Climate–crop yield relationships at provincial scales in China and the impacts of recent climate trends

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ABSTRACT: Understanding climate–yield relationships and the impacts of recent climate trends on crop productivity on a large scale is an important step in predicting regional agricultural production. In this study we investigated climate–crop relationships, recent trends in seasonal climate (maximum and minimum temperatures, diurnal temperature range and precipitation) and their impacts on the yields of major crops (i.e. rice, wheat, maize and soybean) at provincial scales throughout China over the last few decades. We found that major crop yields were significantly related to growing season climate in the main production regions of China, and that growing season temperature had a generally significant warming trend. Due to the trends in growing season climate, total rice production in China was estimated to have increased by 3.2×10^5 t decade^{-1} during the period 1951–2002; total production of wheat, maize and soybean changed by -1.2×10^5, -21.2×10^5 and 0.7×10^5 t decade^{-1}, respectively, during 1979–2002. The warming trend increased rice yield in northeast China and soybean in north and northeast China; however, it decreased maize yield in 7 provinces (autonomous region or municipality) and wheat yield in 3 provinces. Our analysis presents the general response patterns of regional agricultural productivity to seasonal climate variability and change over the last few decades. Crop response mechanisms to local seasonal climate change (and variability) need further investigation to better understand the patterns and predict future consequences of climate change and variability on regional agricultural production.

KEY WORDS: Agriculture · China · Climate change · Food security · Impacts · Yield variability

1. INTRODUCTION

The potential impacts of future climate change on regional agricultural production have attracted considerable attention. Extensive studies have projected the potential impacts of future climate change on agricultural productivity by driving crop models (process-based or statistical) with global climate model outputs (e.g. Rosenzweig & Parry 1994, Tao et al. 2008). To evaluate future climate impacts on crop productivity, the impacts of climate over the past few decades need to be assessed (Nicholls 1997). Climate–yield relationships are quite complex; nevertheless, robust relationships can be established between regional atmospheric circulation, surface climate and crop productivity (e.g. Iglesias & Quiroga 2007, Jones & Goodrich 2008). Climate–

yield relationships are also scale-dependent. While detailed records on crop performance and weather at observation stations are valuable for investigating crop response mechanisms to weather (e.g. Peng et al. 2004, Tao et al. 2006), large-scale statistical data and regional climate datasets are important for investigating general response patterns of crop production to climate change and variability (e.g. Lobell 2007, Lobell et al. 2008).

Spatial patterns of seasonal climate and their impacts on crop productivity at provincial or regional scales are important for understanding vulnerability and adaptation of regional agricultural production to climate change. Here, we systematically investigate climate–yield relationships and the impacts of climate trends over the last few decades on major crop yields at provincial scales throughout China in a spatially explicit way.
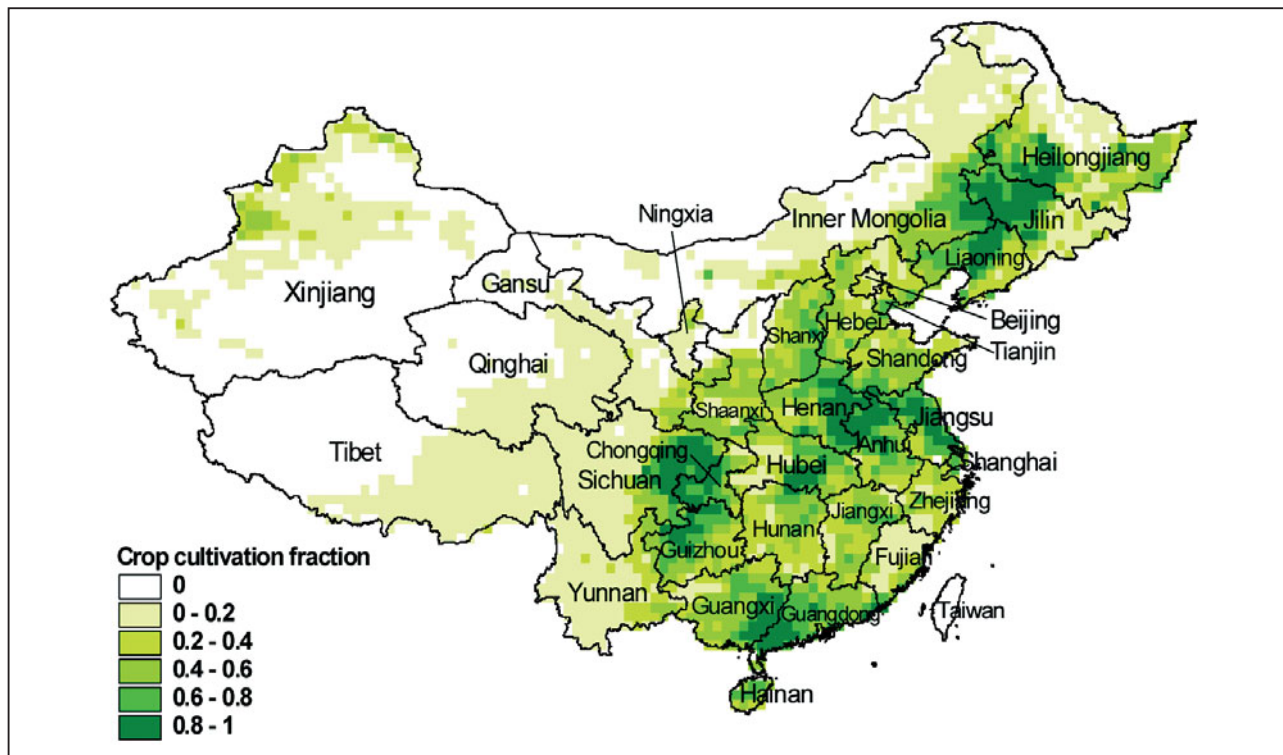
Fig. 1. Crop cultivation fraction and provinces (autonomous region or municipality) in China, around 2000

2. DATA AND METHODS

Areas sown (Fig. 1) to wheat, maize and soybean by province in China from 1979 to 2002 and time series of yields were obtained from the China Agricultural Yearbook (China Agriculture Press, Beijing 1980–2003 [annual]). For rice, such data from 1950 to 2002 were obtained from the world rice statistics of the International Rice Research Institute (IRRI), sources of which were the China Agricultural Yearbook, the Rice Economy Database of China National Rice Institute (unpublished database, National Rice Research Institute, Hangzhou, China) (for the period 1950–1985), 50 Years Rural Statistics of New China (China Statistics Press, Beijing, 1999) and the China Rural Statistics Yearbook 2001–2005 (China Statistics Press, Beijing, 2002–2006) (for the period 1986–2004).

Monthly fields of maximum temperature (T_m), minimum temperature (T_n), diurnal temperature range (DTR) and precipitation (Pre) on 0.5° grids for 1979 to 2002 were obtained from the Climatic Research Unit (CRU, University of East Anglia, UK), Dataset CRU TS 2.1 (Mitchell & Jones 2005). Spatially weighted averages of the CRU data were computed for each crop and each province (autonomous region or municipality), with weights defined by the spatial distribution of crop area on 0.5° grids from Frolking et al. (2002) and Qiu et

al. (2002), resulting in crop-specific monthly time series of T_m, T_n, DTR and Pre by province.

Typical cropping system, planting date and growing season (exact to month) for each crop in each province were obtained from historical records (Tao et al. 2006) and CCSA (1989). For each crop in a province, we assumed a similar growing season throughout the study period because the phenology shift due to weather, climate trend or farm management was generally <1 mo over the period (Tao et al. 2006). For the cropping system of double rice, the growing season was defined to cover the growing period of both early and late rice. We further computed the average of each climate variable during the crop growing season by province.

To investigate the climate–yield relationship by province, we used a common approach (Nicholls 1997, Lobell & Field 2007) based on the first-difference time series for yield (ΔYield) and climate (i.e. year to year changes) $(\Delta T_m, \Delta T_n, \Delta DTR$ and ΔPre$)$. This approach avoids the confounding influence of long-term variations such as changes in crop management. The relationships between ΔYield and ΔT_m, ΔT_n, ΔDTR and ΔPre were evaluated using Pearson correlation analyses. Due to the limited historical sample size, a bootstrap resampling approach was used to estimate the sampling uncertainty associated with the derived
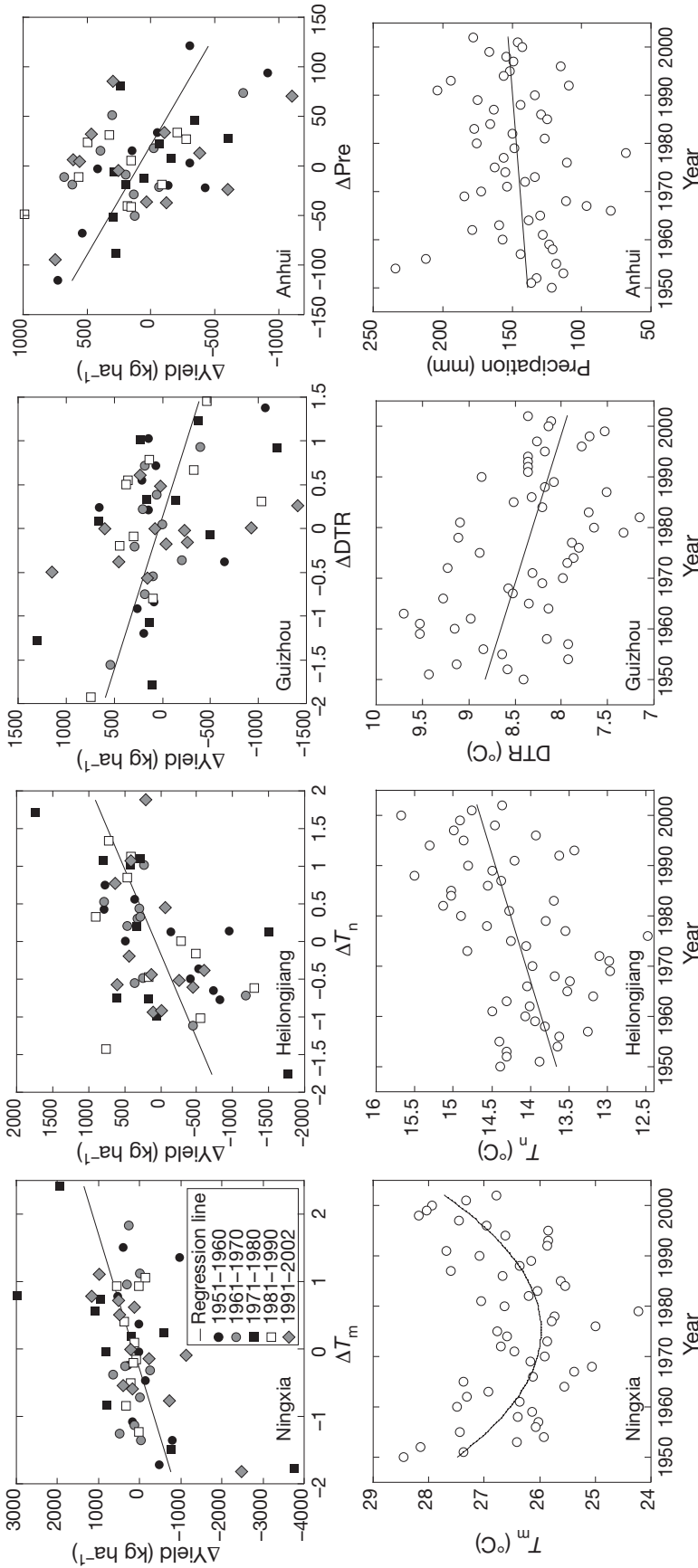
Fig. 2. Top: ΔYield for rice with year to year changes in max. temperature (ΔT_m), min. temperature (ΔT_n), diurnal temperature range (ΔDTR) and precipitation (ΔPre) during the growing season in selected provinces (autonomous region or municipality), and best-fit linear regressions. Bottom: trends in the corresponding climate variables

regression coefficients. Specifically, the original data was resampled with replacement, a new regression model was computed, and this was repeated 1000×. The simple linear regression allows identification of the most relevant climate parameter for each crop and province. We also conducted multiple linear regressions (MUL), with ΔYield as the dependent variable, and ΔPre, 2 variables of ΔT_m and ΔT_n, and ΔDTR (decided by the stepping criteria for entry and removal while regressing) as independent variables.

We also investigated the time trends of changes in the climate variables by regression and Kendall's tau statistic. Statistical significance was tested using 2-tailed *t*-test. Finally, we applied the regression models to observed trends in climate variables to estimate the role of climate in recent yield trends, which, together with the areas sown to each crop in 2002, were further used to esti-mate the total crop production change for the whole of China (weighted by sown area).

3. RESULTS

3.1. Climate–yield relationship at the provincial scale

3.1.1. Rice

Among the 23 major provinces that pro-duce rice throughout China; northeast China including Heilongjiang (Fig. 2), Jilin and Liaoning provinces, and Ningxia autonomous region in north China, showed significant positive correlation (p < 0.01) between rice yield and growing season T_m and T_n (Fig. 3). Growing sea-son T_m was also positively correlated to rice yield in Shanghai (p < 0.05), but neg-atively related to rice yield in Guizhou province in south China (p < 0.05). The crop–climate relationship did not appear to change through time. Compared with the yield in 2002, rice yield decreased by 1.3 to 5.8% in Guizhou for each degree increase in growing season T_m. In con-trast, it increased by 3.1 to 9.0% in Ning-xia (Fig. 3). Up to 27% of the variance in
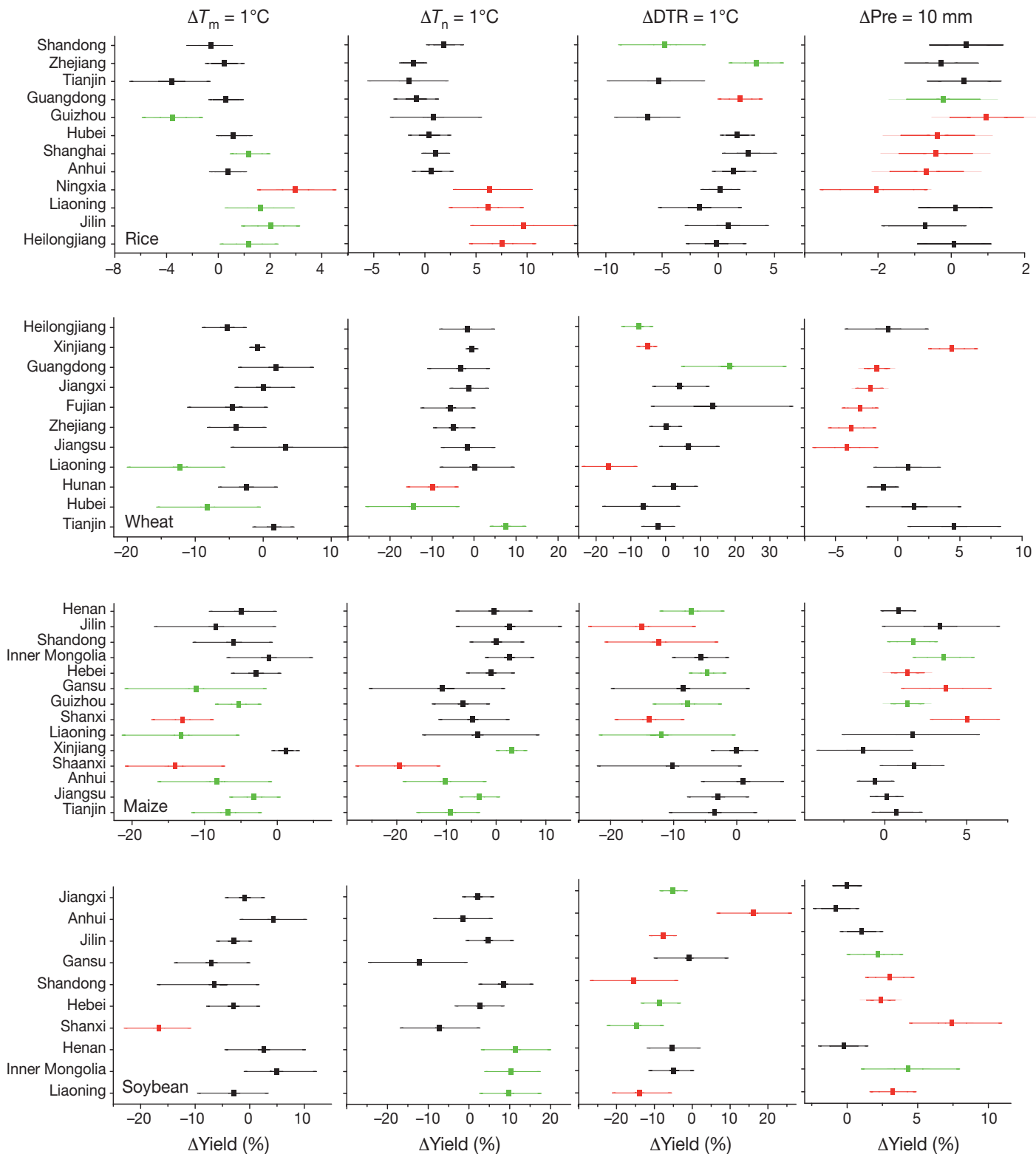
Fig. 3. Estimated coefficients for the response of ΔYield (% of the 2002 yield) to ΔT_m, ΔT_n, ΔDTR and ΔPre in a simple linear regression. Negative (positive) coefficients suggest the negative (positive) correlation between the 2 variables. Red: $p < 0.01$; green: $p < 0.05$; black: $p > 0.05$. Error bars: 90 % CI (5th to 95th percentile) based on bootstrap resampling of historical data with 1000 samples. Only provinces (autonomous region or municipality) where crop yield was significantly related to at least 1 of the 4 climate variables during the growing season are shown

interannual rice yield changes in Ningxia was explained by growing season T_m. The impacts of growing season T_n on rice yield were more pronounced. For example, rice yield significantly increased by 4.6 to 14.6% in Jilin and by 4.5 to 10.7% in Heilongjiang for each degree increase in growing season T_n (Fig. 3). Up to 29% of the variance in interannual rice yield changes in Heilongjiang was explained by growing season T_n.

The impacts of DTR on rice yield were negatively related to those of precipitation (Fig. 3) since DTR is often highly related to solar radiation (Bristow & Campbell 1984), cloud cover and precipitation. DTR was negatively correlated to rice yield in Shandong, but positively related to rice yield in Guangdong and Zhejiang provinces (Fig. 3).

Growing season precipitation was negatively related to rice yield in Anhui (Fig. 2), Ningxia, Shanghai and Hubei (Fig. 3), possibly because frequent precipitation might have lead to insufficient solar radiation and insect infestation. This is in agreement with a previous report that continuous rainy weather during the growing season is unfavourable for rice production in southeast China (Tao & Yokozawa 2005). In contrast, growing season precipitation was positively related to rice yield in the Guizhou and Guangdong provinces. Up to 24% of the variance in interannual rice yield changes in Anhui was explained by growing season precipitation.

3.1.2. Wheat

Among the 26 major provinces that produce wheat throughout China, Liaoning (Fig. 3) and Hubei provinces showed negative correlation between growing season T_m and wheat yield. Wheat yield significantly decreased by 5.9 to 19.8% in Liaoning and 0.6 to 15.4% in Hubei for each degree increase in growing season T_m (Fig. 3).

Growing season T_n was negatively related to wheat yield in Hubei ($p < 0.05$) and Hunan ($p < 0.01$) provinces (Fig. 4), but positively related to wheat
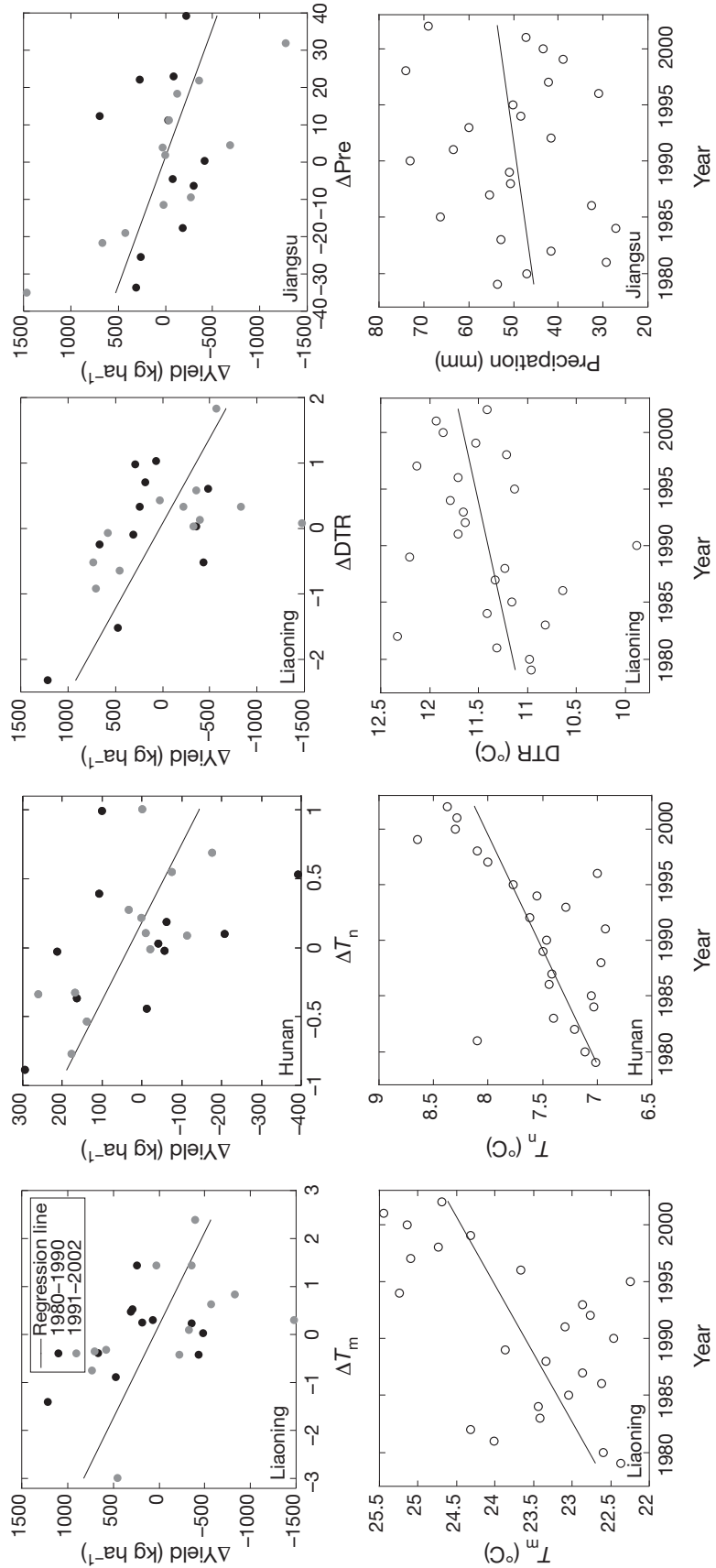

Fig. 4. Top panels: ΔYield for wheat with ΔT_m, ΔT_n, ΔDTR and ΔPre during the growing season in selected provinces (autonomous region or municipality), and best-fit linear regressions. Bottom panels: trends in the corresponding climate variables

Fig. 5. Top panels: ΔYield for maize with ΔT_m, ΔT_n, ΔDTR and ΔPre during the growing season in selected provinces (autonomous region or municipality), and best-fit linear regressions. Bottom panels: trends in the corresponding climate variables
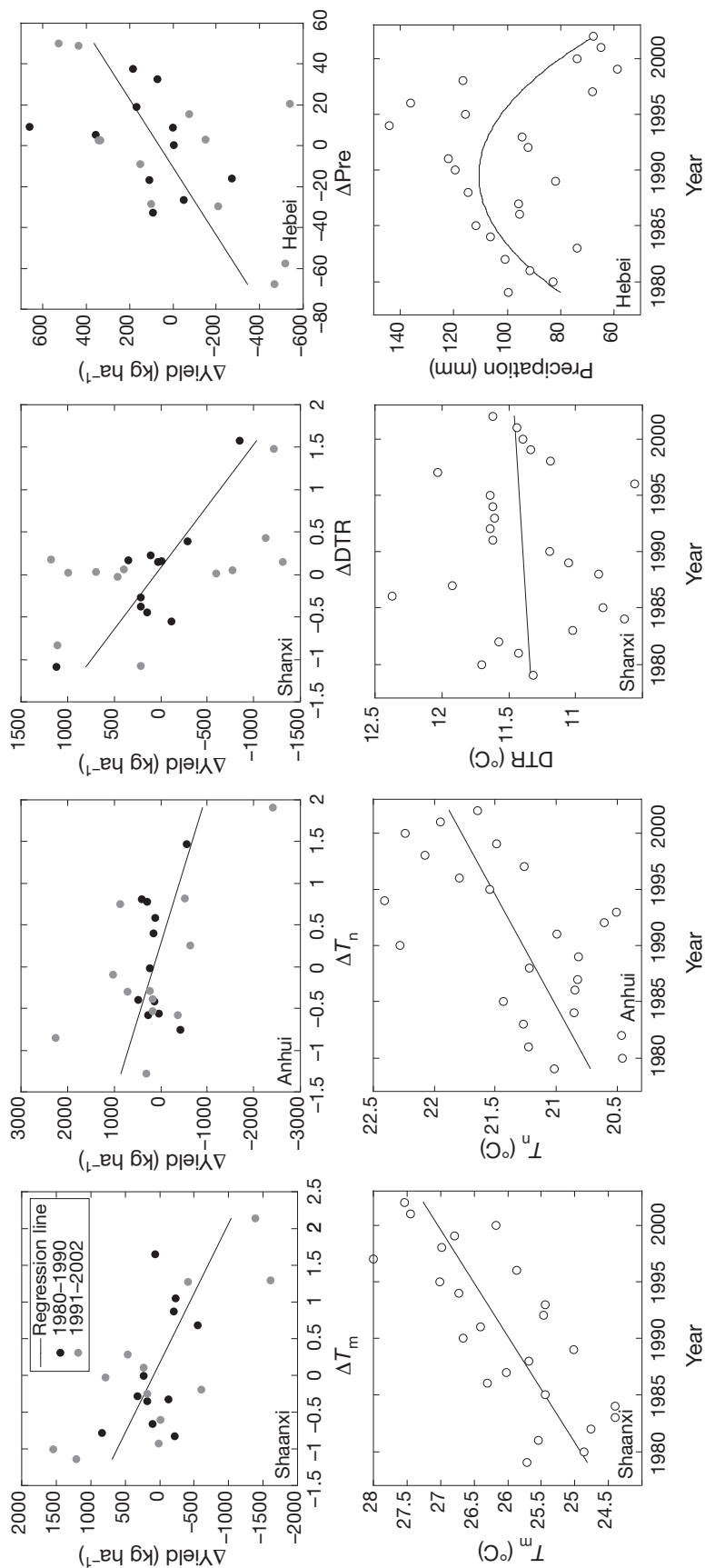
yield in Tianjin (p < 0.05) (Fig. 3). Wheat yield significantly decreased by 3.9 to 25.4 % in Hubei province and by 4.2 to 15.7 % in Hunan province for each degree increase in growing season T_n, but it increased significantly by 4.2 to 12.0 % in Tianjin (Fig. 3).

DTR was negatively related to wheat yield in Heilongjiang and Liaoning (Fig. 4) in the northeast, and Xinjiang in the northwest, but was positively related to wheat yield in Guangdong province in the south (Fig. 3).

Growing season precipitation was negatively related to wheat yield in Jiangsu, Zhejiang, Fujian and Jiangxi in east China, and Guangdong in the south, where annual precipitation is >1000 mm. In contrast, wheat yield in Xinjiang in the northwest, where annual precipitation is <500 mm, was positively related to growing season precipitation (Fig. 3).

3.1.3. Maize

Compared to rice and wheat, maize yields were more sensitive to growing season climate in terms of area and amount of yield change (Fig. 3). Among the 22 major provinces that produce maize throughout China; Liaoning, Tianjin, Shanxi, Gansu, Shaanxi (Fig. 5), Anhui, Jiangsu and Guizhou (Fig. 3), showed negative relation between growing season T_m and maize yield. For example, maize yield significantly decreased by 7.4 to 20.7 % in Shanxi, and by 2.4 to 8.3 % in Guizhou for each degree increase in growing season T_m (Fig. 3).

Growing season T_n was negatively related to maize yield in Tianjin, Shanxi, Jiangsu, and Anhui (Fig. 5), but was positively related to maize yield in Xinjiang (Fig. 3). Maize yield significantly decreased by 11.6 to 27.9 % in Shanxi and by 1.6 to 12.6 % in Guizhou for each degree increase in growing season T_n (Fig. 3).

Growing season DTR was negatively related to maize yields in the major production areas Jilin, Liaoning, Shanxi (Fig. 5), Hebei, Shandong,
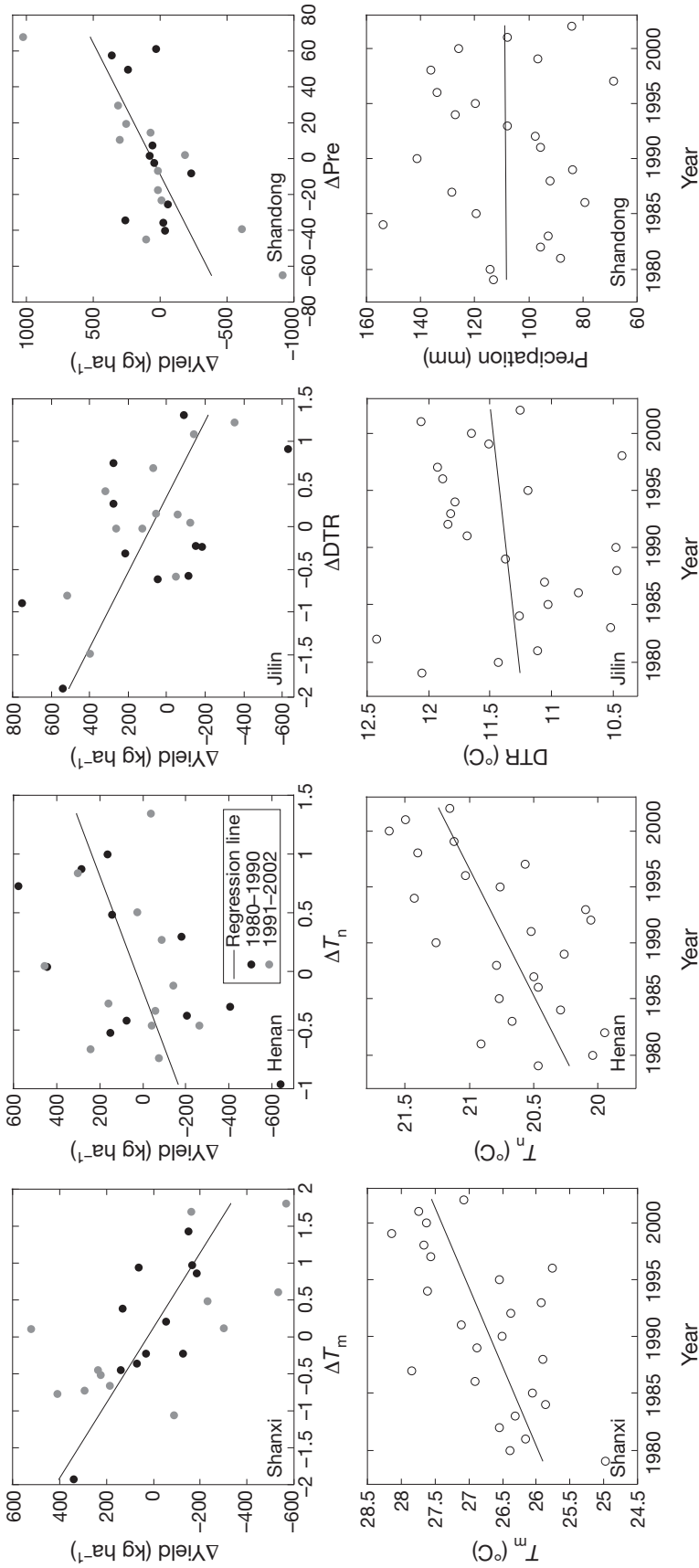
Fig. 6. Top panels: ΔYield for soybean with ΔT_m, ΔT_n, ΔDTR and ΔPre during the growing season in selected provinces (autonomous region or municipality), and best-fit linear regressions. Bottom panels: trends in the corresponding climate variables

Henan and Guizhou (Fig. 3). The effects could be associated with water stress since growing season precipitation was significantly positively related to maize yields in most of these provinces.

3.1.4. Soybean

Among the 16 major provinces that produce soybean throughout China, Shanxi province (Fig. 6) showed negative relation between growing season T_m and soybean yield. Soybean yield significantly decreased by 11.1 to 22.7 % in Shanxi for each degree increase in growing season T_m (Fig. 3).

Growing season T_n was positively related to soybean yield in Liaoning, Inner Mongolia and Henan province (Fig. 6). Soybean yield significantly increased by 3.0 to 17.3 %, and by 3.4 to 19.7 % in Liaoning and Henan, respectively, for each degree increase in growing season T_n (Fig. 3).

DTR was negatively related to soybean yield in Jilin (Fig. 6), Liaoning, Shanxi, Hebei, Shandong and Jiangxi, but positively related to soybean yield in Anhui province (Fig. 3).

Growing season precipitation was positively related to soybean yield in Liaoning, Inner Mongolia, Gansu, Hebei, Shanxi (Fig. 3) and Shandong (Fig. 6), which is in the arid and semi-arid climate zone. Up to 49 % of the variance in interannual soybean yield changes in Hebei and Shandong could be explained by growing season precipitation.

3.2. Recent climate trends and their impacts on crop yield and production

In some of the provinces with significant crop–climate relationships, we found significant trends in the growing season climate (particularly T_n and T_m) over the last few decades (Fig. 7). For example, during the period 1951–2002, rice growing season T_n had a significant trend in Heilongjiang, Jinlin, Liaoning, Anhui, Shanghai, Hubei, Guangdong and Zhejiang. Rice growing season DTR
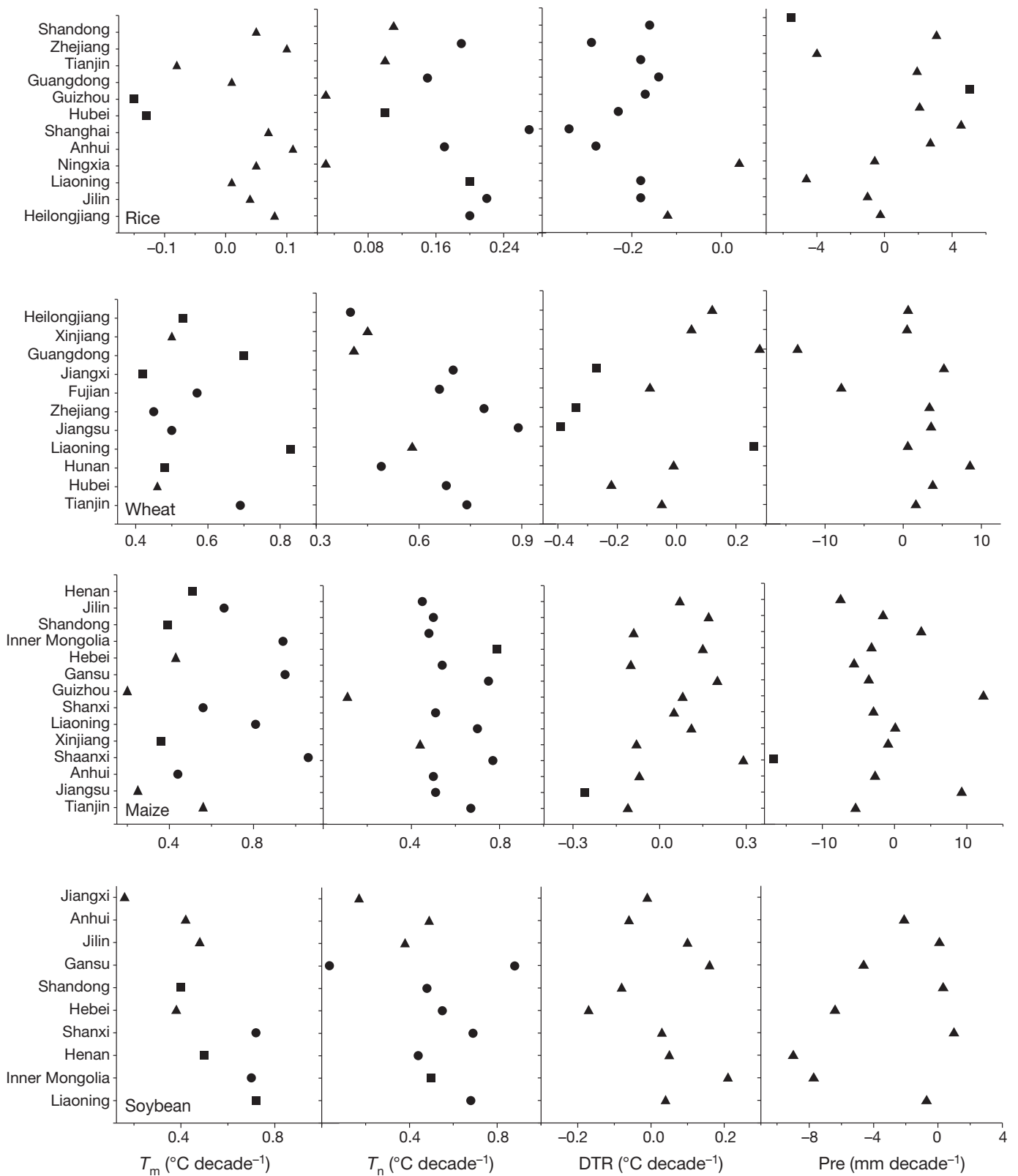
Fig. 7. Trends in climate variables during the crop growing season. (●) $p < 0.01$, (■) $p < 0.05$, and (▲) $p > 0.05$. Only provinces (autonomous region or municipality) where crop yield was significantly related to at least 1 of the 4 climate variables during the growing season are shown

Table 1. Estimated changes in crop yield (% decade⁻¹ relative to the 2002 yield) and (**bold**) total production (10000 t decade⁻¹) that are due to growing season climate trends (T_m, maximum temperature; T_n, maximum temperature; DTR, diurnal temperature range; Pre, precipitation) during 1951–2002 (rice), and 1980–2002 (wheat, maize and soybean), using simple and multiple (MUL) linear regressions. Areas sown to crops are based on those in 2002

Crop	Province	Growing season	T_m Estimate	T_m Range	T_n Estimate	T_n Range	DTR Estimate	DTR Range	Pre Estimate	Pre Range	MUL estimate (% decade⁻¹)	Variables in MUL
Rice	Heilongjiang	Jun–Aug			1.50	0.90 to 2.14					1.94	ΔT_n, ΔDTR, ΔPre
	Jilin	Jun–Aug			2.11	1.02 to 3.21					2.86	ΔT_n, ΔDTR, ΔPre
	Liaoning	Jun–Sep			1.29	0.51 to 1.90					1.48	ΔT_n, ΔDTR, ΔPre
	Guizhou	Jun–Sep	0.51	0.20 to 0.86			1.04	0.60 to 1.54	0.46	0.24 to 0.75	1.15	ΔT_n, ΔDTR, ΔPre
	Tianjin	Jun–Sep					0.86	0.24 to 1.76			1.35	ΔT_n, ΔDTR, ΔPre
	Zhejiang	Jun–Oct					–0.99	–1.64 to –0.31			–0.94	ΔT_n, ΔDTR, ΔPre
	Shandong	Jun–Aug					0.69	0.21 to 1.40			0.64	ΔT_n, ΔDTR, ΔPre
	Total		**1.8**	**0.7 to 3.0**	**26.9**	**1.4 to 39.3**	**–3.3**	**–10.4 to 4.6**	**1.6**	**0.8 to 2.6**	**32.0**	
Wheat	Tianjin	Oct–May			5.19	3.37 to 9.60					5.81	ΔT_m, ΔT_n, ΔPre
	Hubei	Oct–May			–9.61	–17.26 to –2.68					–8.45	ΔT_n, ΔDTR, ΔPre
	Hunan	Nov–May			–4.70	–7.68 to –2.03					–4.67	ΔT_m, ΔT_n, ΔPre
	Liaoning	Apr–Jul	–9.27	–16.42 to –4.88			–4.32	–6.13 to –2.25			–8.01	ΔT_n, ΔDTR, ΔPre
	Guangdong	Nov–Apr					4.48	1.40 to 9.59			3.01	ΔT_n, ΔDTR, ΔPre
	Total		**–1.1**	**–1.9 to –0.6**	**–13.1**	**–26.0 to –0.2**	**–0.35**	**–0.66 to 0.05**			**–11.9**	
Maize	Tianjin	Jun–Sep			–5.59	–10.49 to –2.43					–12.15	ΔT_m, ΔDTR, ΔPre
	Jiangsu	Apr–Aug			–1.91	–3.57 to 0.20					–1.43	ΔT_n, ΔDTR, ΔPre
	Anhui	Jun–Sep	–3.38	–7.15 to –0.43	–5.00	–9.21 to –1.16					–4.74	ΔT_n, ΔDTR, ΔPre
	Shaanxi	Jun–Sep	–14.82	–21.97 to –7.88	–14.59	–21.51 to –8.94					–16.41	ΔT_n, ΔDTR, ΔPre
	Liaoning	May–Sep	–10.54	–17.14 to –4.41							–8.66	ΔT_m, ΔDTR, ΔPre
	Shanxi	Apr–Sep	–7.34	–9.57 to –5.04							–6.68	ΔT_n, ΔDTR, ΔPre
	Gansu	Apr–Sep	–10.54	–19.73 to –1.63							–8.23	ΔT_n, ΔDTR, ΔPre
	Total		**–213.1**	**–339.7 to –94.4**	**–81.4**	**–130.2 to –38.8**					**–212.2**	
Soybean	Liaoning	May–Sep			6.19	2.03 to –11.79					2.72	ΔT_m, ΔDTR, ΔPre
	Inner Mongolia	May–Sep			4.77	2.12 to –8.55					1.79	ΔT_n, ΔDTR, ΔPre
	Henan	Jun–Sep			4.88	1.49 to 8.68					5.20	ΔT_n, ΔDTR, ΔPre
	Shanxi	Apr–Sep	–11.69	–16.36 to –7.99							–7.96	ΔT_n, ΔDTR, ΔPre
	Total		**–6.0**	**–8.4 to –4.1**	**17.4**	**6.5 to 31.5**					**6.6**	

had a significant trend in Jinlin, Liaoning, Anhui, Shanghai, Hubei, Guizhou, Guangdong, Tianjin, Zhejiang and Shandong. During the period 1979–2002, T_n and T_m over the wheat growing season had significant trends in Tianjin, Hunan, Jiangsu, Zhejiang, Fijian, Jiangxi and Heilongjiang (Fig. 7). During the period 1951–2002, rice growing season T_n in Heilongjiang, Jilin and Liaoning provinces significantly increased by 0.20, 0.22 and 0.20°C decade⁻¹, respectively; rice growing season T_m and precipitation in Guizhou province decreased by 0.15°C decade⁻¹ and increased by 5.04 mm decade⁻¹, respectively (Fig. 7). Such significant trends in the climate variables possibly caused changes in crop yield and production over the last few decades.

In Table 1, we estimated the impacts of trends in climate variables on crop yield and production only in provinces where both climate–yield relationships and trends in the relevant climate variable were significant. For example, according to the climate trend (Fig. 7) and the yield response (Fig. 3), we estimated that during the period 1951–2002, rice yield could have increased (relative to the rice yield in 2002) by 1.50, 2.11 and 1.29% decade⁻¹ due to the warming trend in growing season T_n in Heilongjiang, Jilin and Liaoning provinces, respectively; rice yield could have increased by 0.51 and 0.46% decade⁻¹ in Guizhou due to the cooling trend in T_m and increasing trend in precipitation, respectively. Rice yield could have increased by 1.04, 0.86 and 0.69% decade⁻¹ in Guizhou, Tianjin and Shandong, but could have decreased by 0.99% decade⁻¹ in Zhejiang province, relative to the rice yield in 2002, due to the decreasing trend in DTR (Table 1). Because the warming trend became more pronounced from the 1980s, our analysis from 1980 resulted in larger impacts for wheat, maize and soybean (Table 1).

The trends in T_m and T_n over the last few decades increased rice yield in the northeast, and soybean in the north and northeast, but decreased maize yield in 7 provinces and wheat yield in Hubei, Hunan and Liaoning. Using the areas sown in 2002, we estimated that total rice production in China could have increased by 1.8×10^4 t (range 0.7×10^4 to 3.0×10^4 t) decade^{-1} due to the trend in T_m during the period 1951–2002. It could have increased by 26.9×10^4 t (range 1.4×10^4 to 39.3×10^4 t) decade^{-1} due to the trend in T_n. In contrast, it could have decreased by 3.3×10^4 t decade^{-1} due to the trend in DTR (Table 1).

Based on estimates using the MUL method, which accounts for the impacts of the interaction of simultaneous changes in 3 climate parameters (Table 1), we estimated that rice yield could have increased in Heilongjiang, Jilin, Liaoning, Guizhou, Tianjin and Shandong. For example, rice yield would have increased by 1.94, 2.86 and 1.48% decade^{-1} in Heilongjiang, Jilin and Liaoning provinces, respectively, relative to the rice yield in 2002, but decreased by 0.94% decade^{-1} in Zhejiang province (Table 1). Total rice production in China could have increased by 32.0×10^4 t decade^{-1} due to the trend in growing season climate during the period 1951–2002 (Table 1). Wheat yield could have increased in Tianjin and Guangdong, but decreased in Hubei, Hunan and Liaoning; total production of wheat, maize and soybean in China could have changed by -11.9×10^4, -212.2×10^4 and 6.6×10^4 t decade^{-1}, respectively, due to the trend in growing season climate during the period 1979–2002 (Table 1).

4. DISCUSSION

4.1. Response patterns and mechanisms

Our analysis presents the general response patterns of regional agricultural productivity to seasonal climate variability and change; however, the response mechanisms need to be further investigated. Some physiological mechanisms by which T_m, T_n and DTR may affect crop yields have been partly revealed for rice (Matsui & Horie 1992, Tao et al. 2006, Tao et al. 2008), wheat (Metho et al. 1999), maize (Muchow 1990, Schoper et al. 1986) and soybean (Koti et al. 2007). Higher temperatures may accelerate crop development and reduce grain filling duration, while temperature extremes during flowering can reduce grain or seed number (e.g. Matsui & Horie 1992). Crop responses to a change in temperature depend on the temperature optima of photosynthesis, growth and yield, all of which may differ for different crops (Conroy et al. 1994). When temperature is below the

optimum for photosynthesis, a small increase in temperature can greatly stimulate crop growth. The converse is true when temperature is near the maximum for yield. A small increase in temperature can dramatically reduce yield (Baker & Allen 1993). Climate warming may have beneficial or harmful impacts on crop production in high or low latitude regions depending on whether the current temperature is generally less or more than the optimal temperature (T_o) for crop production (IPCC 2001). This mechanism underlies crop response patterns to temperature change in our study. For example, our analysis showed that in Heilongjiang, Jilin and Liaoning provinces, detrended rice yield showed a positively linear relationship with growing season mean temperature, suggesting that the current growing season mean temperature in these provinces is $<T_o$, and that a warming trend could increase rice yield. In contrast, in Guizhou province, detrended rice yield showed a negatively linear relationship with growing season mean temperature, suggesting that the current growing season mean temperature is at or above T_o, and that a warming trend could reduce rice yield.

The impacts of DTR were bilateral, as shown in Fig. 3. An increase in DTR may reduce yield because the associated increase in T_m results in increased water stress or reductions in net photosynthetic rates (Dhakhwa & Campbell 1998, Tao et al. 2006), but may benefit yields in cases when development or grain filling rates are more sensitive to T_n than T_m (Wilkens & Singh 2001). At country scale, Lobell (2007) showed that rice and maize yields in China diminished with increased DTR during the period 1961–2002, while DTR effects on wheat yield were insignificant. Our results showed DTR to be significantly and generally negatively related to crop (particularly maize and soybean) yield variability. Since ongoing climate change is characterized by a marked asymmetry between maxima and minima, with T_n rising faster than T_m, and many climate models project further significant changes in DTR, effects of DTR on crops may be important to consider in impact and adaptation studies (Rosenzweig & Tubiello 1996, Tubiello et al. 2002, Lobell 2007).

Growing season precipitation had a significant negative relation to rice and wheat yield in south China, but significant positive relation to maize and soybean yield in the north and northeast (Fig. 3). These results are quite consistent with the actual status over the last few decades. In south China where the climate is humid and annual precipitation is generally >1000 mm, too much precipitation often occurred during the wheat grain filling period, which could lead to yield losses from disease and root problems. Moreover, too much precipitation often occurred during the rice

heading period, which could lead to yield losses from disease, insects and insufficient solar radiation (Tao & Yokozawa 2005). In the north and northeast China where the climate is arid and semi-arid, and annual precipitation is generally <600 mm, water stress is the most crucial limiting factor for rainfed crop yields (Tao et al. 2003).

Changes in crop yields are eventually subjected to the combined impacts of multiple climate variables. While simple linear regression can clearly distinguish the response of crop yield to the most relevant climate variables, the MUL method can, to some extent, estimate the combined impacts of several relevant climate variables. The crop yield change estimated by MUL could be more or less than the estimate based on a single climate variable (Table 1) depending on the relative impacts of the different climate variables used and their trends.

4.2. Impacts of climate variability and trends

Several reports have shown that the recent warming trend has had discernible impacts on crop development and production (e.g. Nicholls 1997, Lobell & Asner 2003, Chmielewski et al. 2004, Peng et al. 2004, Tao et al. 2006). Our analysis also showed discernible impacts on crop production even on a provincial scale. Across provinces and crops, the trends in T_n (Fig. 7) and their impacts were more pronounced than those of T_m for rice, wheat and soybean (Fig. 3, Table 1).

The yields of the 4 major crops were also significantly related to growing season precipitation in some provinces (Fig. 3), suggesting that the interannual variability in crop yield due to variability in precipitation is quite large (Tao et al. 2004). However, the trends in seasonal precipitation over the last few decades were insignificant in most of the provinces (Fig. 7). As a result, the impacts of precipitation trends on crop yields over the last few decades were generally insignificant (Table 1).

Likewise, our results showed that the DTR trend could have reduced rice yield in Zhejiang by 66.0 kg ha^{-1} decade^{-1}, but increased rice yield in Tianjin, Guizhou and Shandong; the DTR trend could have reduced wheat yield in Liaoning by 99.8 kg ha^{-1} decade^{-1}, but increased wheat yield in Guangdong by 133.9 kg ha^{-1} decade^{-1}. The impacts of DTR trends on maize and soybean yield were insignificant (Table 1). The interannual variability in DTR significantly correlated with maize and soybean yield in the major production regions (Fig. 3), but the trend in DTR since 1980 was generally insignificant (Fig. 7). The impacts of DTR on crop yield and production could become significant if longer time series were available, such as those for rice.

4.3. Uncertainties

Compared with the observed data at experimental stations, uncertainties in the statistical dataset for crop production and the regional climate dataset could be larger. Nevertheless, extensive studies have demonstrated that such datasets are good enough to investigate the climate–yield relationships and climate trends, at least on a large scale (e.g. Lobell 2007, Lobell & Field 2007, Lobell et al. 2008). The statistical datasets on crop productivity did not separate irrigated from rainfed production, which, among other things, could weaken the relationship between precipitation and crop yield for paddy rice or in provinces with high irrigation proportion. Nevertheless, the statistical data can generally capture the trend and interannual variability in crop productivity due to technology development and meteorological disasters at provincial to national scales.

Results could also depend on the length of the study period (as shown above), and agricultural management practices. The analysis was based on the assumption that the impacts of agricultural management practices on crop yields did not change with yearly climate and crop growing conditions. If farmers adapted their management practices to yearly climate and crop growing conditions, the estimated beneficial impacts from climate variables may be exaggerated, while the estimated harmful impacts may be underestimated.

5. CONCLUSIONS

Our analysis showed that the yields of major crops were significantly related to growing season climate in the main production regions of China over the last few decades. Furthermore, the growing season temperature, especially T_n, had a significant warming trend. Such a climate trend has affected regional agricultural productivity. Among the 4 major crops, maize was the most vulnerable to the trends in both T_m and T_n. Rice, wheat and soybean were affected more by T_n than by T_m. The changes in crop yield for each degree change in T_m or T_n generally ranged from –18.9 to 11% (90% CI of –22.7 to 19.7%), which were crop- and region-dependent.

Although precipitation and DTR were also significantly related to crop yields, the trends in growing season precipitation and DTR (since 1980) were generally insignificant.

In this study, we presented the general spatial patterns of climate–yield relationships, climate trends and the impacts of recent climate trends using statistical methods. However, the key response mechanisms of

different crops to local seasonal climate change (variability) need further investigation to better understand the response patterns and predict the consequences of climate change and variability on regional agricultural production.

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