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ORIGINAL PAPER

Observed changes in winter wheat phenology in the North China Plain for 1981–2009

Dengpan Xiao · Fulu Tao · Yujie Liu · Wenjiao Shi · Meng Wang · Fengshan Liu · Shuai Zhang · Zhu Zhu

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Abstract Climate change in the last three decades could have major impacts on crop phenological development and subsequently on crop productivity. In this study, trends in winter wheat phenology are investigated in 36 agrometeorological stations in the North China Plain (NCP) for the period 1981–2009. The study shows that the dates of sowing (BBCH 00), emergence (BBCH 10) and dormancy (start of dormancy) are delayed on the average by 1.5, 1.7 and 1.5 days/decade, respectively. On the contrary, the dates of greenup (end of dormancy), anthesis (BBCH 61) and maturity (BBCH 89) occur early on the average by 1.1, 2.7 and 1.4 days/decade, respectively. In most of the investigated stations, GP2 (dormancy to greenup), GP3 (greenup to anthesis) and GP0 (entire period from emergence to maturity) of winter wheat shortened during the period 1981–2009. Due, however, to early anthesis, grain-filling stage occurs at lower temperatures than before. This, along with shifts in cultivars, slightly prolongs GP4 (anthesis to maturity). Comparison of field-observed CERES (Crop Environment Resource Synthesis)-wheat model-simulated dates of anthesis and maturity suggests that climate warming is the main driver of the changes in winter wheat phenology in the NCP. The findings of this study further suggest that climate change impact studies should be strengthened to adequately account for the complex responses and adaptations of field crops to this global phenomenon.

Keywords Phenology · Winter wheat · Growth stage duration · Climate change · CERES-wheat model · North China Plain

Introduction

A warming climate trend in the last several decades has been reported around the globe (IPCC 2007). In China, climate warming accelerated since the 1980s and future increases have even been projected (Ding et al. 2006; Tao et al. 2006). It is documented that climate change affects the development and productivity of field crops, a growing concern for food security (Semenov 2009; Liu et al. 2010). Phenology is a plant growth progress largely driven by meteorological conditions (Batts et al. 1996; Menzel 2000; Menzel et al. 2006; Estrella et al. 2007; Ma et al. 2011). Phenological changes are vital indicators for changes in climate and other environmental conditions (Zheng et al. 2002; Diskin et al. 2012). Several studies have reported obvious changes in phenological seasons after the 1980s, driven by climate warming (Menzel and Fabian 1999; Zheng et al. 2002; Chmielewski et al. 2004). However, relatively few studies have so far investigated changes in trends of field crops despite their potential socio-economic importance (Chmielewski et al. 2004; Tao et al. 2006). It is widely shown that the impacts of climate change on crop productivity are measurable via timing crop growth stages (Craufurd and Wheeler 2009; Kelman and Dove 2009).

Timing of crop phenological events such as anthesis, maturity, etc. provides measurable indicators for crop

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D. Xiao · F. Tao (✉) · Y. Liu · W. Shi · M. Wang · F. Liu · S. Zhang · Z. Zhu
Institute of Geographical Sciences and Natural Resources Research, Chinese Academy of Sciences,
Beijing 100101, China
e-mail: taofl@igsnrr.ac.cn

D. Xiao
e-mail: xiaodp.10b@igsnrr.ac.cn

D. Xiao · M. Wang · F. Liu · S. Zhang
Graduate University of Chinese Academy of Sciences,
Beijing 100049, China

response to temperature events (Van Bussel et al. 2011; White et al. 2011). Crop phenological developments have been widely analyzed using (climate) data-driven crop models (Jamieson et al. 2007; Challinor et al. 2009; Tao et al. 2009). However, there exists relatively less work on direct crop phenological trend assessments based on field observation data. Winter wheat, a crop with a winter growth-break (dormancy), is especially sensitive to temperature change. This is reflected in the direct response of wheat to temperature via processes such as intrinsic development and vernalization (Porter and Gawith 1999). Changes in winter wheat phenology are readily observable and directly monitored in conventional field experiments. The dates of phenological changes could therefore be used to assess the response of winter wheat to climate change (Stacks et al. 2010).

In this study, the trends in winter wheat phenology for 1981–2009 are investigated based on phenological data from 36 agro-experimental stations in the North China Plain (NCP) (Fig. 1). The plain is a major production base of winter wheat in China. The main objective of this study was to analyze the trends in winter wheat phenology for the last three decades in the NCP. The study also determined the relatedness of the trends in winter wheat phenology to climate change in the

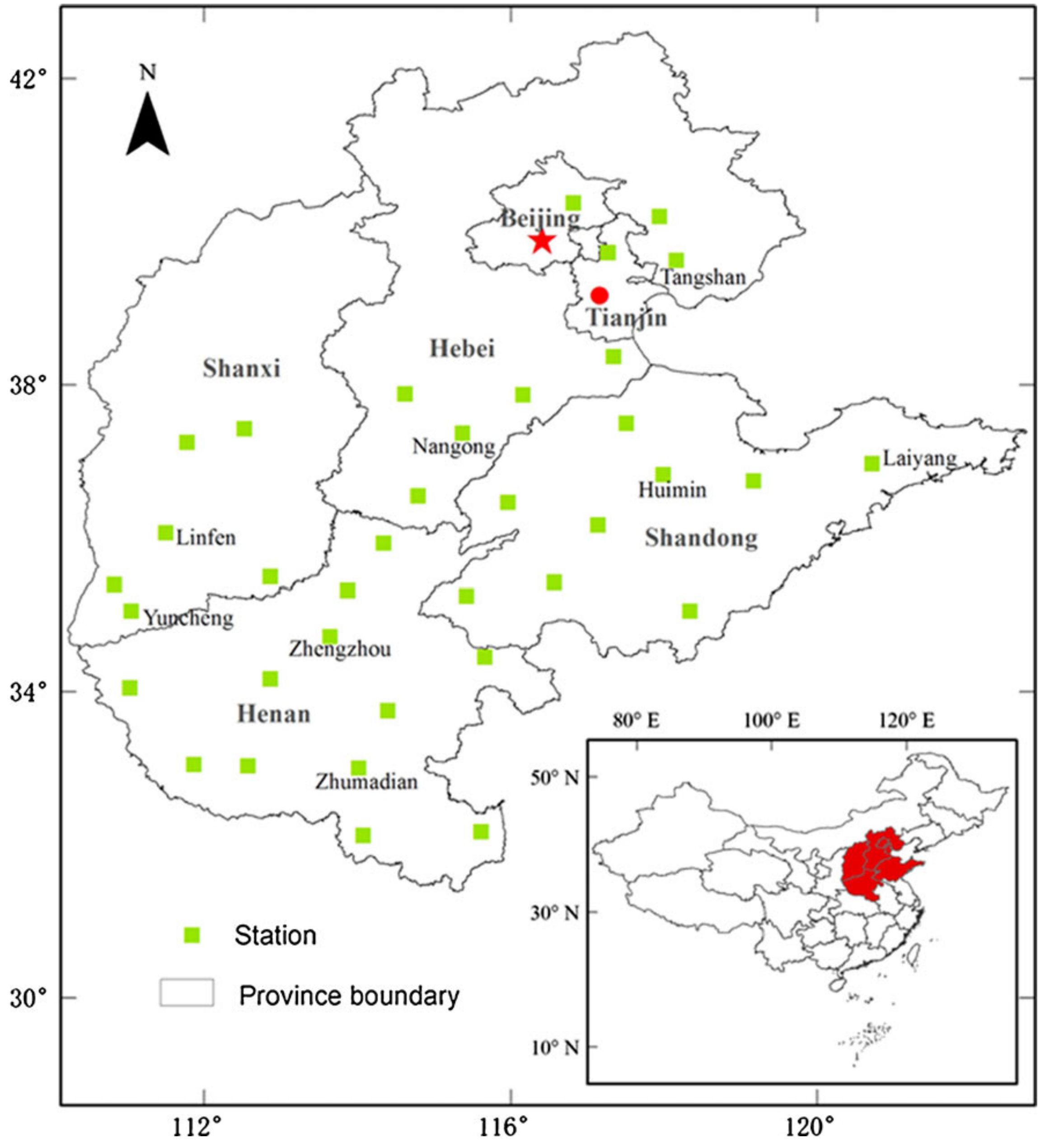

Fig. 1 A geographical location map of the study area (*bottom right inset*) and the locations of the agro-meteorological experiment stations used in the study (*main map*)

plain. The results of the study are critical for not only building deeper insights into the impacts of climate change on crop development and productivity, but also on food security for the millions of people in the region.

Data and methods

Study area

This study area is located in the NCP, which includes Hebei, Henan, Shandong and Shanxi Provinces, and also Beijing and Tianjin Municipalities (Fig. 1). The typical cropping system in the region is rotational winter wheat and summer maize cultivation. Suitable climatic conditions and good soil quality in the NCP favor extensive winter wheat production (Yang 1991; Tao et al. 2006). In this study, 36 stations were selected and investigated for winter wheat phenological trends over the period 1981–2009 (Fig. 1). All the stations are located in typical winter wheat production areas.

Methods

The trends in the phenological events of winter wheat are investigated along with the corresponding durations of each growth stage for the period 1981–2009. Time trend in each investigated phenological event of winter wheat is determined in a linear regression model as follows:

$$Y_i = k\,X_i + b \tag{1}$$

where Y_i is the observed phenological date in year *i*, *k* is the slope, *b* is the intercept, and X_i is the year *i* ($i=1, 2, \cdots\cdots, 29$). In this study, statistical significance was determined using the two-tailed *t*-test analysis.

To also isolate the effect of crop cultivar from that of climate change on the phenological changes in winter wheat, time-series of field observed phenological events in eight representative stations are compared with those simulated by the CERES (Crop Environment Resource Synthesis)-wheat model. The eight representative stations used in the study include Nangong and Tangshan in Hebei Province, Zhengzhou and Zhumadian in Henan Province, Huimin and Laiyang in Shandong Province, and then Linfen and Yuncheng in Shanxi Province (Fig. 1).

The CERES-wheat model was also calibrated and validated for the eight representative stations. For each of the eight stations, the most typical cultivar cultivated in 1981–1985 was identified. Then the observed data for 1981–1983 were used to calibrate the genetic parameters of the CERES-wheat model. Also the observed data for 1983–1985 for each given cultivar were used to validate the model for that cultivar. Finally, the validated model was driven on the historical weather data for 1980–2008 to simulate the dates of anthesis and maturity in each station.

CERES-wheat model description

The CERES-wheat model used in this study is process-based. It simulates growth and development of wheat in response to a range of environmental (e.g., weather and soil variables) and management (e.g., crop variety, planting condition, fertilization, irrigation, etc.) factors. CERES-wheat is embedded within the DSSAT (Decision Support System for Agro-technology Transfer) version 4.0.2 crop systems model (Jones et al. 2003). The model describes the processes that occur in the life-cycle of a given crop on the basis of cumulative degree-day. The duration of growth stages as a direct response to temperature and photoperiod varies with species and cultivar type. Genetic coefficients were used as model input to the model to describe these variations.

The model uses seven genetic coefficients which are related to photoperiod sensitivity, grain-filling duration, mass-to-grain number conversion, grain-filling rate, vernalization requirements, stem size, and cold hardiness (Ritchie et al. 1998). The minimum weather input requirements of the model include daily solar radiation, precipitation, and maximum and minimum air temperatures. Soil input includes drainage and runoff coefficients, first-stage evaporation and soil albedo, soil water characteristics of each soil layer, and rooting preference coefficients at incremental depths. To initiate CERES-wheat model simulation, saturated soil water and initial soil water conditions are also required. The main management input variables include plant population, planting depth, planting date, etc. If irrigation and fertilizer modes are used, the dates of application and amounts applied are required. Also the latitude of the site is required for calculating day length in the study area. The model simulates phenological development, biomass accumulation and partitioning, leaf area index (LAI), and root, stem, leaf and grain growths from sowing to maturity in daily time step. This study lays special focus on the simulation of the dates of anthesis and physiological maturity.

Table 1 Average phenology of winter wheat in the North China Plain during the period of 1981–2009

Variables	SW	EM	DR	GU	AT	MT
Average dates (day of year)	281	289	348	54	124	157
Standard deviations	8.5	9.0	12.2	7.9	7.8	7.4

Note that SW is sowing date (BBCH 00); EM is emergence date (BBCH 10); DR is dormancy date (start of dormancy); GU is greenup date (end of dormancy); AT is anthesis date (BBCH 61); and MT is maturity date (BBCH 89)

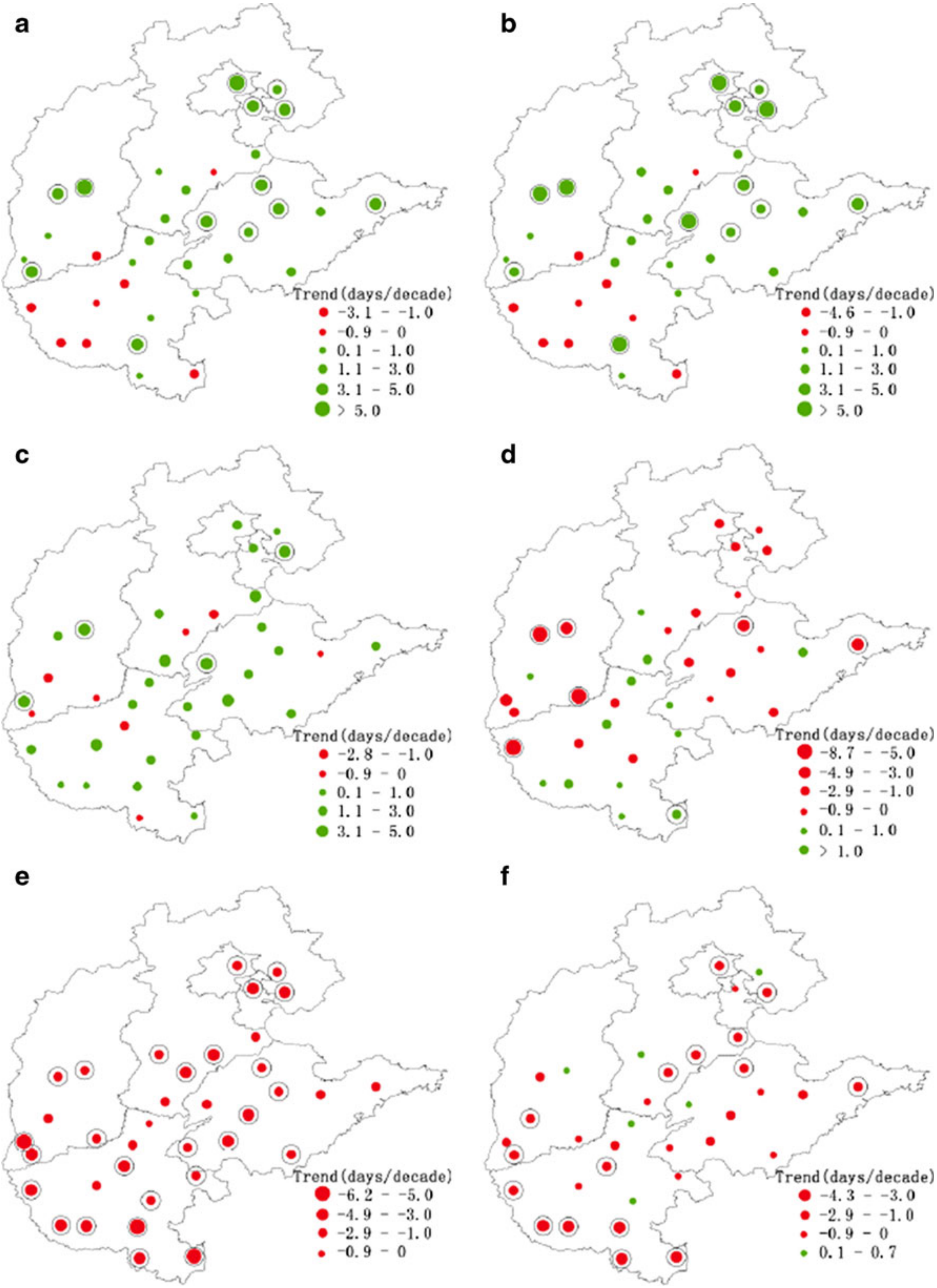

Fig. 2 Trends in sowing (**a**), emergence (**b**), dormancy (**c**), greenup (**d**), anthesis (**e**) and maturity (**f**) dates of winter wheat in the North China Plain for 1981–2009. *Circles* shows trend is significant at 5 % probability level

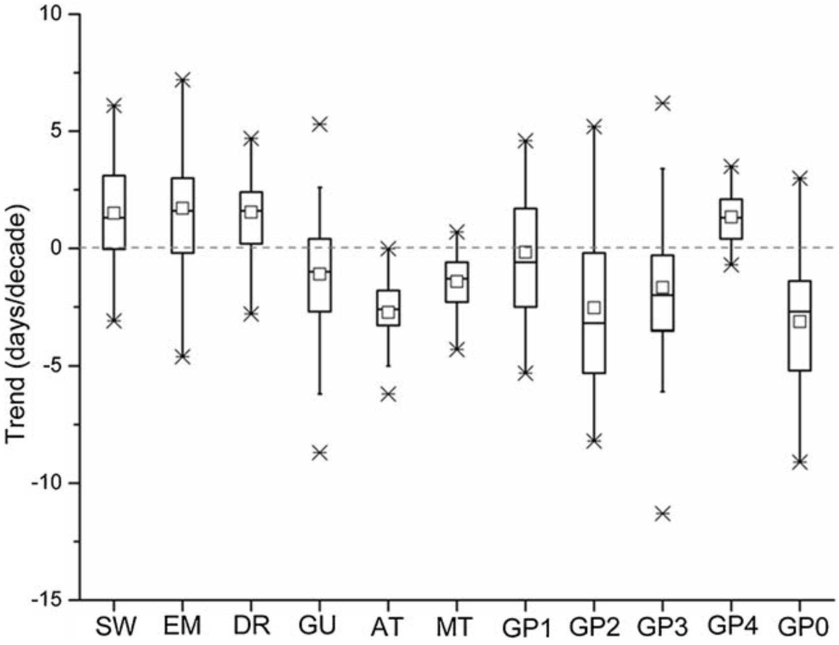

Fig. 3 Trends in winter wheat phenology in the North China Plain for 1981–2009 across the investigated stations. Note that SW is sowing date; EM is emergence date; DR is dormancy date; GU is greenup date; AT is anthesis date; MT is maturity date; GP1 is duration from emergence to dormancy; GP2 is duration from dormancy to greenup; GP3 is duration from greenup to anthesis; GP4 is duration from anthesis to maturity; and GP0 is duration from emergence to maturity

Data

Winter wheat phenology data for 1981–2009 are from experiments conducted at the national agro-meteorological stations, which are maintained by the Chinese Meteorological Administration (CMA). The dates and other details of sowing (BBCH[1] 00; SW), emergence (BBCH 10; EM), dormancy (start of dormancy; DR), greenup (end of dormancy; GU), anthesis (BBCH 61; AT) and maturity (BBCH 89; MT) are recorded field observations. Historical daily whether data, including minimum and maximum temperatures, sunshine duration, and precipitation for 1980–2008 in the eight representative agro-meteorological stations are from CMA. Solar radiation trends for the stations are estimated from observed sunshine hour data using the Angstrom-Prescott equation (Angstrom 1924; Prescott 1940).

Results

Winter wheat phenology trend for 1981–2009

Winter wheat is generally sowed somewhere in September to October in the NCP (Table 1). As shown in Fig. 2a, the sowing dates of winter wheat in 1981–2009 were delayed in 28 of the 36 locations investigated, and the delay is significant in 13 stations ($p<0.05$). The date of sowing, however, occurs early in eight stations (mainly in the southwest region), all of which are insignificant at $p>0.05$. Among other factors, the date of emergence of winter wheat mainly depends on sowing date. Figure 2b shows that the trend in the date of emergence is similar to that in the date of sowing. In most of the stations therefore, the date of emergence of winter wheat is somehow delayed (Fig. 2b). Across the investigated stations, the date of sowing and the subsequent date of emergence are delayed on the average by 1.5 and 1.7 days/decade, respectively (Fig. 3).

The dates of dormancy (start of dormancy) and greenup (end of dormancy) of winter wheat are mainly a function of temperature. As shown in Fig. 2c, the date of dormancy of winter wheat is delayed in 28 stations. The delay is significant ($p<0.05$) for four stations, and is on the average of 1.5 days/decade for all the stations (Fig. 3). Dormancy delay is apparently caused by increasing temperatures over the last three decades. This same temperature factor, however, causes early greenup of winter wheat in most of the stations. This is especially the case in the northern region of the study area where early greenup is significant ($p<0.05$) for six stations (Fig. 2d). For the investigated stations, greenup occurs early with an average of 1.1 days/decade (Fig. 3).

Generally in the NCP, anthesis and maturity occur in May and June, respectively (Table 1). As shown in Fig. 2e, anthesis date of winter wheat occurs early in all the investigated stations and the trend is in fact significant for 27 stations. Similar to the date of anthesis, most of the stations experience early maturity of winter wheat. However, the number of days for which winter wheat maturity occurs in advance is less than that of anthesis (Fig. 2f). Across the investigated stations, the date of anthesis and subsequent date of maturity occur early with an average of 2.5 and 1.7 days/decade, respectively (Fig. 3).

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[1] (BBCH: Biologische Bundesanstalt, Bundessortenamt, Chemische Industrie (Federal Biological Research Centre for Agriculture and Forestry, Federal Office of Plant Varieties, Chemical Industry). This code is recommended for phenological observations, Strauß et al. (1994).)

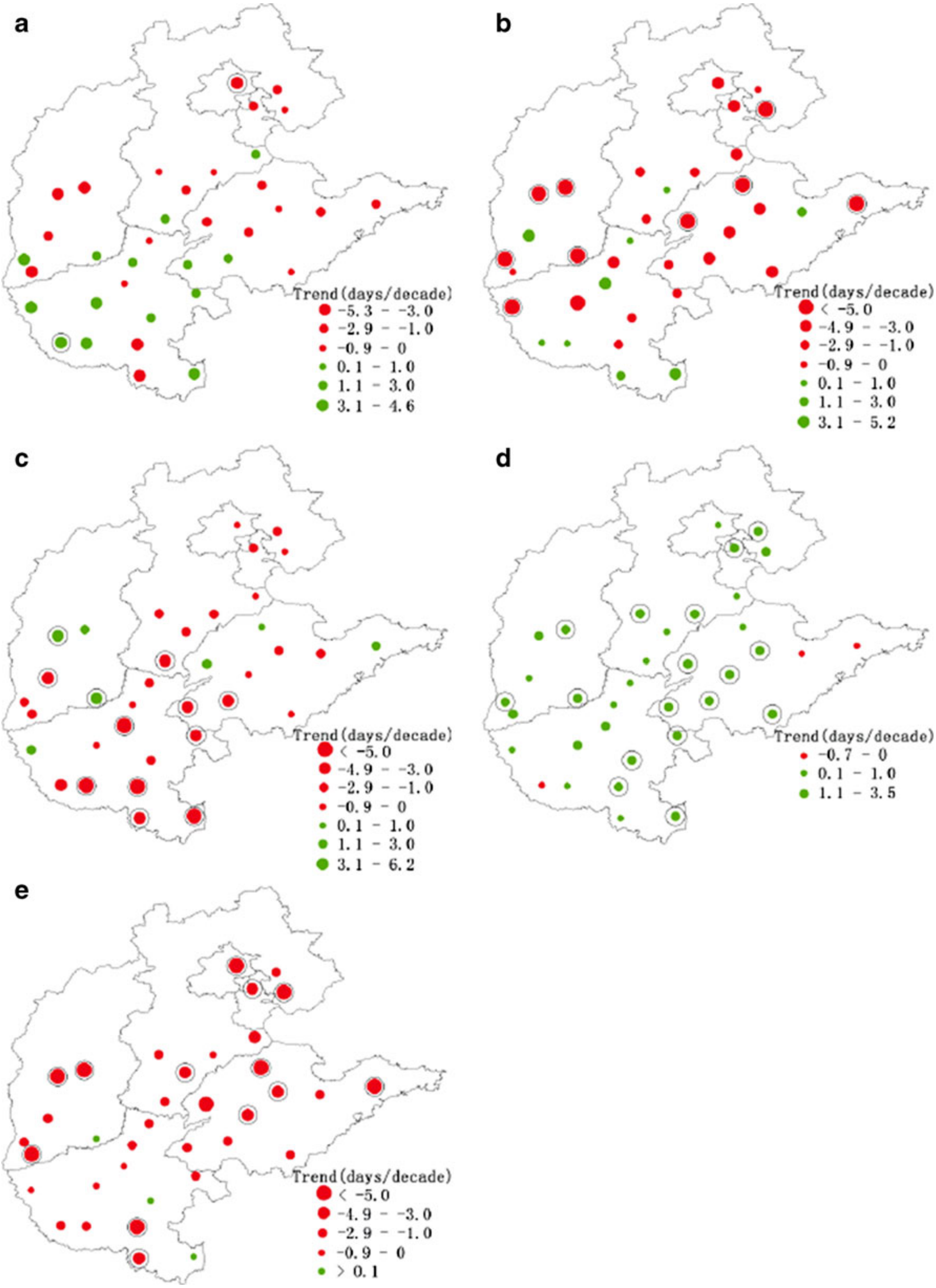

Fig. 4 Trends in mean durations of the different growth stages of winter wheat in the North China Plain. Note that **a** is GP1 stage (emergence to dormancy); **b** is GP2 stage (dormancy to greenup); **c** is GP3 stage (greenup to anthesis); **d** is GP4 stage (anthesis to maturity); and **e** is GP0 stage (emergence to maturity). Circle denotes a significant trend at the 5 % probability level

Winter wheat growth stage trend for 1981–2009

The advance or delay of winter wheat phenology leads to corresponding changes in the durations of the different growth stages. As shown in Fig. 4a, GP1 (emergence to dormancy) shortens in stations in the north of the study area. By contrast, it is prolonged in some of the other stations in the southwest of the study area. For all the investigated 36 stations, only two stations show significant ($p<0.05$) shortening and lengthening. This suggests that generally there exists no significant change in GP1 duration for the period of study.

Figure 4b shows that GP2 (dormancy to greenup) drastically decreases in most of the stations during the period 1981–2009, and significantly at nine stations ($p<0.05$). Also GP3 (greenup to anthesis) decreases in most of the stations. This is especially the case for the southern region of study area. Among the stations, 10 have significant trends at $p<0.05$ (Fig. 4c). By contrast, GP4 (anthesis to maturity) slightly prolongs in 33 stations, and is significant in 17 stations (Fig. 4d). As shown in Fig. 4e, GP0 (emergence to maturity) shortens in most of the stations, and is significant in 13 stations ($p<0.05$).

In summary, GP1, GP2 and GP3 across the investigated area shorten on the average by 0.2, 2.5 and 1.7 days/decade, respectively. However, GP4 increases on the average by 1.3 days/decade. This implies that winter wheat GP0 (entire growth period) in the NCP decreases on the average by 3.1 days/decade (Fig. 3).

Climate change, crop cultivar and winter wheat phenology

Overall, the model-simulated and field-observed dates of anthesis and maturity are in close agreement for the selected stations (Fig. 5). The difference between the simulated and observed dates of anthesis and maturity is less than 5 days, suggesting that the CERES-wheat model fairly well simulates winter wheat phenology in the study.

Observed changes in winter wheat phenology are subjected to both climate change and management practices (especially the shifts in cultivars). By contrast, simulated time series of phenological events are only subjected to climate change. It is therefore possible to compare the role of climate change with that of cultivar regarding changes in winter wheat phenology in the last three decades.

As shown in Fig. 6a–h, there are frequent changes in cultivars sowed in the selected eight stations during 1981–2009. With the exception of Zhengzhou station, the trends in sowing dates in the selected stations are delayed by 0.9–4.6 days/decade.

For the selected eight stations, observed and model-simulated anthesis and maturity in 1981–2009 are similar in trend (Fig. 6a–h). Also based on observed data, both anthesis and maturity dates occur earlier for years with the same cultivated cultivars (Fig. 6a–h). The number of days for which field-observed winter wheat anthesis occurs in advance is less than that simulated by the model for selected stations, except for Zhumadian station. Also the extent by which the field-observed date of maturity occurs in advance is less than the model-simulated one for selected stations, except for Tangshan station. This suggests that climate change plays a dominant role in winter wheat phenological change. However, the effect of cultivar shift on winter wheat phenological changes could not be entirely neglected.

Discussion

The sowing date of winter wheat is contingent upon not only climatic conditions, but also on other factors including

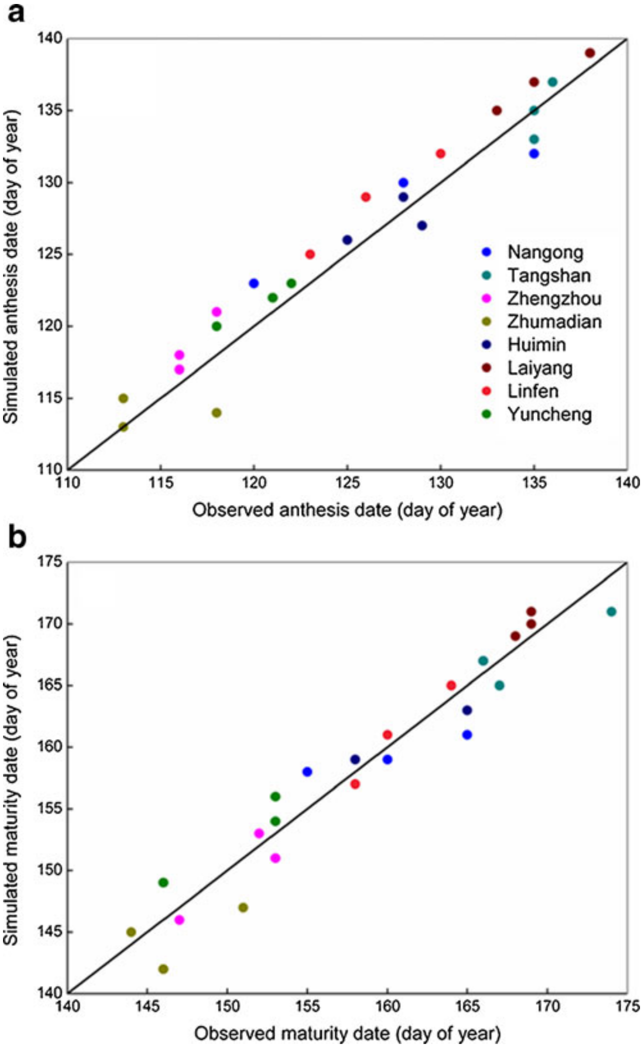

Fig. 5 Validation plot of CERES-wheat model simulation with observed anthesis and maturity dates in different stations in the study area (stations are represented by different colors)

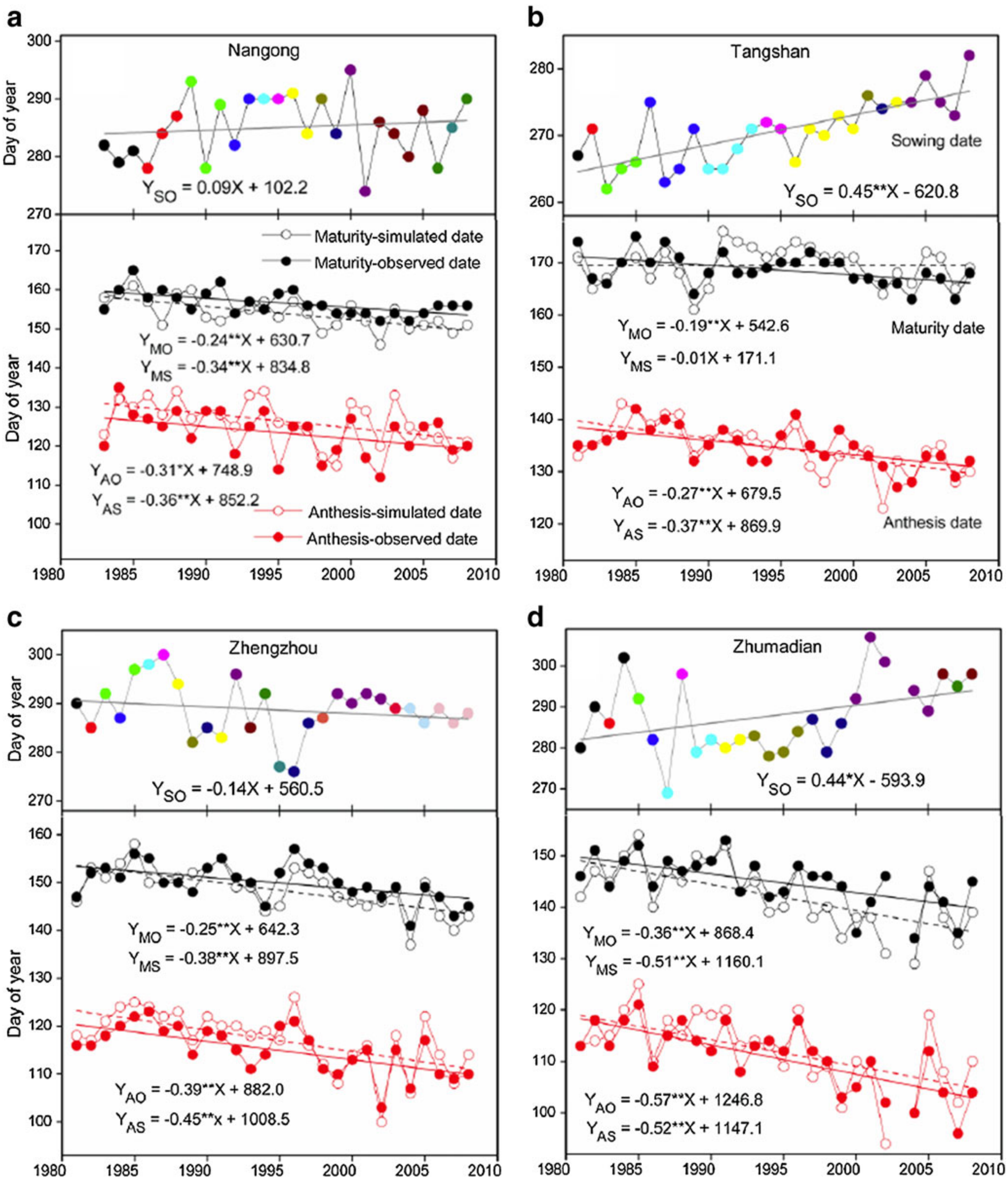

Fig. 6 Time series plots of model-simulated and field-observed dates of sowing, anthesis and maturity of winter wheat for the eight representative stations in the study area. Cultivars are represented by different colors for sowing date. In the regression equations, Y_{SO}, Y_{AO}, Y_{AS}, Y_{MO} and Y_{MS} denote sowing-observed, anthesis-observed, anthesis-simulated, maturity-observed and maturity-simulated dates, respectively. Single asterisk (*) denotes that the trend is significant at the 5 % probability level and double asterisks (**) denote that the trend is significant at the 1 % probability level

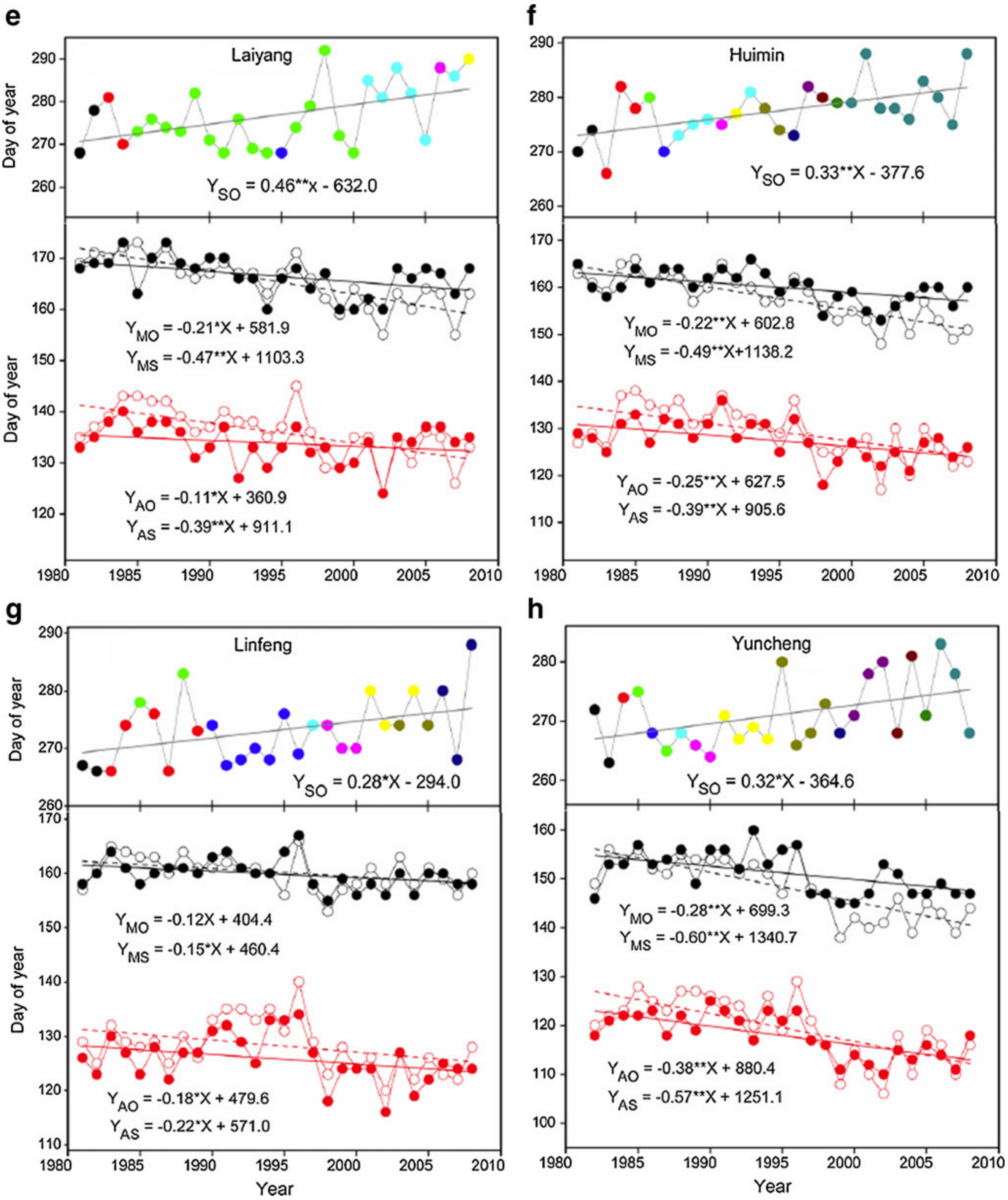

Fig. 6 (continued)

farmers' decisions. Winter wheat generally needs sufficient growth before dormancy sets in. This requires sowing of the crop to commence in sufficient time before the warm days of the year are replaced by cold winter conditions. In addition, winter wheat is grown in rotation with summer maize in the NCP. This implies that sowing date of winter wheat also depends on the date of harvesting of summer maize (Harrison et al. 2000). As winter wheat tends to be less profitable than summer maize, farmers prefer to optimize the date of harvesting of summer maize. This of course is at the expense of optimizing the date of planting of winter wheat. Studies show that delays in the dates of summer maize harvest are among the principal reasons for delays in sowing dates of winter wheat in the NCP (Yang et al. 2011).

Winter wheat in cool and temperate zones somewhat adapts to the seasonal cycles in these zones. Such cycles normally include a dormancy period in winter, which is triggered mainly by seasonal variations in temperature and light intensity. Therefore the dates of dormancy (start of dormancy) and greenup (end of dormancy) of winter wheat are mainly functions of temperature. Over the past several decades, surface air temperature significantly increased, especially in winter (December to February), in the NCP under global climate change (Ding et al. 2006). Temperature increase causes delays in winter wheat dormancy and early greenup, which in turn shortens dormancy period.

The timing of anthesis of winter wheat is largely governed by the interactions of genetic variables and environmental conditions (such as temperature and photoperiod), which is also affected by crop management practices including sowing date and cultivar selection (Kirby et al. 1987). To identify the impacts of climate and cultivar shifts on winter wheat phenology, the CERES-wheat model is used to simulate the anthesis and maturity dates under a fixed cultivar and actual climate conditions. It is noted that the dates of the model-simulated anthesis and maturity are similar in trends to ones observed in the field. This suggests that cultivar shift could not be the main cause of early anthesis and maturity in the study area. Climate warming induces shifts that favor early anthesis and maturity. To some extent, such shifts make the grain-filling phase less susceptible to high temperature effects (Tao and Zhang 2012).

To a large extent, however, winter wheat yield is determined by the length and timing of various phenological stages/phases (Jamieson et al. 1998). Although warming trend shortens the durations of GP2, GP3 and the entire growth period, the duration of grain-filling stage (GP4), a critical yield formation stage, slightly lengthens. Grain-filling duration is also primarily dependent on temperature, which shortens under warmer temperatures (Sofield et al. 1977). Due, however, to early anthesis, the grain-filling stage occurs under temperatures lower than before, a phenomenon that in turn prolongs GP4. The assertion that climate warming shortens grain-filling period and consequently reduces crop yield, as is widely cited in literature among the main impacts of climate change on crop yield (e.g., Lawlor and Mitchell 2000; Ainsworth and Ort 2010; Welch et al. 2010), is actually not observed in this study. In addition, dry grain weight (quantified as the product of time duration and grain-filling rate) increases linearly with the duration of grain-filling (Gallagher et al. 1976; Biscoe and Gallagher 1977). Therefore prolonged GP4 stage is potentially beneficial for high wheat productivity.

Conclusions

This study shows the trends in the timing of winter wheat phenology for the period 1981–2009 in the NCP. The findings indicate that early anthesis and maturity in the last three decades are mainly caused by climate warming. However, due to earlier dates of anthesis, grain-filling occurs at temperatures lower than before. This, in conjunction with cultivar shifts, actually prolongs GP4. Warming climate in the last three decades does not shorten winter wheat grain-filling period in the NCP. To some extent, early anthesis makes the grain-filling less susceptible to high temperature effects. This could be potentially beneficial for high wheat productivity in the NCP.

The response of crop development and phenology to climate change in the last three decades provides valuable insights into the understanding of the impacts of climate on crop development and productivity. It also fosters understanding of field crop adaptation to climate change in especially the last three decades. Since changes in the durations of the development stages of field crops affect yield formation, the findings in this study further reiterate the call for intensive research on the complex responses and adaptations of field crops to climate change and possible implications for crop production and food security.

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