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Impacts of recent climate warming, cultivar changes, and crop management on winter wheat phenology across the Loess Plateau of China

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ABSTRACT

Crop yields are influenced by growing season length, which are determined by temperature and agronomic management, such as sowing date and changes in cultivars. It is essential to quantify the interaction between climate change and crop management on crop phenology to understand the adaptation of farming systems to climate change. Historical changes in winter wheat phenology have been observed across the Loess Plateau of China during 1981–2009. The observed dates of sowing, emergence, and beginning of winter dormancy were delayed by an average of 1.2, 1.3, and 1.2 days decade^{-1}, respectively. Conversely, the dates of green-up (regrowth after winter dormancy), anthesis, and maturity advanced by an average of 2.0, 3.7, and 3.1 days decade^{-1}, respectively. Additionally, the growth duration (sowing to maturity), overwintering period, and vegetative phase (sowing to anthesis) shortened by an average of 4.3, 3.1, and 5.0 days decade^{-1}, respectively. The changes in phenological stages and phases were significantly negatively correlated with a temperature increase during this time. Differently to most other phase changes, the reproductive phase (anthesis to maturity) prolonged by an average of 0.7 day decade^{-1}, but this was spatially variable. The prolonged reproductive phase was due to advanced anthesis dates and consequently caused the reproductive phase to occur during a cooler part of the season, which led to an extended reproductive phase. Applying a crop simulation model using a field-tested standard cultivar across locations and years indicated that the simulated phenological stages have accelerated with the warming trend more than the observed phenological stages. This indicated that, over the last decades, later sowing dates and the introduction of new cultivars with longer thermal time requirement have compensated for some of the increased temperature-induced changes in wheat phenology.

1. Introduction

The Loess Plateau (LP) is located in the northwest China and covers an area of 0.65 million km^2 (Fig. A.1). Continental semi-arid and arid climate dominates this area with annual mean temperature from 3.6 to 14.3 °C and annual precipitation from 200 to 700 mm from the northwest to southeast. Most precipitation occurs in the summer season, which causes serious soil erosion in poor vegetation cover areas. The crops in the LP mainly depend on rainfall because of the lack of water available for irrigation (He et al., 2014). As a result of the adverse environmental conditions such as soil erosion, unreliable rainfall and desertification, the LP is one of most vulnerable areas in China to climate change.

Wheat is the dominant crop in the Loess Plateau. The LP has a planting area of approximately 5 million ha, which accounts for 10% of the total wheat production in China (Wang and Li, 2010). During the last decades, air temperature has increased by 0.6 °C decade^{-1} in this region (Wang X.C. et al., 2011;Wang Q. et al., 2012)

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which is more than the global average temperature change (0.13 °C decade^{-1}) (IPCC, 2013). Increasing temperature accelerates the crop phenological development, which could potentially impact wheat production (Tao et al., 2014). A better understanding of how crop phenology responds to increasing temperature is essential for adapting the farming practices and crop breeding to mitigate the negative effects and even taking advantage of climate change (Hoffmann and Sgrò, 2011).

Crop phenology is codetermined by environmental conditions, mainly thermal time requirement, and agronomic practices, including sowing dates and cultivar characteristics. Detecting phenological responses to climate warming is difficult because of the continuously changing sowing dates and introducing new cultivars (Chmielewski et al., 2004; Estrella et al., 2007). For example, earlier flowering dates in winter wheat were observed throughout the last 70 years in the U.S. Great Plains because of a temperature increase during spring, which caused less time for light interception and biomass growth (Hu et al., 2005). In another study, Xiao et al. (2012) reported that from 1981 to 2009, climate warming in the North China Plain caused the dates of green-up after winter dormancy, anthesis, and maturity of winter wheat to occur in average of 1.1, 2.7, and 1.4 days earlier per decade, respectively. Wang et al. (2008) suggested that a warming trend in the LP from 1983 to 2004 led to earlier stem elongation, booting, anthesis, and maturity of winter wheat by an average of 13.2, 9.8, 11.0, and 10.8 days, respectively. However, there are uncertainties in this study because of the limited number of stations (only one station was used) and the cultivar shift during this period (Liu Y. et al., 2010; Wang et al., 2013). Warming temperature could accelerate the crop development, while a long-duration cultivar or late sowing date could result in a delayed development. Statistical models could fail to capture the interactions between environmental changes, management practices and the cultivar change. Process-based crop models can dynamically simulate the interactions between crops, environmental conditions and management practices (Zhao et al., 2014). The effect of one factor can be separated from other factors (Liu Y. et al., 2010; Liu L. et al., 2012; Wang et al., 2013).

This study examined the trends of winter wheat phenological development using observed data from 16 agro-meteorological stations in the LP from 1981 to 2009. We correlated these records with temperature trends to analyze how climate warming has affected winter wheat phenological stages and phases. A crop model was applied to separate the effects of climate warming, crop management and cultivar changes on phenology.

2. Material and methods

2.1. Agro-meteorological stations and data

Winter wheat is mainly distributed across the southeastern and central LP. In this study, we selected 16 stations with the largest number (24 or more) of recorded years (Fig. A.1). The data on winter wheat phenology from 1981 to 2009 are from local agro-meteorological experimental stations maintained by the Chinese Meteorological Administration (CMA). Phenological data included dates of sowing, emergence, start of dormancy, green-up (start of regrowth in spring after dormancy), anthesis (50% anthesis), and maturity (physiological maturity). With these data, four phenological phases were derived, including growth duration (sowing to maturity), overwintering period (DG, start of dormancy to green-up), vegetative growth stage (SA, sowing to anthesis), and reproductive growth stage (AM, anthesis to maturity). The local farmers determined the management practices of the winter wheat crop. Approximately every 3–6 years (average 10 cultivars per station), these farmers changed to a new wheat cultivar, which could alter crop temperature requirements. Cultivar names were listed in Table A.1. Historical daily weather data, including maximum, minimum, and mean temperatures for 1980–2009 at the 16 stations, were also obtained from CMA website at http://cdc.cma.gov.cn/.

2.2. Data analysis

Trends in observed phenology and corresponding mean temperature were estimated with a linear regression, using the year as the independent variable. Time windows for calculating temperature trends were determined by the longest phenological stages at each station. For example, the time window of growth duration (i.e. sowing to maturity) was from the earliest sowing date to the latest date of maturity during the last decades at each station. By holding a time window of a growth duration constant, the calculated temperature trend was independent from the corresponding phenology changes.

We correlated the sowing dates with monthly mean temperature during the month of occurrence of sowing to evaluate whether the sowing dates were driven by temperature. The responses of phenology to temperature were calculated as follows:

$$OP_{nt} = a_{nt}T_{nt} + b_{nt} + \epsilon_{nt} \quad (1)$$

where OP_{nt} is the observed phenological phases (DOY, day of year) or phenological length (days) for the nth stations in year t. T_{nt} is the mean daily temperature (°C) during the corresponding development stage for the nth stations in year t. The variable a_{nt} is the coefficient of phenology responses to temperature (days °C^{-1}) for the nth station. The variable b_{nt} represents the intercept, and ϵ_{nt} is the error term for each station. The regression coefficients are considered as the phenology responses to temperature and crop management changes.

2.3. Thermal time calculation and phenology simulation with the APSIM-wheat model

The Agricultural Production Systems sIMulator (APSIM) is a modular modeling framework developed by the Agricultural Production Systems Research Unit in Australia (Keating et al., 2003). In the APSIM model, wheat phenology is determined by accumulation of thermal time (ATT in degree-days) and the cultivar specific thermal time requirement for each development stage. The phenology before flowering is also influenced by the vernalization and photoperiod sensitivity. The total thermal time from sowing to anthesis (SA) and from anthesis to maturity (AM) is calculated as:

$$ATT = \sum_{i=1}^{n} DTT \quad (2)$$

where DTT is thermal time per day, n is the days of phenological stages. DTT is calculated from 3-hourly air temperature interpolated from the daily maximum and minimum crown temperature. The detailed description of APSIM can be found at http://www.apsim.info.

APSIM operates at a daily time-step, and it is driven by daily weather data including daily maximum and minimum temperatures, rainfall, and solar radiation. In this study, APSIM version 7.4 was used.

We simulated the crop phenology by using a single cultivar and the same agronomic practices throughout the years to separate the effects of temperature, crop management, and cultivar on crop phenology. We simulated the anthesis, maturity date, and growth duration from 1981 to 2009 across all agro-meteorological stations in the LP. APSIM was calibrated with a single, most frequently-used cultivar (1981–1983) at each site. Sixteen cultivars, each different