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RESEARCH ARTICLE

Effects of meteorological factors on different grades of winter wheat growth in the Huang-Huai-Hai Plain, China

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Abstract

The sown area of winter wheat in the Huang-Huai-Hai (HHH) Plain accounts for over 65% of the total sown area of winter wheat in China. Thus, it is important to monitor the winter wheat growth condition and reveal the main factors that influence its dynamics. This study assessed the winter wheat growth condition based on remote sensing data, and investigated the correlations between different grades of winter wheat growth and major meteorological factors corresponding. First, winter wheat growth condition from sowing until maturity stage during 2011–2012 were assessed based on moderate-resolution imaging spectroradiometer (MODIS) normalized difference vegetation index (NDVI) time-series dataset. Next, correlation analysis and geographical information system (GIS) spatial analysis methods were used to analyze the lag correlations between different grades of winter wheat growth in each phenophase and the meteorological factors that corresponded to the phenophases. The results showed that the winter wheat growth conditions varied over time and space in the study area. Irrespective of the grades of winter wheat growth, the correlation coefficients between the winter wheat growth condition and the cumulative precipitation were higher than zero lag (synchronous precipitation) and one lag (pre-phenophase precipitation) based on the average values of seven phenophases. This showed that the cumulative precipitation during the entire growing season had a greater effect on winter wheat growth than the synchronous precipitation and the pre-phenophase precipitation. The effects of temperature on winter wheat growth varied according to different grades of winter wheat growth based on the average values of seven phenophases. Winter wheat with a better-than-average growth condition had a stronger correlation with synchronous temperature, winter wheat with a normal growth condition had a stronger correlation with the cumulative temperature, and winter wheat with a worse-than-average growth condition had a stronger correlation with the pre-phenophase temperature. This study may facilitate a better understanding of the quantitative correlations between different grades of crop growth and meteorological factors, and the adjustment of field management measures to ensure a high crop yield.

Keywords: growth condition, meteorological factors, remote sensing, spatiotemporal correlation, winter wheat, Huang-Huai-Hai (HHH) Plain region, China

1. Introduction

In recent years, climate change and its effects on nature, economy, and human life have become global issues of concern for governments, society, and scientific communities (Lee *et al.* 1999; Stuczyński *et al.* 2000; Walther *et al.*

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2002; Arnella *et al.* 2004; Raskin 2005; Trnka *et al.* 2009; Moriondo *et al.* 2010; Preston *et al.* 2011; Xiao *et al.* 2013). The historical evolution of climate change and its causes, as well as future climate change trends, continue to be the subject of debate, but there is no doubt that climate change has profound effects on every aspect of global ecological systems (Yohe and Dowlatabadi 1999; Sr 2005; Ye *et al.* 2013). In particular, agricultural ecosystem is greatly affected by the climate and weather (Reilly 1995; Smit *et al.* 1996; Smit and Skinner 2002; Howden *et al.* 2007; Falloon and Betts 2010; Gornall *et al.* 2010; Iglesias *et al.* 2011). Climate change may lead to variation in the agro-ecological environment, production patterns, and cropping structures over time and space (Viglizzo *et al.* 1995; Olesen and Bindi 2002; Giupponi *et al.* 2006; Smith *et al.* 2013), thereby affecting global or regional food production and food security. Thus, it is important to understand the impacts of climate change on agriculture, as well as the response of agriculture to climate change in China. This type of information would be helpful for developing adaptation strategies, guiding grain production, and promoting policies to deal with the impacts of climate change.

Many previous and ongoing studies have analyzed the impacts of climate change on agriculture in China (Xu *et al.* 2006; Xiong *et al.* 2007, 2008; Challinor *et al.* 2010; Jiang *et al.* 2013; Ye *et al.* 2013). However, most of these studies focused on the effects of climatic factors on the cropping system, crop distribution, and crop yield/production based on empirical analyses, bioclimatic models, and crop growth models. For example, Thomas (2006) analyzed the spatial differences in agricultural productivity based on historical and future climate conditions in China. Mo *et al.* (2009) explored the response of the regional crop yield to climate change between 1951 and 2006 in the North China Plain and predicted the impacts of future climate change on the wheat-maize double-cropping system using Intergovernmental Panel on Climate Change (IPCC) scenarios A2 and B1. Bachelet and Gay (1993) predicted the responses of rice to elevated CO_2 and increased temperature by comparing four physiology-based rice models. In general, these studies utilized time-series datasets to analyze the long-term correlations between climate change and crop production. By contrast, there have been few studies in real time of the short-term impacts of meteorological factors on crop growth during an entire growing season.

Crop cultivation is climate dependent and crop growth is highly sensitive to meteorological variables. Field observations are commonly used in traditional methods to investigate crop growth condition and its relationship with meteorological factors in specific small areas. However, it is almost impossible to extend these studies to larger areas because large-scale observations of crop growth are very expensive, time-consuming, and subject to uncertainties attributable to operator bias. Moreover, models calibration at specific scales may not be accurate when applied at larger scales. Spatial information technology, particularly remote sensing, has the advantages of low-cost sampling with good temporal repeatability over large and inaccessible regions, which means it is an important tool for crop monitoring (Cihlar 2000; Wang *et al.* 2008; Huang *et al.* 2010).

Furthermore, the correlations between crop growth and meteorological factors are complex. Thus, the following questions need to be addressed. How do temperature and precipitation affect the crop growth process throughout an entire growing season? Are there quantitative correlations between different grades of crop growth and meteorological factors? Is there a time lag between different grades of crop growth and meteorological factors throughout the growing season due to a time lag in the response of crop growth to meteorological factors (Zhai 1999)? Exploring these questions is extremely important because they may help guide agricultural production and ensure food security. The main objectives of this study were to assess the crop growth condition throughout the entire growth season based on a time-series of remotely sensed data and to analyze the effects of meteorological factors on different grades of crop growth in the Huang-Huai-Hai Plain region in China.

2. Materials and methods

2.1. Study area

The well-known Huang-Huai-Hai (HHH) Plain in China was selected as the study area (Fig. 1). HHH Plain is located approximately between 114°–121°E and 32°–42°N and has a total area of 3.5×10^5 km^2. This area includes parts of Beijing and Tianjin cities, the southern part of Hebei Province, Shandong Province, the eastern part of Henan Province, the northern part of Jiangsu Province, and the northern part of Anhui Province (Liu 1997). The HHH Plain has a continental monsoon climate, which is temperate and semi-humid in the south, and semiarid in the north. The cumulative temperature ≥°C is about 4 500–5 500°C and the cumulative active temperature ≥10°C is approximately 3 800–4 900°C. The frost-free period is 190–220 d and the annual average precipitation during 1956–2000 ranged from 480 to 1 050 mm (NAZC 1989). The HHH Plain is one of the most important agricultural zones in China. It has a dominant double-cropping system and winter wheat and summer maize are the main two crops in this area. The area of winter wheat in the HHH Plain accounts for over 65% of the total sown area in China and over 75% of the national production (NAZC 1989). In the present study, winter wheat was selected as the target crop for analysis.

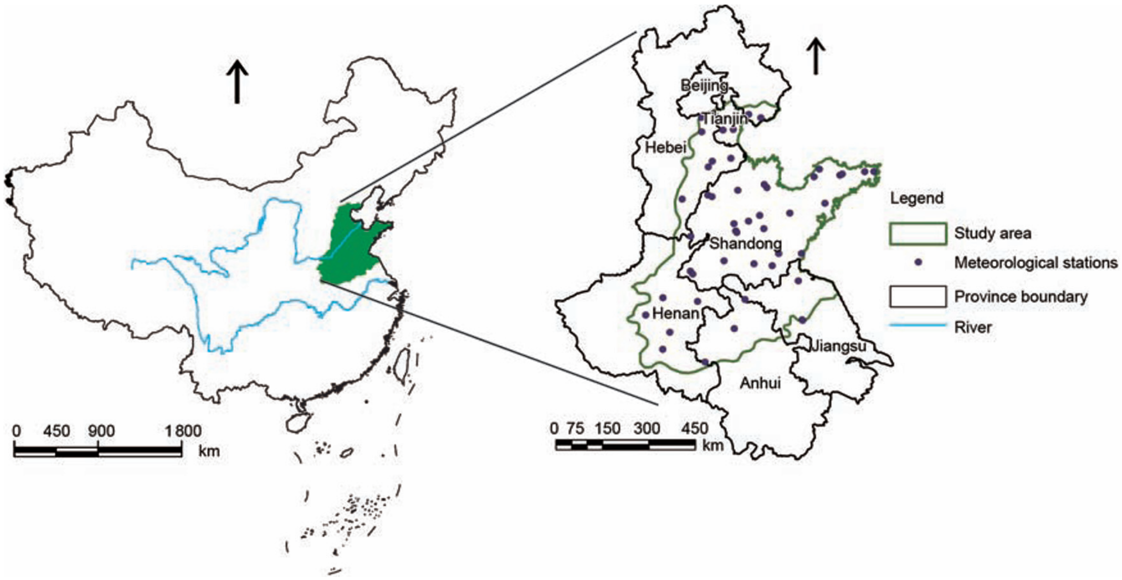

Fig. 1 Study area and meteorological stations.

2.2. Materials

Datasets used in this study included winter wheat spatial distribution data, remote sensing time-series dataset, field survey and meteorological data. Winter wheat distribution data were obtained using the automatic identification method described by Huang *et al.* (2012), and these data formed the basis of this study. A time-series of moderate-resolution imaging spectroradiometer (MODIS) datasets were acquired at a spatial resolution of 250 m in the period of October 2007 to June 2012 (except July, August and September when there was no winter wheat in field) from the remote sensing application center of the Ministry of Agriculture, China. These datasets, with some field survey data, were used to determine the growth stage and growth condition of winter wheat. Daily meteorological data, including temperature and precipitation data, were collected from 48 meteorological stations operated by the China Meteorological Administration from September 2011 to June 2012 and used to analyze the relationships between the crop growth condition and meteorological factors.

All of the input data were reprocessed. Radiation calibration and geometric corrections were applied to the original MODIS data and the daily normalized difference vegetation index (NDVI) was calculated. Next, the MODIS NDVI datasets for each phenophase of winter wheat during 2007–2012 were generated from the daily NDVI data using the maximum value composite technique. This method produces a composite image for a fixed period of time by retaining the maximum NDVI value for each pixel from the daily images acquired during a specific period. This method can remove some of the nonvegetation effects caused by sensor degradation and clouds etc. The NDVI for individual phenophases were then used to monitor the crop growth condition during the same period. The average temperature and total precipitation at each meteorological station were calculated for the different winter wheat phenophases using the daily temperature and precipitation data. The meteorological data for each phenophase were interpolated with a 250 m×250 m grid using the Kriging interpolation method to comply with the cell size of NDVI data.

2.3. Methods

Crop growth monitoring The NDVI is one of the most important and widely used vegetation indices for monitoring the condition of crops (Wang *et al.* 2008; Huang *et al.* 2012; Bolton and Friedl 2013; Hmiminaa *et al.* 2013). Most global agricultural monitoring systems monitor the growth condition of crops using the NDVI obtained from remote sensing techniques, such as the European Union Joint Research Center (JRC) through the "Monitoring Agriculture with Remote Sensing (MARS)" project (JRC-MARS 2005), the USDA's Global Agriculture Information Network through the "Agriculture and Resources Inventory Surveys through Aerospace Remote Sensing" project (USDA 2005), which has operated since the 1980s, and the CropWatch System used by the Chinese Academy of Sciences (Meng *et al.* 2006).

In the present study, NDVI grade models were used to assess the winter wheat growth condition. First, the winter wheat distribution data were used as a mask and the NDVIs superimposed with the winter wheat distribution were calculated using ARCGIS tools. Second, the 5-year average NDVIs from 2007–2012 were calculated for the same phenophases and a crop growth index (R) for winter wheat was calculated as:

$R=NDVI-NDVI_{average}$

Where, $NDVI$ is current year NDVI value (2011–2012) at the pixel level for each different phenophases and $NDVI_{average}$ is the average NDVI for the same time period of recent 5 years (2007–2012) at the same pixel level. Finally, the R values were graded into three levels to assess the crop growth condition. The winter wheat growth was classified as better than average (better) when R was 5% higher than 5-year average, as worse than average (worse) when R was 5% lower than 5-year average, and as average (normal) when R was between –5 and 5% to average. The areas covered by clouds were treated as non-monitored areas where the crop growth condition was not evaluated.

Correlations between meteorological factors and crop growth condition The growing season of winter wheat was divided into seven phenophases, they are sowing–emergence, tillering, overwintering, revival, elongation, earing–flowering, and physiological maturity–maturity according to field survey and meteorological data. The correlations between the meteorological factors and different grades of winter wheat growth were analyzed for each phenophase. The correlation coefficients were calculated between the NDVI values at pixel scale in different grades of winter wheat growth and temperature, and precipitation during the same phenophase, the previous phenophase, and the cumulative total in different phenophases (here, cumulative total of each different phenophase includes the phenophase itself and phenophase(s) before it). The formula was:

$$r_{xy}=\frac{\sum_{i=1}^{n}(x_i-\bar{x})(y_i-\bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i-\bar{x})^2\sum_{i=1}^{n}(y_i-\bar{y})^2}}$$

In above formula, r_{xy} is the correlation coefficient between x and y. Here, x stands for meteorological factors, and y stands for NDVI values in different grades of winter wheat growth. The significance level for hypothesis testing was $P<0.05$.

3. Results

3.1. Spatiotemporal changes in winter wheat growth

Fig. 2 shows the spatiotemporal distribution of winter wheat growth for the entire growing season from October 2011 (sowing–emergence) to June 2012 (physiological maturity–maturity).

In September 2011, the month before the winter wheat sowing, the total precipitation in the HHH Plain was 200% more than that in the average year, which produced excellent sowing condition for winter wheat.

The soil moisture status was well suited to sowing, and there was ample sunshine from the seedling stage until the tillering stage. Therefore, the meteorological conditions were suitable for winter wheat growth. Table 1 shows the percentage changes in the different grades of winter wheat growth during the seven phenophases. We can see that at sowing-emergence, tillering and overwintering stage, the proportions of better-than-average (better) growth condition were more than three times than worse-than-average (worse). Therefore, the overall situation in early growth season was better. Then the revival stage was affected by the relatively low temperature, and the growth rate was slow, so the winter wheat growth rate reduced slightly in some areas and the proportion of a worse-than-average (worse) growth condition increased. After the elongation stage, however, the growth condition improved because there was abundance sunshine and growth condition was generally good. Although the overall growth situation was worse in the middle stage, it recovered at the end of the growing season.

In summary, the climate conditions were relatively favorable during the seven phenophases, and the overall winter wheat growth condition was generally good in the HHH Plain region between 2011 and 2012. However, there were spatiotemporal variations in the winter wheat growth condition. The temporal pattern can be summarized as: "better during the early growth season, worse in the middle, with a good recovery later". The spatial pattern was good during all seven phenophases in Henan Province, especially in the tillering and overwintering phenophases, whereas the growth condition was better before winter in Hebei and Shandong provinces, and worse than average during the revival and elongation stages, and followed by an improvement after the earing–flowering stage.

3.2. Correlations between meteorological factors and crop growth condition

As mentioned above, there were correlations between the changes in the winter wheat growth condition and the meteorological factors. Fig. 3 showed the changes of different grades of winter wheat growth condition and changes of average temperature and total precipitation during the seven phenophases. The abundant precipitation before winter wheat sowing and the winter season produced a good growth condition, since precipitation increased soil moisture, with suitable soil moisture, winter wheat had not only rapid and regular emergence, but also good promotion of tillering before winter. The most suitable temperature for emergence

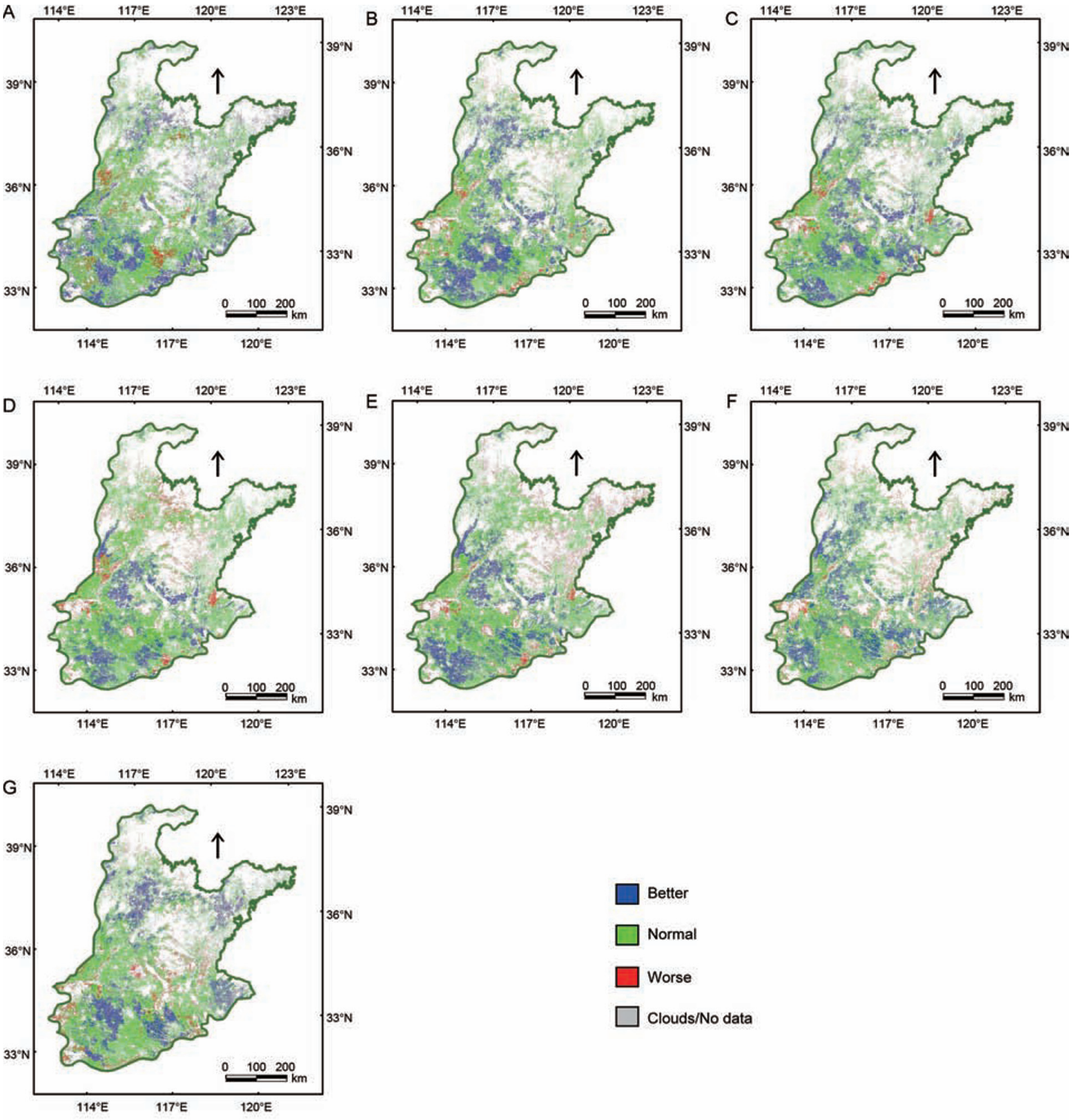

Fig. 2 Spatiotemporal changes in the winter wheat growth condition during seven phenophases. A, sowing–emergence. B, tillering. C, overwintering. D, revival. E, elongation. F, earing–flowering. G, physiological maturity–maturity.

Table 1 Percentage of different grades of winter wheat growth condition during the seven phenophases

	Phenophase	Worse than average (%, worse)	Average (%, normal)	Better than average (%, better)
1	Sowing–emergence	6.3	70.9	22.8
2	Tillering	6.7	67.6	25.7
3	Overwintering	6.9	68.4	24.7
4	Revival	8.6	73.9	17.5
5	Elongation	9.4	69.1	21.5
6	Earing–flowering	8.3	69.4	22.3
7	Physiological maturity–maturity	8.0	68.8	23.2

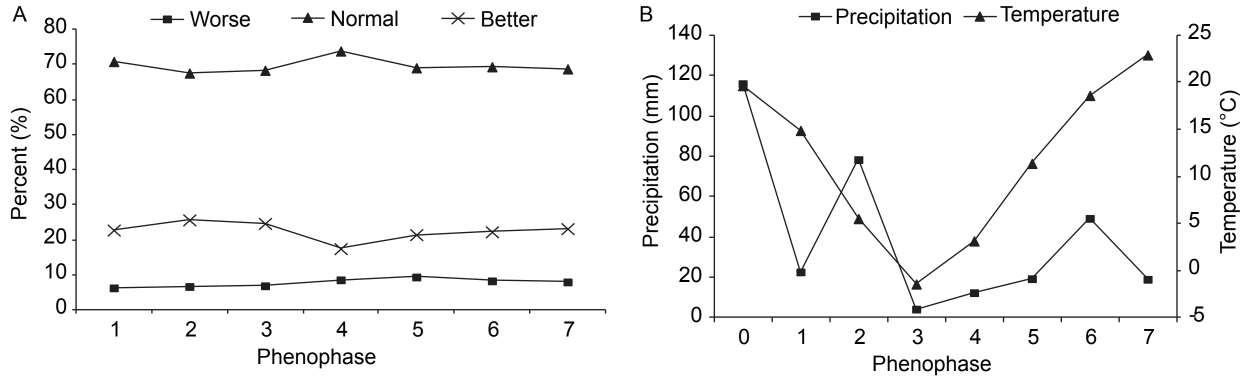

Fig. 3 Dynamic changes in winter wheat growth condition (A) and meteorological factors during seven phenophases (B). 0, September; 1, sowing–emergence; 2, tillering; 3, overwintering; 4, revival; 5, elongation; 6, earing–flowering; 7, physiological maturity–maturity. The same as below.

of winter wheat is 15–18°C (Zhai 1999), and we can see that the temperature during the sowing–emergence stage was just within the most suitable range. Whereas the low temperature and relatively low precipitation during the spring season had detrimental effects on winter wheat growth. The winter wheat crop growth had a close correlation with the temperature and precipitation. In general, most of the winter wheat had a better growth condition (Zhai 1999; Zhang *et al.* 2014) with adequate precipitation and sunshine, whereas the amount of wheat with a good growth condition declined when the precipitation and the temperature levels were low. Studies show that when temperature drops below zero, winter wheat will stop growing, and enter a dormant state. Fig. 3 showed the poor growth condition increased for a time, e.g., during overwintering and revival, and the lag in the growth condition was obviously correlated with low precipitation. It is a critical time for winter wheat's spikelet differentiation and the improvement of spike rate when average temperature rises to 8–10°C. Winter wheat begins to shooting when the temperature rises to 10°C.

There was a time lag in the crop growth due to climate change, but was the time lag the same with different grades of growth condition? The changes in the winter wheat growth condition and the variations in meteorological factors during different phenophases were analyzed as a whole. However, we were more interested in the length of the lag between different grades of crop growth and the meteorological factors during different phenophases, as well as the effects of meteorological factors on the different grades of growth condition in each phenophase. Thus, we analyzed the pixel-level correlations between the temperature, precipitation, and the different growth grades during each phenophase. We also analyzed the correlations between the different growth grades, temperature, and precipitation during each pre-phenophase, as well as the cumulative phenophases.

In areas where the winter wheat growth condition was better than average (Fig. 4-A), the correlations between the growth condition, synchronous precipitation (zero lag), pre-phenophase precipitation (one lag), and the cumulative precipitation varied between different phenophases. The maximum correlation between the growth condition and synchronous precipitation was 0.756 during the winter wheat revival stage, which showed that the precipitation in the revival stage had the greatest effect on the improved growth condition of winter wheat. Furthermore, the correlation between the growth condition and pre-phenophase precipitation was also stronge during the winter wheat revival stage, which demonstrated the importance of precipitation during the overwintering stage. Among the seven phenophases, the maximum correlation between the growth condition and pre-phenophase precipitation occurred at three stages, i.e., tillering, elongation, and physiological maturity–maturity, while the maximum correlation between the growth condition and cumulative precipitation also occurred at three stages, i.e., sowing–emergence, overwintering, and earing–flowering.

In areas where the winter wheat growth condition was normal (Fig. 4-B), the maximum correlation between the growth condition and cumulative precipitation was 0.790 during the elongation stage. Among the seven phenophases, the maximum correlation between the growth condition and pre-phenophase precipitation occurred at two stages, i.e., tillering and physiological maturity–maturity, while the maximum correlation between the growth condition and cumulative precipitation occurred at five stages, i.e., sowing–emergence, overwintering, revival, elongation, and earing–flowering. These results demonstrated that the cumulative precipitation had the most important effect on growth for most of the winter wheat.

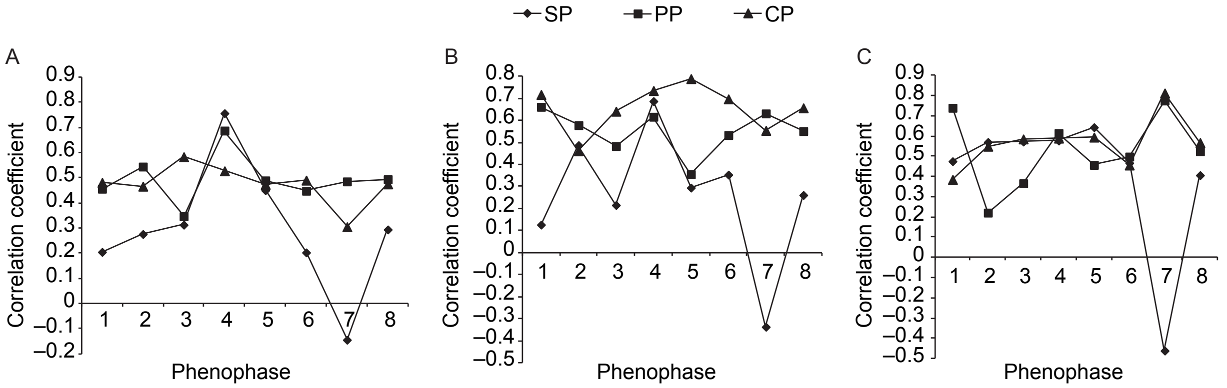

Fig. 4 Correlation coefficients between different grades of winter wheat growth and precipitation with different time lags in different phenophases. A, areas in better-than-average growth condition. B, areas in normal growth condition. C, areas in worse-than-average growth condition. SP, synchronous precipitation (zero lag); PP, pre-phenophase precipitation (one lag); CP, cumulative precipitation. The same as below.

In areas where the winter wheat growth condition was worse than average (Fig. 4-C), the maximum correlation between the growth condition and cumulative precipitation was 0.812 during the physiological maturity–maturity stage. Among the seven phenophases, the maximum correlation between the growth condition and synchronous precipitation occurred two stages, i.e., tillering and elongation, while the maximum correlation between growth condition and pre-phenophase precipitation occurred at three stages, i.e., sowing–emergence, revival, and earing–flowering. The maximum correlation between the growth condition and cumulative precipitation also occurred two stages, i.e., overwintering and physiological maturity–maturity. Irrespective of the grade of winter wheat growth, the growth condition had its maximum correlation with the cumulative precipitation on average, whereas the correlation between the growth condition and synchronous precipitation was relatively weak, which showed that the cumulative precipitation throughout the whole growing season had the greatest effect on the growth condition.

The correlations between different grades of growth condition, synchronous average temperature (zero lag), pre-phenophase average temperature (one lag), and cumulative average temperature (here means average temperature of several phenophase) varied greatly during different phenophases compared with precipitation. In areas where the winter wheat growth condition was better than average (Fig. 5-A), the maximum correlation generally occurred between the better growth condition and the synchronous average temperature. Among the seven phenophases, the maximum correlation between the better-than-average growth condition and the synchronous average temperature occurred at five stages, with the exception of the revival and physiological maturity–maturity stages. The maximum correlation between the normal growth condition (Fig. 5-B) and the synchronous average temperature occurred at four stages, i.e., sowing–emergence, revival, elongation, and earing–flowering. The maximum correlation between the normal growth condition and pre-phenophase temperature occurred only once, i.e., in the physiological maturity–maturity stage. The maximum correlation between the growth condition and temperature was 0.863 during the winter wheat tillering stage, which showed that the temperature in the tillering stage had the greatest effect on winter wheat growth. In areas where the growth condition was worse than average (Fig. 5-C), the maximum correlation between the growth condition and the synchronous average temperature occurred at three stages, i.e., sowing–emergence, tillering, and revival. The maximum correlation between the worse-than-average growth condition and the pre-phenophase average temperature occurred at three stages, i.e., overwintering, earing–flowering, and physiological maturity–maturity.

Overall, the better-than-average growth condition had its maximum correlation with the synchronous average temperature; the normal growth condition had its maximum correlation with the cumulative temperature; and the worse-than-average growth condition had its maximum correlation with the pre-phenophase average temperature.

Among the seven phenophases, the maximum correlation coefficients between different grades growth condition and precipitation were higher than those with temperature in 13 cases, whereas the maximum correlation coefficients between different grades of growth condition and temperature were higher than those with precipitation in eight cases, which showed that precipitation had greater effects on the growth condition than temperature throughout the overall growing season. In the final two phenophases, the correla-

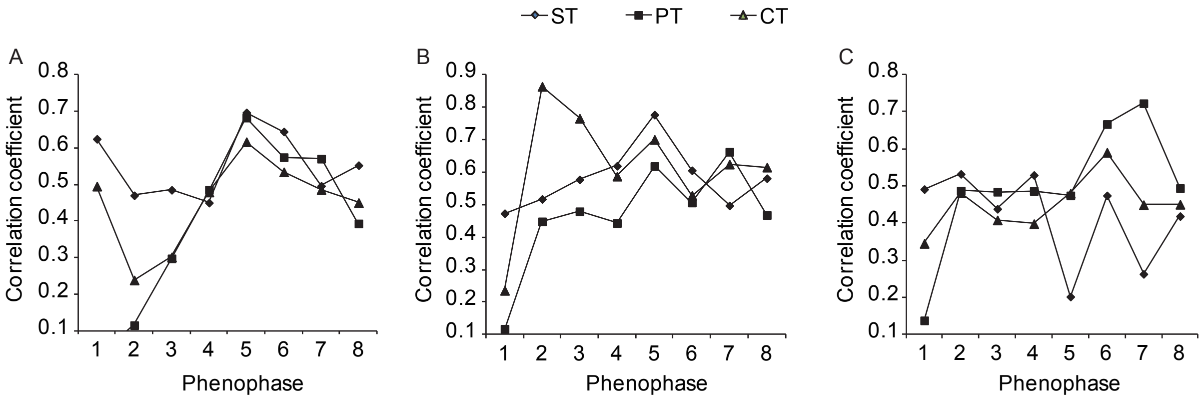

Fig. 5 Correlation coefficients between different grades of winter wheat growth and temperature with different time lags in different phenophases. A, areas in better-than-average growth condition. B, areas in normal growth condition. C, areas in worse-than-average growth condition.

tion coefficients between different grades of growth condition and temperature were higher than those with precipitation in four cases among six, which demonstrated the importance of temperature for the growth condition during the earing–flowering and physiological maturity–maturity stages.

4. Discussion

The majority of previous studies in this field have focused on the correlations between climate change and crop yield. The time scale of climate change research is generally a long period, such as 30 years or more. Many researchers have studied the long-term correlations between climate change and crop yields to predict future yields (Bolton *et al.* 2013; Jiang *et al.* 2013; Ju *et al.* 2013; Ye *et al.* 2013), which are important for ensuring national food security. In a short time, however, it may be more practical to understand how real-time changes in meteorological factors might affect crop growth during each different phenophases. Meteorological factors could have different effects on crop growth condition during each different phenophase. Therefore, this study did not treat the winter wheat yield as the only important factor to explore the correlation between crop yield and meteorological factors. Instead, we focused on the effects of meteorological factors during different phenophases in the growth and development of winter wheat, which hasn't been studied much up to now.

This study produced several very interesting results. For example, the winter wheat growth grades had the maximum correlations with the cumulative precipitation on average, which showed rather than the synchronous precipitation, the cumulative precipitation throughout the overall growing season had the strongest effect on the growth condition. This result agrees with previous studies in some respects (Bachelet and Gay 1993; Southworth *et al.* 2000; Kutcher *et al.* 2010; Barnwal and Kotani 2013), although the majority of them analyzed the correlations between the NDVI and meteorological factors at 10 days or month time scales rather than the crop phenophases (Schultz and Halpert 1993; Mo *et al.* 2007; Eklundh 2012). Li *et al.* (2007) analyzed the correlations between NDVI variations of winter wheat and climatic factors in the Yellow River Delta (which is within the HHH region) using data from 2000–2004, and concluded that the NDVI had close correlations with temperature and precipitation, but they did not analyze the correlations between the NDVI and cumulative meteorological factors. Liu and Xu (2007) analyzed the correlations between the NDVI of the main vegetation and meteorological factors in the Yellow River Basin from March to October of 1982–1999, but they did not distinguish winter wheat from other crops and simply treated all crop types as one form of vegetation. March to May is the main growing season for winter wheat, which is the main crop in this area, and our results were similar to those reported by Liu and Xu (2007) for this period.

Xu *et al.* (2015) simulated the potential effects of drought on winter wheat in HHH Plain based on meteorological data and field observations from six agricultural sub-regions of the HHH Plain from 1981 to 2010, the results showed that regional distribution of winter wheat yield reduction rate of each agricultural region was mainly caused by the climatic factors, and drought was the main factor, which had larger effects on the yield reduction rate in elongation stage than that in filling stage. Zhang *et al.* (2014) analyzed the climatic suitability index of winter wheat in HHH, the results showed precipitation was a limited key factor to the winter wheat production in this region, and temperature's effects on winter wheat growth are different in different stages. All these results were coincident with ours.

Considering there might exist some occasionalities of using one year data in one place to analyze the effects of meteorological factors on crop, the authors also did some work in other winter wheat main growth area (Huang *et al.* 2014). The results in Gansu and Shaanxi provinces, which located in western China, also showed that no matter what grades of winter wheat growth, the correlation coefficients between winter wheat growth condition and accumulated precipitation were higher than synchronous precipitation and pre-phenophase precipitation in terms of the average value in 7 phenophases, which showed the same results as HHH. In addition, there are the same correlations between different grades of winter wheat growth and temperature both in HHH and in Gansu and Shaanxi provinces. The same results at different areas showed the robustness to some extent.

Although it may get some further interesting patterns if a long-term time-series dataset was used. We still confirmed that studying the correlations between meteorological factors and crop growth grades appears to be a very promising approach. Another problem which may need discussing is we categorized the crop growth condition into three different grades based on the difference in the NDVI relative to the average NDVI, which might not be entirely representative of the true growth condition. It is very difficult to assess the crop growth condition since there exist differences in soil types, sub-regional ecological background and phenology, although NDVI is widely recognized as the best vegetation index for monitoring the condition of crops. However, the use of a long-term remote sensing time-series dataset might better facilitate the classification of winter wheat growth grades. Finally, the winter wheat growth condition could have been affected by many different factors in the HHH Plain during 2011–2012. We did not consider factors such as the effects of different soil types in the area, crop pests and the implementation of control measures to combat pests, or changes in management practices, such as irrigation. Irrigation was applied to winter wheat during the growing season in the study area, especially in arid conditions. In this study, we did not consider the effects of irrigation because most of the winter wheat was not irrigated before the winter of 2011. After the spring, however, there was irrigation of winter wheat in some areas, so the correlations between different growth grades and meteorological factors may have been affected by field management measures.

5. Conclusion

Using the HHH Plain as the study area, we analyzed the dynamic changes in the winter wheat growth condition throughout all phenophases and we explored the effects of meteorological factors on the different growth grades in this area. The results showed that remote sensing technology has many advantages for monitoring the large-scale crop growth in real time. The overall winter wheat growth condition was generally good in the HHH region between 2011 and 2012. However, there were spatiotemporal variations in the winter wheat growth condition. The temporal pattern can be summarized as: "better during the early growth period, worse in the middle, with a good recovery later."

Using correlation analysis, this study demonstrated clearly that the cumulative precipitation and temperature during all phenophases had important effects on winter wheat growth. The cumulative precipitation had the highest correlation with all of the winter wheat growth grades on average, which showed that the cumulative precipitation throughout the entire growing season had the strongest effect on the growth condition, rather than synchronous precipitation. We've got the same results in other winter wheat main growth area — Gansu and Shaanxi provinces. With respect to temperature, the better-than-average growth condition had the most strongly correlation with the synchronous average temperature; the normal growth condition was most strongly correlated with the cumulative temperature; and the worse-than-average growth condition had its highest correlation with the pre-phenophase average temperature.

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