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Phenological responses of spring wheat and maize to changes in crop management and rising temperatures from 1992 to 2013 across the Loess Plateau

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A B S T R A C T

The observed historical changes in crop phenological events are not only as a sensitive indicator to temperature variations but also the consequence of agronomic management such as adjustment of sowing date, cultivar selection and innovative farming practices. Clarifying how these factors influence crop phenology is of paramount importance in understanding/implementing adaptation strategies to future climate change. Changes in phenophases of dryland spring-sown wheat and maize were investigated using the observed phenological data from 1992 to 2013 across the Loess Plateau. Using a series of phenological growth models, we illustrated that once the varietal effect was fixed, rising temperature alone produced a general advancement on dates of heading and maturity, leading to a significant shortening of the vegetative phase (5.2 days decade^{-1} in wheat and 1.1 days decade^{-1} in maize), a shortened duration of reproductive phase (0.9 and 2.0 days decade^{-1} respectively) and the length of whole growing season (6.1 days decade^{-1} in wheat and 3.0 days decade $^{-1}$ in maize). In contrast, cultivar shifts prolonged the reproductive duration and the growing season length by 2.2 and 4.7 days decade^{-1} for spring wheat, and 3.3 and 1.5 days decade^{-1} for maize, respectively. The continuous update of cultivars during the past two decades has offset 63.5% of the shortening effect of growing season length caused by rising temperature for both crops. Our data indicate that adjusting sowing date and shifts to longer season cultivars are the critical adaptive strategies to cope with temperature increases in dryland spring-sown wheat and maize in the Loess Plateau or regions with similar environments.

1. Introduction

Along with a warming trend around the globe, the study of relationships between crop phenophase (an observable stage or duration in the annual life cycle of a crop that can be defined by a start and end point) and temperature increase has received growing attention since plant phenology was acknowledged as one of the most reliable bio-indicators of climate change (Myneni et al., 1997; White et al., 1997; Tao et al., 2008; White et al., 2009). The growing evidence from various regions in the world has shown marked phenological changes in response to rising temperatures (Chmielewski et al., 2004; Menzel et al., 2006; Estrella et al., 2007; Kalbarczyk, 2009; Sacks and Kucharik, 2011; Siebert and Ewert, 2012; Xiao et al., 2013; Li et al., 2014). In general, rising temperatures result in an accelerated developmental rate and a shortened growing season (Liu et al., 2010b; Tao et al., 2012; Zhang et al., 2013; Oteros et al., 2015), leading to a reduced duration for acquisition of resources (radiation, water and nutrient) and thus harmful to crop productivity in warm environments (Craufurd and Wheeler, 2009; Nord and Lynch, 2009). Previous studies stated that future growth in crop productivity strongly depends on the magnitude of the changes in duration of growing season, and thus the sensitivity of growing season length to warming temperatures is viewed as an important indicator of agricultural vulnerability (Adams et al., 1990; Xiong et al., 2008).

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Besides climatic factors, management practices could also modify the crop phenophases. For example, sowing dates can affect the onset of crop phenological stages, the duration of growing season, and hence crop yields. Farmers across the U.S. (Sacks and Kucharik, 2011), and Canada (Ma and Biswas, 2015) have been shifting maize (*Zea mays*) and soybean (*Glycine max*) planting to earlier dates over the last three decades, leading to longer vegetative growth periods, higher peak leaf area indices, and greater grain yields. In contrast, farmers in the Loess Plateau of China postponed sowing dates to shorten the duration of vegetative growth and thereby increase seedling survival rates of winter wheat (He et al., 2015). Egli and Cornelius (2009) proposed that there is no consistent yield advantage for very-early soybean planting dates with the traditional cultivars, but a significant yield loss for planting after the critical date in late May or early June. Changes in crop phenology could also be caused by the changes in cultivar selection with respect to thermal requirements. Tao et al. (2014) found that across China between 1981 and 2009, a shift to longer growth duration cultivars has delayed the heading date by 1.5 days decade^{-1} and maturity by 6.5 days decade^{-1} in maize production. Accordingly, the reproductive growth duration has prolonged by 6.5 days decade^{-1}, due to the early planting and delayed maturity dates. Liu et al. (2010b) argued that the adoption of newly improved cultivars with longer growth cycle can stabilize the length of growing season against the shortening effect induced by climate warming. In a study with rice (*Oryza sativa*), Zhang et al. (2013) illustrated that for short-season cultivars, crop development was accelerated on average by 0.9 days for each additional degree Celsius increase in temperature. In contrast, the shortening of growth duration in full-season cultivars displayed a positive but insignificant response to rising temperatures.

Farming techniques can alter crop phenology by modifying water and temperature conditions of the field microenvironments during the growing season. In the Loess Plateau of China, several recently developed dryland farming techniques, aimed at increasing harvesting rain water and adjusting thermal balance, have substantially contributed to the optimization of maize phenological patterns and improvement of grain yields (Mo et al., 2013). Of these techniques, the ridge-furrow with film mulching system (RFMS) has been demonstrated to be a very effective approach and has been widely implemented in the last decade (Liu et al., 2009; Zhou et al., 2009; Zhao et al., 2014). In comparison with conventional planting, the RFMS led to a general acceleration of maize seedling establishment and a shortening of growing season, which were positively associated with yield performance (Yi et al., 2010; Bu et al., 2013; Li et al., 2013).

The Loess Plateau is situated in northern China with a total area of almost 640,000 km^2. Over the past three decades, air temperature in this region has risen by 0.6 °C decade^{-1}, which is considerably higher than the global average temperature change of 0.13 °C decade^{-1} (Wang et al., 2012). Rain-fed agriculture is the predominant type of crop production in the Loess Plateau because there are no natural water resources available for irrigation (Huang et al., 2005). Additionally, low vegetation cover, high erodibility of soils and frequent high intensity storms during rainy-seasons have all contributed to make the Loess Plateau one of the most severely eroded and vulnerable areas in the world (Wang et al., 2012). Despite temperatures over the last few decades are rising at a rapid, unprecedented rate, crop yields of dryland spring-sown wheat and, most notably, maize in the Loess Plateau region have been improved significantly (Fig. S1). There are three possible factors, related to optimizing crop phenological events that may have contributed to the historical yield increases: The adjustment of sowing dates (He et al., 2015), selection of new cultivars with longer growing seasons (Tao et al., 2012), and adoption of innovative farming techniques (Zhou et al., 2009; Liu et al., 2010a; Gan et al., 2013). For spring wheat and maize in Loess Plateau, however, current research has poorly quantified the relative contributions of climatic and agronomic factors on crop phenophase changes. Further investigation of the effects of these individual factors on crop phenology is necessary to better understand the adaptive mechanisms of farming systems under temperature change and thus ensure that crop yields continue to thrive.

In this study, phenological data collected from dryland spring-sown wheat and maize crops from 1992 to 2013 in 18 locations across the Loess Plateau, were used to examine the historical changes in temperature conditions during different crop growth stages. We also quantified the general responses of spring-sown wheat and maize phenological events to the combined effects of rising temperature and altering crop management practices, such as sowing dates and cultivar selections, over the study period. A series of phenological growth models were employed to estimate the individual effects of temperature increase and cultivar shift on the crop phenophases of spring-sown wheat and maize.

2. Materials and methods

2.1. Data source and cropping system

Crop phenological data from 1992 to 2013 were collected at the Agro-Meteorological Experimental Stations (AESs) of the Chinese Meteorological Administration, across the Loess Plateau. Following a standardized observation method (China Meteorological Administration, 1993), the dates of major phenological events, including sowing, emergence, jointing, heading, and maturity, were recorded by local well-trained agro-technicians at each station in each year. For example, maize heading date was noted when the tassel was fully emerged and separated from the whorl and other leaves, on at least 50% of the plants. Maturity dates for spring-sown wheat and maize were recorded when grain on at least 50% plants in a plot became hard, showing the inherent color, and became difficult to divide with the thumbnail. The phenophase observations were generally performed every other day but notes were also taken daily when the expected phenological events were approaching. At each station, the common, locally planted cultivars grown under the conventional flat planting pattern were selected for phenological observations in each year. Crop management, including weed/disease control and fertilization, was carried out by following the provincial agronomy guide. This was to make sure that, the observed historical phenological events were recorded as a consequence of temperature variations and crop management, such as adjustment of sowing date and cultivar changes. In this study, we focused on three important phenophases (i.e. sowing, heading and maturity) for both crops and further calculated the length of vegetative growth (from sowing to heading), reproductive growth (from heading to maturity), and the whole growing season (from sowing to maturity) for each station. Finally, the phenological data from a total of 18 stations comprising of 10 spring wheat and 8 summer maize stations were compiled (Fig. 1). The meteorological observation data, including daily mean, maximum and minimum temperature, and day length were obtained from the onsite weather stations administered by the Chinese Meteorological Administration.

Rain-fed agriculture is the predominant type of crop production in the Loess Plateau since precipitation is the sole water resource for agriculture production. In the southwest of Loess Plateau, a drought-prone semiarid region, spring wheat was normally sown in late March (Table S1). In the semiarid central and eastern Loess Plateau, summer maize was usually planted in early May. The growing season mean temperature ranged from 11.3 to 17.5 °C (spring wheat) and 17.3–21.8 °C (maize) across the stations (Table S1). Newly-bred wheat and maize cultivars were shifted at approxi-