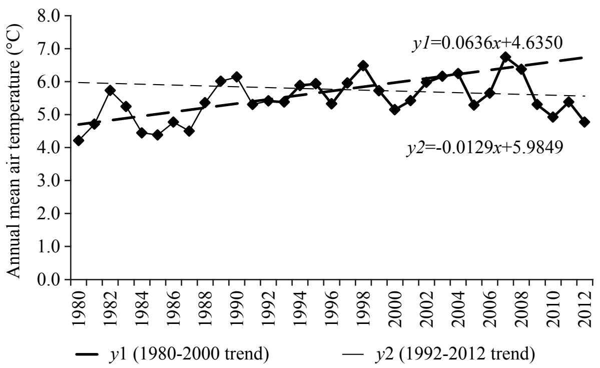

Fig. 3 Annual mean temperatures in NEC for the period 1980-2000 and 1992-2012.

for spring maize and 1.11 d/decade for paddy rice, contributing to 257 and 55% of the extension of the growing season, respectively. The prolonged durations of GS3 were beneficial to crop yield. For spring maize, however, the decreasing Pre and increasing AAT10°C in GS3 would exacerbate the conditions of crop drought. Thus, the use of drought-resistant crop varieties and the construction of farmland water-conserving facilities are necessary.

Farmers initiatively adapt to climate change through crop variety selection. As shown in this study, Pre in the GS0 and GS3 periods of spring maize was decreasing. Drought-resistant maize varieties have been widely preferred by farmers in NEC in recent years, and the acreage sown with them has increased rapidly over the last 20 years. Furthermore, the growing season of new paddy rice varieties extended significantly from 1958 to 2008. New varieties adapted to global warming (Zhang *et al*. 2012). The initiative adjustments taken by farmers could fully exploit the potential positive effects of climate change on crop production and reduce its negative effects.

CONCLUSION

Observed climate change during the growing seasons in this study provides valuable information for its effect on crop production. This study showed the trends of phenological events and climatic resources in the phenophases from 1992 to 2012. Findings revealed that almost all phenological dates were delayed because of the relative cold weather. The prolonged growing seasons of spring maize and paddy rice, particularly in the GS3 period, were favorable in enhancing crop yield. However, reduced Pre and increased temperature in the growing season have increased drought risks. To adapt to climate change, farmers initiatively adjust crop cultivars. For policy makers, the construction and improvement of irrigation facilities is an alternative choice.

MATERIALS AND METHODS

Study area

Northeast China (NEC), including Liaoning, Jilin, and Heilongjiang provinces (the three northeast provinces), contains the main grain-producing provinces and accounts for almost 20% of the total grain production in China. Most of the region is above 40°N, with a humid or semihumid climate. The annual accumulated temperature above 10°C (AAT10°C) is 1 700-3 200°C and the frost-free period is 90-180 d. The annual precipitation (Pre) is 400-800 mm, of which 70-80% falls from May to September (Chen *et al*. 2012). The main cropping systems in the region are single spring maize, soybean, and paddy rice. The good soil quality in NEC favors extensive grain production.

Data

Climatic data Daily weather datasets were obtained from the CMA. These data were the observations of 86 meteorological stations in NEC and comprised 7 variables: daily mean air temperature, daily maximum air temperature, daily minimum air temperature, daily total Pre, relative humidity, wind speed, and hours of sunshine. Although quality assurance (QA) procedures were applied to check the validity of the weather data from the CMA, numerous missing data existed because of station transfers. Missing data can have serious consequences in the detection of climate change (Stooksbury *et al*. 1999). Therefore, selecting stations with complete meteorological records and interpolating missing data are important. In this study, we selected 71 meteorological stations based on the completeness of records from 1992 to 2012. We also interpolated air temperature with the gradient plus inverse distance weighting (GIDW) method and other climatic variables with the inverse distance weighting (IDW) method. Interpolation was conducted after comparing 6 methods of spatial interpolation (Liu 2013): nearest neighbor, IDW, IDW based on elevation, GIDW, multiple regression with the least absolute deviation criteria, and geographically weighted regression. Thus, we created a continuous and complete (no missing data values) daily dataset.

Phenological data Spring maize and paddy rice are the main cultivated crops in NEC and represent the typical cropping systems in this region. The phenological datasets of spring maize and paddy rice from 1992 to 2012 were from agro-meteorological stations maintained by the CMA. Based on the completeness of records, we selected 34 agro-experimental stations for spring maize and 13 stations for paddy rice to explore phenological variability (Fig. 4).

Data processing and analysis

Phenological data from single sites are often "noisy" because the quality of data depends on the skill and precision of observers (Chmielewski and Rötzer 2001). In this study, an objective QA scheme was developed and applied to detect potential erroneous records in phenological data (Fig. 5). A linear regression model was used to determine the time trend of the phenology dates and durations of each growing season from 1992 to 2012. Pearson correlation analyses were used to ascertain the response of growing periods to the variations in Pre and temperature. Statistical significance was monitored by a two-tailed Student's *t*-test.

Repeated record check Depending on whether the values of repeated observed records in a particular phenology period were the same, we defined two types of repeated record phenomena and considered a different approach. When the values were the same, a type I repetition was detected, and extra records were simply removed. When the values were different, a type II repetition was detected, and records were flagged as suspicious.

Agro-meteorological station selection The raw dataset contained a large number of agro-experimental stations. However, most agro-experimental stations only had a few records. We selected 34 stations for spring maize and 13 stations for paddy rice based on the criterion that the proportion of missing data was less than 20%.

Internal consistency check The rules for checking suspicious records were as follows: (1) a logical check, which ensured that the phenology was logically consistent and physically impossible relations (e.g., EM is earlier than MT) were flagged as suspicious; and (2) a "flat line" check, which marked records with the same value for at least 3 consecutive years as suspicious (Table 4).

Temporal outlier check Based on the premise that an individual value should be similar to the values for the same phenology for other years in the observation period, the temporal check was designed to monitor a large step change from previous observed values at the same station (Eischeid *et al*. 1995). An outlier was flagged when the following expression was satisfied:

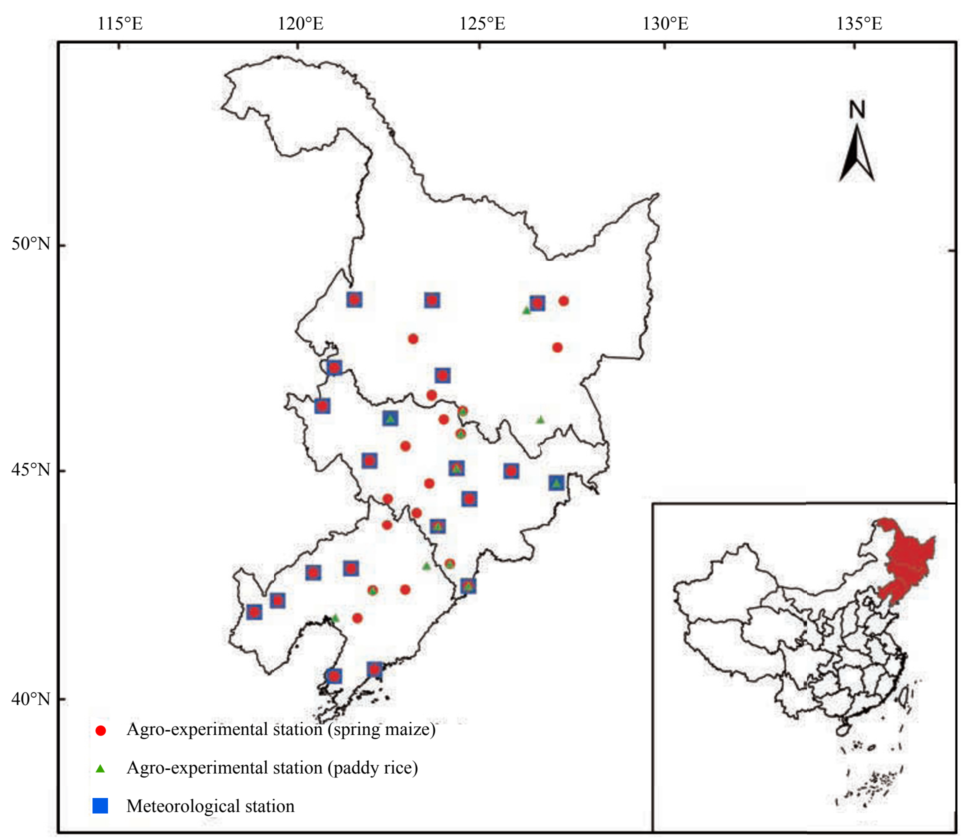

Fig. 4 Geographical location of the study area and the spatial distribution of the agro-experimental and meteorological stations used in the study.

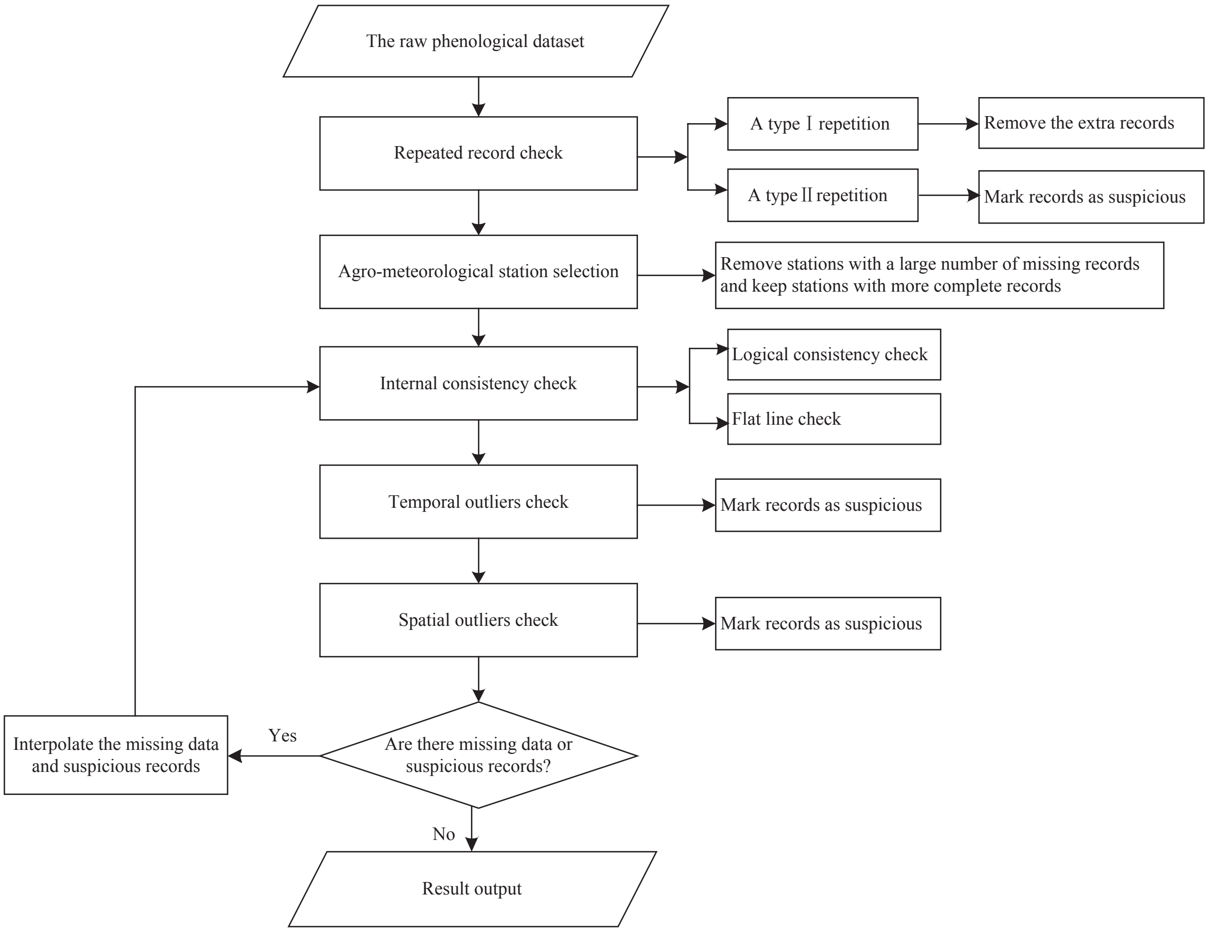

Fig. 5 Quality assurance (QA) flow chart.

Table 4 Proportion of suspicious records to observed records by categories

	Number of observed records		Proportion of suspicious records (%)			
	Observed records	Percentage of missing data (%)	Internal check	Temporal check	Spatial check	Total
Spring maize	4787	16.19	0.48	0.40	0.54	1.42
SW	622	12.89	0.32	0.64	0.64	1.61
EM	454	36.41	0.22	0.00	0.88	1.10
TL	621	13.03	0.32	0.16	0.97	1.45
SL	638	10.64	0.31	0.31	0.94	1.57
JT	623	12.75	1.12	0.64	0.00	1.77
HD	597	16.39	1.01	0.50	0.34	1.84
MM	613	14.15	0.33	0.16	0.49	0.98
MT	619	13.31	0.16	0.65	0.16	0.97
Paddy rice	2213	9.93	0.36	0.14	0.41	0.90
SW	245	10.26	0.82	0.00	1.63	2.45
EM	259	5.13	0.77	0.00	0.77	1.54
TP	217	20.51	0.46	0.46	0.00	0.92
GU	255	6.59	0.39	0.39	0.00	0.78
TR	262	4.03	0.00	0.00	0.00	0.00
BT	233	14.65	0.00	0.00	0.43	0.43
HD	248	9.16	0.40	0.40	0.40	1.21
MM	243	10.99	0.41	0.00	0.00	0.41
MT	251	8.06	0.00	0.00	0.40	0.40
Total	7000	14.31	0.44	0.31	0.50	1.26

$|x_i - \bar{x}| \leqslant f_1 \sigma_x$

Where, x_i is a value (DOY, which indicates the time of phenological events) of year i, $\bar{x}$ is the mean value in the period 1992-2012, σ_x is the standard deviation, and f_1 is the temporal multiplier.

Spatial outlier check This check identified outliers by comparing the data of neighboring stations. A record was determined to be suspicious based on the magnitude of the difference between the observed and estimated values. GIDW was used to calculate the estimated values (Nalder and Wein 1998; Price *et al*. 2000). We tested whether the difference between the observed and estimated values fell within the threshold:

$|Z_k - Z_k'| \leqslant f_2 \bar{e}$

Where, Z_k and Z_k' are the observed and estimated values of the target station, respectively, $\bar{e}$ is the mean absolute error in the search radius, and f_2 is the spatial multiplier.

The temporal multiplier f_1 and spatial multiplier f_2 used to examine outliers are important for results (Hubbard and You 2005, 2007). Fig. 6 illustrates the percentage of suspicious records for various values of multiplier f. For this study, values of 3.0 and 5.0 were used for the temporal multiplier f_1 and the spatial multiplier f_2, respectively.

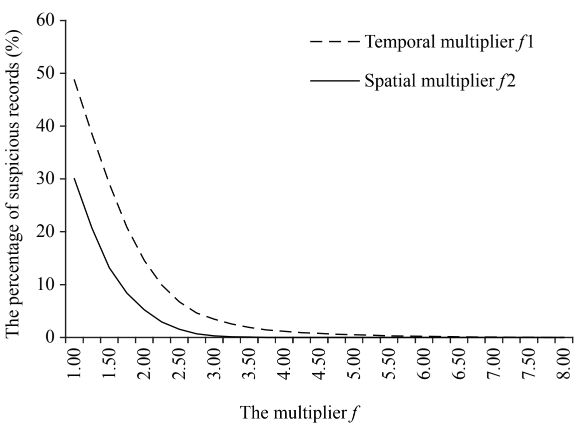

Fig. 6 Relationship between percentage of suspicious records and multiplier.

Interpolation of missing data Missing data (data gaps) have a negative effect on climate change analysis (Stooksbury *et al*. 1999). Thus, we used the arithmetic average of phenology date over years at the target station to replace missing and suspicious records. After the interpolation, we conducted a logical consistency check until all values, including interpolated values, passed QA.

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