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The observed relationships between wheat and climate in China

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ABSTRACT

Recent changes in climate have had a measurable impact on crop yield in China. The objective of this study is to investigate how climate variability affects wheat yield in China at different spatial scales. First the response of wheat yield to the climate at the provincial level from 1978 to 1995 for China was analysed. Wheat yield variability was only correlated with climate variability in some regions of China. At the provincial level, the variability of precipitation had a negative impact on wheat yield in parts of southeast China, but the seasonal mean temperature had a negative impact on wheat yield in only a few provinces, where significant variability in precipitation explained about 23–60% of yield variability, and temperature variability accounted for 37–41% of yield variability from 1978 to 1995.

The correlation between wheat yield and climate for the whole of China from 1985 to 2000 was investigated at five spatial scales using climate data. The Climate Research Unit (CRU) and National Centers for Environmental Prediction (NCEP) proportions of the grid cells with a significant yield–precipitation correlation declined progressively from 14.6% at 0.5° to 0% at 5° scale. In contrast, the proportion of grid cells significant for the yield–temperature correlation increased progressively from 1.9% at 0.5° scale to 16% at 5° scale. This indicates that the variability of precipitation has a higher association with wheat yield at small scales (0.5°, 2°/2.5°) than at larger scales (4°/5.0°); but wheat yield has a good association with temperature at all levels of aggregation. The precipitation variable at the smaller scales (0.5°, 2°/2.5°) is a dominant factor in determining inter-annual wheat yield variability more so than at the larger scales (4°/5°). We conclude that in the current climate the relationship between wheat yield and each of precipitation and temperature becomes weaker and stronger, respectively, with an increase in spatial scale.

1. Introduction and aims

An increase in atmospheric temperature and carbon dioxide concentration, and altered precipitation under climate change are likely to have impacts on agricultural productivity. Despite ongoing improvements in technology and crop varieties, weather and climate are still the main uncontrollable factors affecting agricultural production (Decker, 1994). An average increase in global surface warming of 0.13 °C per decade has been found over the last 50 years with the last years (1995–2006) being the 12 warmest years (IPCC, 2007). The rising temperature in combination with a change in precipitation in some regions has affected crop yield. Lobell and Field (2007) reported a 0.6–8.9% reduction in mean crop (wheat, rice, maize, barley soybean, sorghum) yield per 1 °C rise in temperature at the global scale. A relative decline of about 17% in corn and soybean yield occurred per 1° rise in the growing-season temperature in the USA from 1982 to 1998 (Lobell and Asner, 2003). Rice grain yield has declined by about 10% for every 1 °C enhancement in the growing-season minimum temperature in the Philippines from 1992 to 2003 (Peng et al., 2004). Therefore, recent changes in climate had a measurable impact on crop yield. This indicates that the current temperature is already close to or above the optimum for maximum crop yields in some regions.

In China, the mean annual surface air temperature has increased by approximately 1.1 °C over the last 50 years; almost 60% of the warming occurred in the most recent 16 years (Ren et al., 2003). An analysis of observations by Tao et al. (2006) showed that the warming trends from 1981 to 2000 have had a negative impact on crop yield at six representative stations (including Tianshui, Changsha, Hefei and Zhengzhou) except at Harbin in northeast China. For example, wheat yield at Tianshui station was reduced by 10.2% for each 1 °C rise in growing-season temperature. The increased temperature trends have impacted on wheat yield in China.

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In addition to changes in mean climate, climate variability affects crop productivity. During the growing season, the variation in temperature and rainfall were demonstrated to be the principal factors influencing corn yield in Missouri from 1895 to 1998 (Hu and Buyanovsky, 2003). The response of variation in crop yield to the climate varies widely among regions, depending on the cropping system, climate and spatial scale. Some studies find that temperature is more important and others find that rainfall is the most important factor. For example, the global analysis of Lobell and Field (2007) found a stronger effect of temperature, possibly because rainfall is not nearly as variable at global scales as it is on local scales. In a monsoon country such as India, rainfall is the key determinant of the productivity of rainfed crops. Challinor et al. (2003) showed that 50% of the variability in groundnut yield on the all-India scale could be explained by the variability in total seasonal rainfall from 1966 to 1995. In contrast, the UK inter-annual climate variability can only account for about 10% of crop yield temporal variability (Landau et al., 1998). In China, agriculture has been negatively impacted by frequent disasters such as droughts and floods, and inter-annual crop yield varies in response to the fluctuation of the East Asian Summer Monsoon (EASM) and El Niño-Southern Oscillation (ENSO). Seasonal climate variability associated with EASM and ENSO explained about 14.4% and 15.6% of the variability in maize yield, respectively, from 1978 to 2002 in Henan Province in central China (Tao et al., 2004). It is possible that the associations between climate variability and crop yield also vary at the different spatial scales, but this topic is still little researched. Cool, moist conditions are most favourable for wheat growth. Wheat is highly vulnerable to climate change and variability (Wheeler et al., 1996). It is therefore important to know how climate variability affects wheat yield to understand the response of crops to the climate at different spatial scales.

The objective of this study is to investigate the observed relationships between wheat yield and climate under the current climate in China. An analysis of the observed trends in wheat yield and yield variability at the provincial level over China is presented in Section 3.1. The correlation between wheat yield, rainfall and temperature at the provincial level will be analysed in Section 3.2.1. The crop–climate relationships in China were firstly analysed using two approaches: first-differences (the difference in values from one year to the next) and removal of a linear time trend. The responses of wheat yield to rainfall and temperature at the 0.5°, 2°/2.5° and 4°/5.0° scales are shown in Section 3.2.2 to understand how yield variability is correlated to climate variability at different spatial scales. Finally, the conclusions are presented in Section 4.

2. Materials and methods

China is divided into provinces that are comprised of a number of counties. The area of the provinces is in the range of 34,000 km^2 in Hainan to 1,200,000 km^2 in Xizang (Tibet) and each province includes 4–120 counties. The area per county varies from 56 km^2 to 270,000 km^2. The county level wheat yield data (spring and winter wheat combined) from 1985 to 2000 covering the major wheat planting area of China were calculated from the statistical wheat plantation area and production data at the county level in China. The county level wheat plantation area and production data in China are available from the Climatic Data Centre, Meteorological Information Centre, China Meteorological Administration in Beijing. The provincial level wheat yield (spring and winter wheat combined) for 1978–2000 was obtained from the China Statistical Yearbook (ZGTJNJ, 1979–2001). The spatial distribution of the spring wheat and winter wheat planting regions in China is shown in Fig. 1. The wheat plantation area is divided into spring wheat and winter wheat areas, based on wheat agro-ecological production zones in China (Fig. 1) for analysing the crop and climate correlations. In China, the growing season for spring wheat is normally from April to September, and October to May for winter wheat.

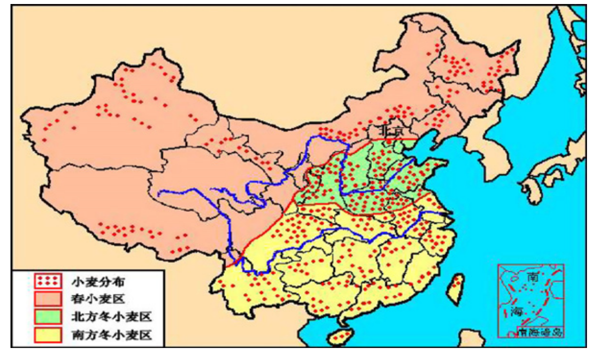

Fig. 1. The spatial distribution of spring wheat and winter wheat planting regions in China. Red points are distribution of wheat, pink areas are spring wheat region, green and yellow areas are winter wheat regions (http://www.dlpd.com/Photo/UploadPhotos/200703/20070327092908652.jpg). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of the article.)

The 0.5° CRU climate data from the Climate Research Unit (CRU TS 2.1; Mitchell and Jones, 2005) were aggregated to the provincial level to match the observed provincial level wheat yield. The provincial level yields were linearly regressed against time ($p < 0.05$) in 27 out of 29 provinces in China. Yield anomalies at the provincial level were obtained by removing the linear yield trend from the yield. The correlation between wheat yield anomalies and seasonal mean temperature and total precipitation at the provincial level was analysed using two different detrending methods: (1) removal of a linear time trend of yield, (2) the first-difference time series for yield and climate (i.e. the difference in values from one year to the next; Lobell et al., 2005; Nicholls, 1997; Lobell and Field, 2007).

The observed climate data, including monthly mean precipitation and temperature (minimum and maximum) at the 0.5° × 0.5° scale for 1978–2000 were obtained from the CRU TS 2.1 (Mitchell and Jones, 2005). In order to evaluate the crop/climate relationships at different spatial scales, 2° × 2° and 4° × 4° climate data were obtained by aggregating 0.5° × 0.5° CRU data. For examining the consistency in crop–climate relationships for different climate data, the NCEP (National Centers for Environmental Prediction) Reanalysis data (http://www.cdc.noaa.gov/data/reanalysis/) covering the seasonal monthly mean temperature and total precipitation at the 2.5° × 2.5° scale were also used for analysing the crop–climate relationships. 5° × 5° climate data were obtained by aggregating 2.5° × 2.5° NCEP data. The county level wheat yields were aggregated into 0.5°, 2°/2.5° and 4°/5° scale yields using software ArcGIS to match the climate data. Yield and climate correlations at different spatial scales were evaluated using the first-difference time series for yield and climate because the wheat yields at the 0.5°, 2°/2.5° and 4°/5° scales did not fit the linear regression well in some grid cells.

3. Results

3.1. Yield, yield trends and yield variability

Fig. 2 shows that China's observed national wheat yield obtained from FAO increased dramatically from 1845 kg ha^{-1} in 1978 to 3542 kg ha^{-1} in 1995 with a linear trend ($r = 0.94$, $p < 0.001$). The national wheat yield increased at an average rate of 89 kg ha^{-1} year^{-1} from 1978 to 1995. Rozelle and Huang (2000) reported that in China the increase in wheat yield from 1976 to

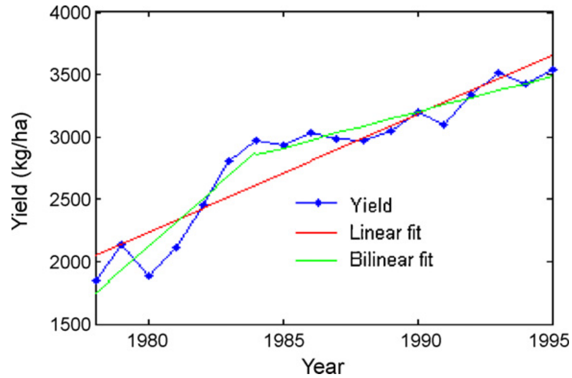

Fig. 2. Time series of national wheat yield (kg ha^{-1}) in China from 1978 to 1995, linear trend (red line) and two separate linear fits (green line). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of the article.)

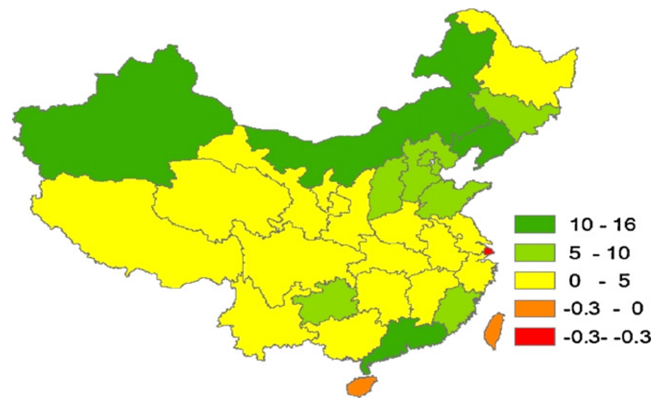

Fig. 4. The provincial level wheat yield change rate (% $year^{-1}$) from 1978 to 1995, in China.

1995 was mainly attributed to improvements in technology from research expenditure (62%), institutional changes (36%) and irrigation investment (9%), whereas the decrease in land (−0.4%), labour price (−8%) and erosion (−2%) had an adverse impact on yield growth. After 1984, the variation in the national wheat yield (standard deviation of yield is 227 kg ha^{-1}) became lower than that before 1984 (standard deviation of yield is 439 kg ha^{-1}), which was probably caused by improvements in technology around 1984 offsetting the negative impact of environmental stress, as indicated by Rozelle and Huang (2000). An analysis by Rozelle and Huang (2000) showed that after 1984 the increase in the wheat production proportion that accounts for irrigation and plant genetic research by introducing semi-dwarf varieties, greatly improved. Two separate (pre-1984 and after 1984) linear fits ($r = 0.975$, $p < 0.001$) to the national yield are better than the linear regression ($r = 0.94$, $p < 0.001$) over the whole time period (1978–1995).

Both the average provincial wheat yields and yield trends differ greatly among provinces. The average provincial yield ranges from 940 kg ha^{-1} in the south of China to nearly 4299 kg ha^{-1} in parts of east China and Xizang (Fig. 3a). The trends of yield against time between 1978 and 1995 were fitted using linear regression, and the slope of the regression line is termed the yield trend. In 27 out of 29 provinces, linear regressions fit these trends in yields well ($p < 0.05$). Positive yield trends (Fig. 3b) were observed in 28 out of 29 provinces, at an average rate of from 7.0 kg ha^{-1} $year^{-1}$ to 217 kg ha^{-1} $year^{-1}$, except in Shanghai city, where there was a slightly decreased rate of 13 kg ha^{-1} $year^{-1}$. In the whole of China, the provincial wheat yield changed at the rate of −0.33% $year^{-1}$ to 13.80% $year^{-1}$ between 1978 and 1995 (Fig. 4).

A small increase in yield might be caused by cold stress in northeast China, drought stress and the limitation of nutrients in northwest China, and excess moisture damage and shortage of solar radiation in south China. The yield trends in Shandong, Hebei provinces and Xinjiang and the Tibetan autonomous regions are higher than those in the other provinces. The high yield trends are generally the result of improved technology and favourable environmental conditions. However, a significant spatial variation in the yield trend is shown, which indicates the fact that the improvement in wheat yield is affected not only by advances in technology but also by the environmental conditions, because changes in technology are uniform across the country.

3.2. *The observed relationships between crop and the climate*

3.2.1. *Crop–climate correlation at the provincial level*

The crop–climate relationships at the provincial level from 1978 to 1995 were analysed using two approaches: first-differences and removal of a linear time trend. The response of crop yield to the climate shows a different spatial pattern with these two methods (Fig. 5). The two yield–rainfall correlations are significantly different at the 10% significance level only in 1 out of 29 provinces. When the crop–climate correlation is estimated by the first-differences method, the rainfall has a significant ($p < 0.05$) negative impact on the wheat yield in Qinghai and four provinces in southeast China, and a beneficial ($p < 0.05$) effect on yields in the Tibet Autonomous Region (Fig. 5a). In these six provinces, the variability of precipitation can explain about 23% of yield variability in Qinghai to 60% of yield variability in Guangdong province from 1978 to 1995. In contrast, only in two provinces in southeast China, a significant negative correlation ($p < 0.05$) between yields and rainfall is found with the method of removing a linear trend (Fig. 5b). In these two provinces, precipitation variability can account for about 32–47% of wheat yield variability between 1978 and 1995.

The yield–rainfall correlation coefficients from the first-differences ($r = 0.63$, $p < 0.001$) and removal of a linear time trend ($r = 0.59$, $p < 0.001$) methods linearly decrease with total seasonal rainfall (Fig. 6a). In drought areas, the yield positively correlates

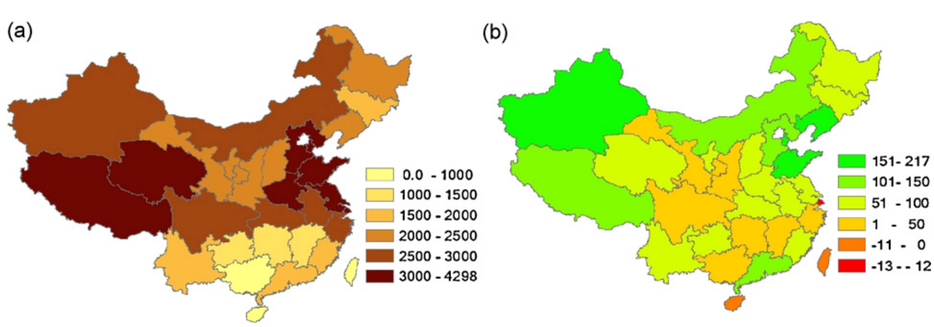

Fig. 3. (a) Average provincial wheat yield (kg ha^{-1}) from 1978 to 1995 in China, (b) trends of provincial wheat yield (kg ha^{-1} $year^{-1}$), 1978–1995, in China.

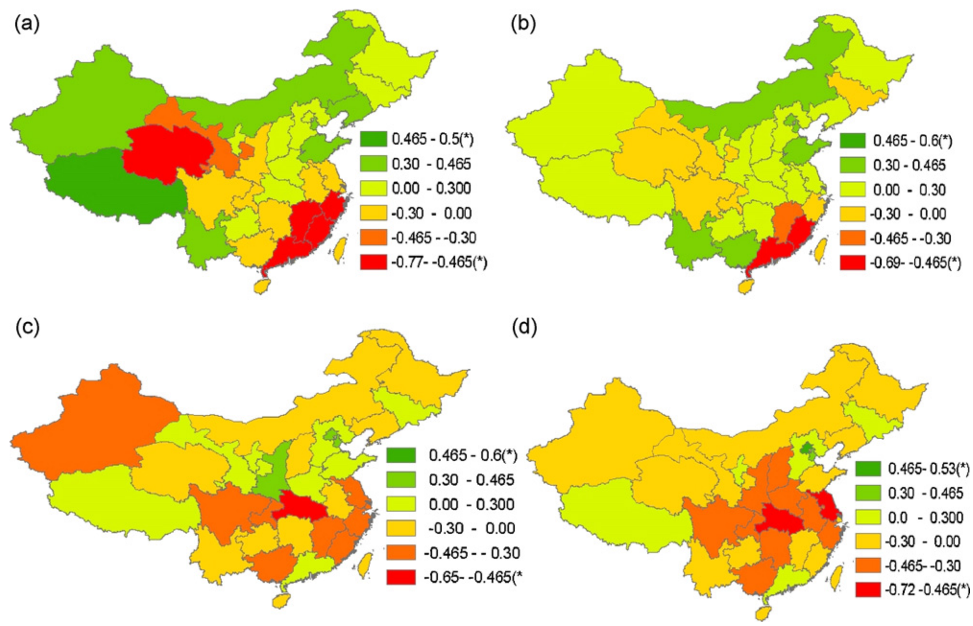

Fig. 5. The correlation coefficient between wheat yield and climate at the provincial level for 1978–1995 using different detrending methods: (a) and (b) yield–rainfall correlation (c) and (d) yield–temperature correlation, (a) and (c) using the method of first-differences, (b) and (d) using the method of removal of a linear time trend.

with the total seasonal rainfall. When the total seasonal rainfall is above 750 mm, there is a significant negative correlation between the yield and rainfall in some areas of south China.

When using the methods of first-differences and removal of a linear time trend, these yield–temperature correlations at the provincial level have different strengths only in 1 out of 29 provinces at the 10% significance level. There is a significant negative correlation ($r = -0.646$, $p < 0.05$) between the yield and seasonal mean temperature in Hubei province using the methods of first-differences (Fig. 5c). Also, the seasonal mean temperature has a negative impact on the wheat yield in Hubei and Jiangsu provinces (Fig. 5d) with the method of removal of a linear time trend. In these two provinces, the variability of temperature explains a 37–41% of yield variability from 1978 to 1995. Overall, at the provincial level there is a weak correlation between the wheat yield and seasonal temperature in most of the provinces of China. The yield–temperature correlation coefficients have no significant correlation ($p > 0.05$) with the seasonal mean temperature (Fig. 6b).

Across China, the provincial average wheat yield shows a significant negative response ($r = -0.53$, $p < 0.05$) to the total seasonal rainfall (Fig. 7a). Despite the total seasonal rainfall is low in some provinces of the north China plain, there are higher yields maybe because wheat yield depends on irrigation in this region. Over China, in the provinces where there are higher temperatures, there are lower yields ($r = -0.62$, $p < 0.001$; Fig. 7b). The warmer regions are also the humid areas ($r = 0.56$, $p < 0.05$; Fig. 7c). This indicates that excess rainfall, a higher temperature and the related shorter growth duration are the main reasons of lower provincial wheat yields in China.

3.2.2. Crop–climate correlations at the 0.5°, 2°/2.5° and 4°/5° scales

The responses of first-differences of yield to first-differences of seasonal total precipitation and seasonal mean temperature from 1985 to 2000 at the 0.5°, 2° and 4° scales are shown in Figs. 8–10. The responses of wheat yield to the seasonal total precipitation show different patterns among different scales. At the 0.5° scale, in 104 out of 1315 grid cells, the first-differences of yield have a significant positive correlation ($r = 0.52$–0.9, $p < 0.05$) with the first-differences of total seasonal rainfall (Fig. 8a) in some areas of southeast, south and north China. In 88 out of 1315, a significant negative yield and rainfall correlation ($r = -0.52$ to -0.73, $p < 0.05$) is found at the 0.5° scale (Fig. 8a) in some grid cells of east China, where the yield is probably restricted by waterlogging and water-related diseases or the yield is affected by irrigation. In northwest China where water resources are lacking and water stress is the main constraint that limits wheat production. However, there is a negative correlation between rainfall and wheat yield in some grid cells of northwest

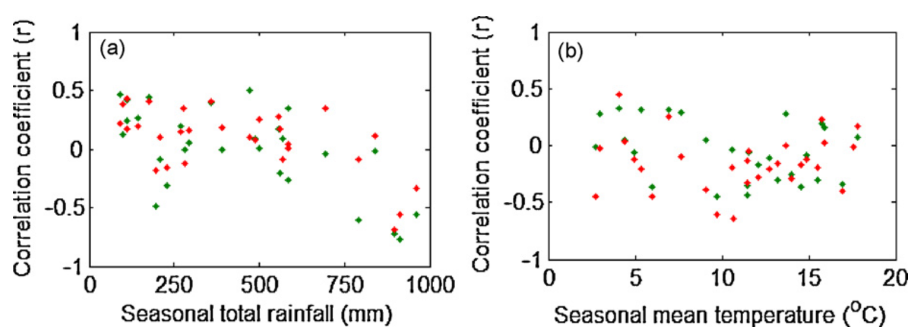

Fig. 6. The correlation between wheat yield and climate at the provincial level for 1978–1995 using the method of first-differences (green points) and removal of a linear time trend (red points): (a) yield–rainfall correlation against seasonal total rainfall, (b) yield–temperature correlation against seasonal mean temperature. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of the article.)

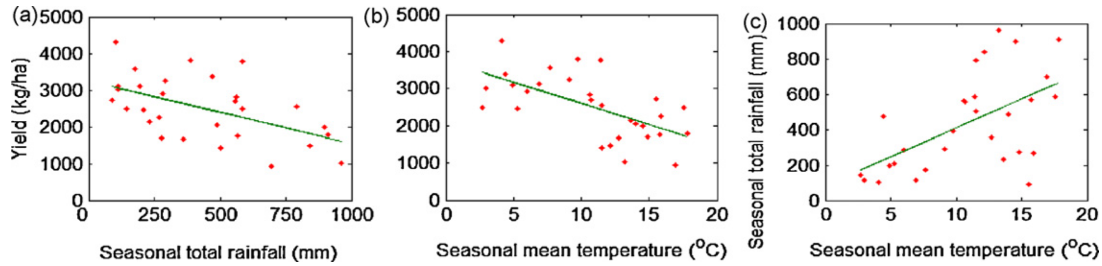

Fig. 7. (a) Provincial average yield against average total seasonal rainfall for 29 provinces during 1978–1995, (b) provincial average yield against average seasonal mean temperature for 29 provinces during 1978–1995, (c) provincial average total seasonal rainfall against average seasonal mean temperature for 29 provinces during 1978–1995.

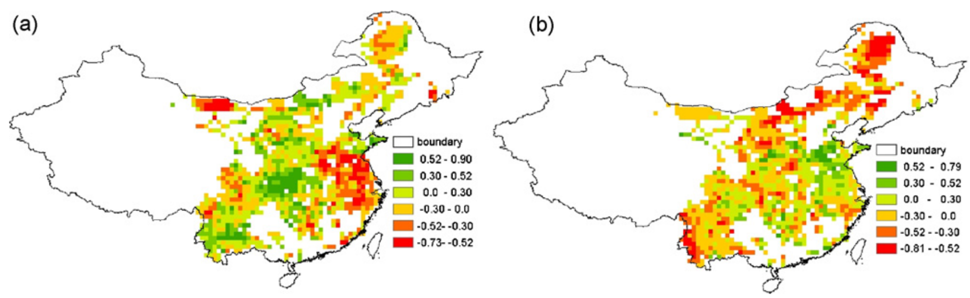

Fig. 8. (a) The correlation between first-differences of yield (kg ha^{-1}) and first-differences of seasonal total precipitation (mm) from CRU, (b) the correlation between first-differences of yield (kg ha^{-1}) and first-differences of seasonal mean temperatures (°C) from CRU for 1985–2000 at the 0.5° scale (grid cells in dark red and dark green show a significant correlation with $p < 0.05$). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of the article.)

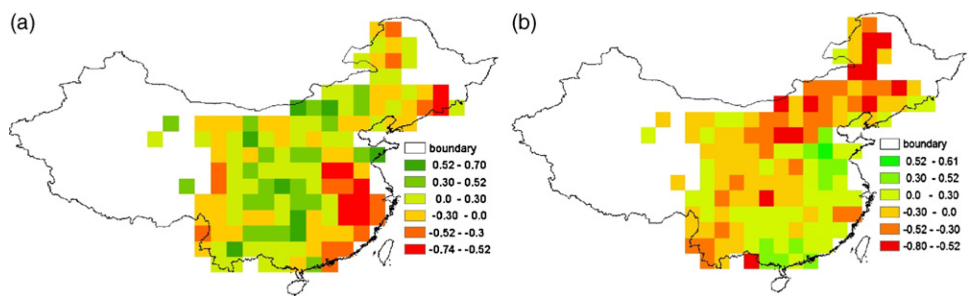

Fig. 9. (a) The correlation between first-differences of yield (kg ha^{-1}) and first-differences of seasonal total precipitation (mm) from CRU, (b) the correlation between first-differences of yield (kg ha^{-1}) and first-differences of seasonal mean temperatures (°C) from CRU for 1985–2000 at the 2° scale (grid cells in dark red and dark green show a significant correlation with $p < 0.05$). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of the article.)

China probably because in those fields where the irrigation systems are perfect or inaccurate estimates of rainfall from CRU data due to limited rainfall gauge station in that region.

At the 2° scale, the precipitation signal is weaker than that at the 0.5° scale in south China, southwest China and northwest China (Fig. 9a, Table 1). There is a significant positive (first-differences) yield–precipitation correlation ($r = 0.52$–0.7, $p < 0.05$) in 8 out of 140 grid cells, and a significant negative correlation ($r = -0.52$ to -0.74, $p < 0.05$) in 9 out of 140 grid cells at the 2° scale. In contrast, at the 4° scale the first-differences of yield show a significant correlation with the first-differences of precipitation in only two grid cells (Fig. 10a). The percentage of grid cells significant for the correlation between yield and precipitation from CRU is from 14.6% at the 0.5° scale to 4.9% at the 4° scale (Table 1). Similarly, the percentage of grid cells significant for the relationship between yield and precipitation from NCEP declined from 7.4% at the 2.5° scale to 0%

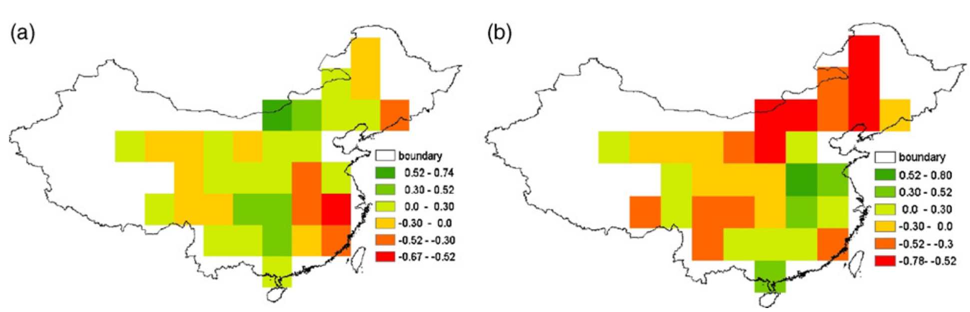

Fig. 10. (a) The correlation between first-differences of yield (kg ha^{-1}) and first-differences of seasonal total precipitation (mm) from CRU, (b) the correlation between first-differences of yield (kg ha^{-1}) and first-differences of seasonal mean temperatures (°C) for 1985–2000 at the 4° scale (grid cells in dark red and dark green show a significant correlation with $p < 0.05$). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of the article.)

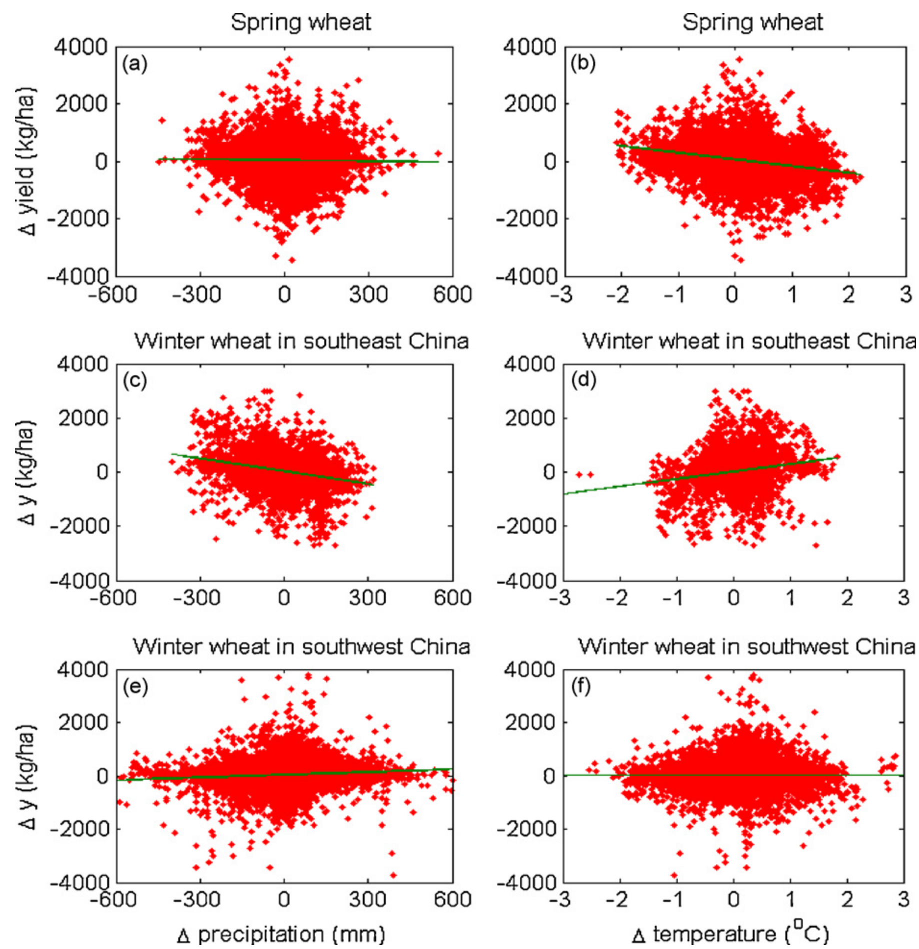

Fig. 11. Scatter plots of the first-differences of wheat yield and the first-differences of seasonal mean temperatures and seasonal total precipitation at the 0.5° scale from 1985 to 2000 in China; the green lines show the best-fit linear regression. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of the article.)

at the 5° scale. This indicates that the impact of precipitation on crop yields becomes weaker with increasing spatial scale. A relatively coarse scale ignores the highly detailed crop–precipitation relationship. The precipitation variable at the smaller scale (0.5°, 2°/2.5°) is a more dominant factor in determining inter-annual wheat yield variability than at the larger scale (4°/5°).

The response of the first-differences of wheat yield to the first-differences of temperature from 1985 to 2000 at the 0.5°, 2° and 4° scales are shown in Figs. 8–10b. Overall, the response of the first-differences of wheat yield to the first-differences of temperature at the 0.5° scale shows a similar spatial distribution pattern to those at the 2° and 4° scales in north China and east China. However, in a few grid cells of south China the positive relationship between crop and temperature at the 0.5° is not found at the 2° and 4° scales. The first-differences of seasonal mean temperature are negatively correlated with the first-differences of yield in some areas of north China and for few grid cells in south China, and are positively correlated for grid cells in East China (Figs. 8–10b).

At the 0.5° scale, in 123 out of 1315 grid cells, there is a significant negative correlation ($r = -0.52$ to -0.79, $p < 0.05$) between the first-differences for seasonal mean temperature and wheat yield, and a significant positive correlation in 31 grid cells (Fig. 8b). In contrast, the first-differences of temperature show a significant negative correlation ($p < 0.05$) with the first-differences of yield in 13 out of 140

Table 1
A comparison of the percentage (%) of grid cells that are significant at the 5% significance level for the relationships between wheat yield and climate from CRU and NCEP for China from 1985 to 2000 (using the method of first-differences).

	Data source	Scale	Number of grid cells significant	Total number of grid cells	Percent of grid cells significant (%)
Prec-yield	CRU	0.5°	192	1315	14.6
		2°	17	140	12.1
		4°	2	41	4.9
	NCEP	2.5°	7	94	7.4
		5°	0	25	0
T-yield	CRU	0.5°	154	1315	11.7
		2°	19	140	13.6
		4°	8	41	19.5
	NCEP	2.5°	9	94	9.6
		5°	4	25	16

Prec – growing-season total precipitation; *T* – growing-season mean temperature.

grid cells at the 2° scale, and in 6 out of 41 grid cells at the 4° scale (Figs. 9b and 10b). At the 4° scale the negative impact of temperature is much more widespread. At the 2° and 4° scales, only in one grid cell there is a significant positive correlation between the first-differences for temperature and yield. The percentage of grid cells with a significant correlation between yield and temperature increases from 11.7% at the 0.5° scale to 19.5% at the 4° scale, which is consistent with the relationships (percentage of grid cells significant from 9.6% at the 2.5° scale to 16%) between yield and temperature from NCEP (Table 1). In contrast to precipitation, the impact of temperature on crop yield is greater at the larger scale (4°/5°) than at the smaller scale (0.5°, 2°/2.5°); with the increase in spatial scale, the signal of temperature increases.

To further assess the impact of the climate on wheat yield variability over China, the response of the first-differences of wheat yield to the first-differences of temperature and precipitation in all 0.5° grid cells from 1985 to 2000 were analysed (Fig. 11). The first-differences of both winter wheat yield ($r = 0.096$, $p < 0.01$) in southwest China (Fig. 11e) and spring wheat yield ($r = 0.013$, $p = 0.27$: Fig. 11a) show a weak correlation with the first-differences of total seasonal rainfall. However, the total seasonal precipitation has a negative ($r = -0.26$, $p < 0.001$) impact on winter wheat yield in southeast China (including grid cells in Shandong, Henan, Jiangsu, Anhui, Zhejiang provinces and Shanghai city, Fig. 11c) maybe due to waterlogging in some grid cells. In Hebei, Shandong, Henan, Jiangsu and Anhui provinces, and Beijing and Tianjin, the irrigated winter wheat area accounts for 71% of winter wheat sown areas in 2000 (Fischer, 2005).

For spring wheat, the first-differences of yield linearly decrease ($r = -0.254$, $p < 0.001$) in response to an increase in the first-differences of seasonal mean temperature (Fig. 11b). Each 1 °C rise in seasonal mean temperature has reduced spring wheat in China by about 9.3%. This value is close to the 10.2% of reduction in spring wheat for each 1 °C rise in the growing-season temperature at Tianshui station in China between 1981 and 2000 from Tao et al. (2006), but greater than the observed global mean reduction in wheat yield (3.2–8.4%) reported by Lobell and Field (2007). In contrast, an increase in the seasonal mean temperature has a positive impact ($r = 0.19$, $p < 0.001$) on winter wheat yields in southeast China. In this region, winter wheat increased by 7.8% for each 1 °C increase in the growing-season temperature. Similarly, a positive correlation between temperature and wheat yield in southeast China between 1979 and 2000 was found by You et al. (2009). In southwest China, the temperature has no significant impact ($r = 0.01$, $p = 0.89$) on winter wheat yields (Fig. 11f).

4. Conclusions

In China, national level wheat yields increased at an average rate of 89 kg ha^{-1} year^{-1} from 1978 to 1995, mainly due to improvements in technology, institutional changes and irrigation investment. However, the average wheat yield, yield trends and yield variability showed large variations across China. Positive wheat yield trends were found in most of the provinces at an average rate of from 7.0 kg ha^{-1} to 217 kg ha^{-1}, except in Shanghai city. However, a large spatial variation in yield trends was observed. This highlights the fact that the increased wheat yield depends on both the advances in technology and the environmental conditions.

When the correlation between wheat yield and climate at the provincial level was estimated using the two methods, first-differences and removal of a linear time trend, the two correlations were significantly different only in 1 out of 29 provinces (Fig. 5) at the 10% significance level. It was consistent that rainfall had a significant ($p < 0.05$) negative impact on wheat yield in some provinces of southeast China (Fig. 5a and b), and the precipitation variability explained about 23–60% of yield variability from 1978 to 1995. The seasonal mean temperature had a negative impact on wheat yield only in a few provinces (Fig. 5c and d), and the variability of temperature accounted for 37–41% of yield variability between 1978 and 1995. Overall, there was a weak correlation between provincial wheat yield and seasonal climate in most of the provinces of China.

The responses of the first-differences of yield to the first-differences of seasonal total precipitation showed different spatial distribution patterns at the different scales. For the climate data from both CRU and NCEP, the percentage of grid cells significant for the yield–precipitation correlation from 1985 to 2000 declined from the smaller scales (14.6% at the 0.5° scale; 12.1% at the 2° scale/7.4% at the 2.5° scale) to the larger scales (4.9% at the 4° scale/0% at the 5° scale) (Table 1). The precipitation variable at the smaller scales (0.5°, 2°/2.5°) is a dominant factor in determining inter-annual wheat yield variability more so than at the larger scales (4°/5°). The impact of precipitation on crop yield became weaker with the increase in spatial scale. The study of Zhang et al. (2008) found that correlations between rice yield and temperature switched signs around 1980 because more irrigation was introduced. Rozelle and Huang (2000) also showed that after 1984 wheat production greatly improved due to an increase in irrigation and crop research which encouraged the use of semi-dwarf varieties. In this study, the period from 1985 to 2000 is short enough that technology improvement is not a huge issue affecting the crop and climate correlation.

Over China, at the 0.5° scale the response of wheat yield to seasonal temperature from 1985 to 2000 showed a similar spatial distribution pattern as those at the 2° and 4° scales in north China and east China. An increase in the seasonal mean temperature has had a negative impact on wheat yield in north China when examined at the 0.5°, 2°/2.5° and 4°/5° scales. In addition, a positive impact of temperature was found in some grid cells for east China. For the climate data from both CRU and NCEP, the percentage of grid cells significant for the yield and temperature correlation increased from the smaller scales (1.9% at the 0.5° scale; 13.6% at the 2° scale/9.6% at the 2.5° scale) to the larger scales (19.5% at the 4° scale/16% at the 5° scale) (Table 1). In contrast to precipitation, the impact of temperature on crop yield is greater at the larger scale (4°/5°) than at the smaller scales (0.5°, 2°/2.5°).

At the regional level, the seasonal total precipitation from 1985 to 2000 has a weak correlation with both winter wheat yield ($r = 0.096$, $p < 0.01$) in southwest China (Fig. 11e) and spring wheat yield ($r = 0.013$, $p = 0.27$: Fig. 11a) of China. However, the total seasonal precipitation negatively ($r = -0.26$, $p < 0.001$) correlated with winter wheat yield in southeast China (Fig. 11c). From 1985 to 2000, an increase in seasonal mean temperature has had a negative impact on spring wheat yield of China. Each 1 °C rise in seasonal mean temperature has reduced spring wheat in China by about 9.3%. In contrast, an increase in seasonal mean temperature has a positive impact ($r = 0.19$, $p < 0.001$) on winter wheat yield of southeast China. In this region, winter wheat increased by 7.8% for each 1 °C increase in the growing-season temperature.

As a result, it was concluded that wheat yield variability was correlated with climate variability under the current climate in some regions of China. The yield variability showed a higher association with precipitation at small scales (0.5°, 2°/2.5°) than at the larger scale (4°/5°), but with temperature at all levels of aggregation. As shown by Challinor et al. (2003), for larger averaging areas the correlation between groundnut and rainfall is lower and less robust (over time) than in the subdivisional case. Currently, the high temperature has a negative impact on wheat productivity in some regions of China at the small scale, large scale and regional level. At the larger scale the variability of wheat yield is dominated by the temperature, in contrast to precipitation at the small scale.

Similarly, Lobell and Burke (2008) showed that at regional scales temperature uncertainties were more important than precipitation responses for most regions. Overall, the response of crop to climate depends on the scale of interest. Models of future impacts may be more sensitive to temperature at the larger spatial scale, but be more sensitive to rainfall at the smaller scale. It indicates that a strong (or very weak) correlation at one scale should not be assumed to translate to other scales.

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