

Response of crop yields to climate trends since 1980 in China

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ABSTRACT: We used improved datasets on both climate and crop production to investigate climate trends during the crop growing period and their impacts on yields of major crops (rice, wheat, maize and soybean) in China by county, during 1980–2008. We found clear regional climate trends during this period, particularly for temperature. Such trends have had measurable impacts on crop yields, with a distinct spatial pattern. For the entire country, the planting area-weighted average showed that climate trends from 1980–2008 reduced wheat, maize and soybean yields by 1.27, 1.73 and 0.41 %, respectively, while increasing rice yields by 0.56 %. As a result, climate trends as a whole reduced wheat and maize production by 3.60×10^5 t and 1.53×10^6 t, respectively, and increased rice and soybean production by 7.44×10^4 t and 4.16×10^3 t, respectively. Estimates of climate impacts are smaller than previous estimates that used different scales, datasets and methods. The particular crops and regions that have been most affected and should be priorities for adaptation are maize and wheat in arid and semi-arid areas of northern and north-east China, where droughts induced by increases in temperature and solar radiation could limit the benefits of improved thermal conditions. Climate warming decreases crop yields by accelerating crop development rate, and thus reducing crop growth duration and yield accumulation, and by increasing temperature extremes and heat stress.

KEY WORDS: Climate change · Impacts and vulnerability · Sensitivity · Adaptation · Agriculture

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1. INTRODUCTION

Annual anomalies of global land-surface air temperature, relative to the 1961–1990 mean, indicate a warming of 0.27°C per decade since 1979, with the greatest warming during winter (December to February) and spring (March to May) in the Northern Hemisphere (IPCC 2007). Such changes have had measurable and spatially explicit effects on agricultural systems and crop production worldwide (e.g. Nicholls 1997, Peng et al. 2004, Tao et al. 2006, 2008, Piao et al. 2010, Lobell et al. 2011a,b). However, the effects of climate change are still not well understood (Lobell et al. 2011a), and some key unknowns and uncertainties hamper efforts to improve the prediction of crop production in the face of climate change (Tao et al. 2009). Our understanding of key unknowns and uncertain-

ties of climate-change effects, and vulnerability and adaptation to this, can be advanced by studying data from the past few decades. Observed climate change and its effect on crop yields, at various spatial scales from local to global, has recently been studied by a number of authors (e.g. Nicholls 1997, Peng et al. 2004, Sheehy et al. 2006, Tao et al. 2006, 2008, Lobell & Field 2007, You et al. 2009, Li et al. 2010, Kristensen et al. 2011, Lobell et al. 2011a,b, Zhang & Huang 2012). These studies generally suggest that climate-yield relationships are scale-dependent. Improved datasets on climate and crop production, as well as novel approaches to analysis, are needed to better understand the effects of climate on crop yields.

In China for example, Tao et al. (2008) investigated climate-crop relationships, recent trends in seasonal climate, and the effects of these trends on major crop

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yields throughout the country over the last few decades. This was based on census data at the provincial scale and a monthly dataset from the Climatic Research Unit (CRU, University of East Anglia, UK) (Mitchell & Jones 2005). Recently, improved datasets on both climate and agricultural production have become available. These include agricultural census data at the county scale, detailed crop phenological records at hundreds of agricultural experimental stations across major crop production regions, and an updated homogenized temperature dataset for mainland China for 1960–2008 (Li & Yan 2009). We used the improved datasets and analysis methods to investigate climate–crop relationships, recent trends in seasonal climate, and the effects of these trends on major crop yields (rice, wheat, maize and soybeans) by county throughout China, during the period 1980–2008. Our aims are: (1) to improve understanding of the mechanisms, extent and degree of climate impacts on major crop yields over the past few decades; (2) to identify particular crops and regions that are vulnerable to climate change, as well as potential adaptation strategies; (3) to identify uncertainties in estimating crop yield response, by comparing the results with previous estimates using different datasets, analysis methods, and scales.

2. DATA AND METHODS

2.1. Data

Time series of yields for rice, wheat, maize and soybeans by county from 1980 to 2008 were obtained from the Agricultural Yearbook of each province (autonomous region or municipality) the Agricultural Yearbook of each province (autonomous region or municipality), which is published annually by China Agriculture Press in Beijing and unpublished data from county-level census bureaus. A preliminary quality check was conducted, and observations were flagged as outliers when they fell outside the range of biophysically attainable yield records. Finally, we used time series of yield data from 1980 to 2008 across the major production regions, from 1670 counties for rice, 2021 counties for wheat, 2111 counties for maize, and 1943 counties for soybeans (Fig. S1 in the supplement, at www.int-res.com/articles/suppl/c054p233_supp.pdf).

Phenological records of rice, wheat, maize and soybeans from about 300 agro-meteorological experimental stations across major production regions were obtained from the China Meteorological Administration (CMA). These records include the dates of major

phenological events since 1980, such as planting, transplanting, flowering, and maturity. For each phenological event, mean date during 1980–2008 was first computed at each station. Then, mean date of the event for each county was computed from the nearest station. These detailed phenological records provide a unique opportunity to determine exact crop growing periods and, therefore, seasonal climate during the growing period of each county.

Daily weather data including mean temperature (Tmean), precipitation (P), and sunshine duration were obtained from 756 national standard stations (NSSs) of the CMA. Inhomogeneity in daily temperature series is almost unavoidable, owing to various non-natural changes such as those in observing location, environs, and other factors (Manton et al. 2001, Li & Yan 2009). In the present study, for daily Tmean, we used the China Homogenized Historical Temperature Dataset (Li & Dong 2009), in which inhomogeneities in daily Tmean series from 1960 to 2008 at 549 NSSs were analyzed and corrected using the Multiple Analysis of Series for Homogenization software package (Li & Yan 2009). Daily sunshine duration was observed at the 756 NSSs of CMA, although daily solar radiation (SR_D) was observed at only 122 NSSs. SR_D at the 756 NSSs was computed from sunshine duration using the Ångström–Prescott (A–P) equation (Prescott 1940):

$$SR_D = (a + b \frac{n}{N})R_a \quad (1)$$

where R_a is extraterrestrial SR_D ($MJ\ m^{-2}d^{-1}$); a and b are the A–P coefficients; and n and N actual and theoretical sunshine duration (h), respectively. The A–P coefficients a and b were first calibrated for the 122 NSSs with both SR_D and sunshine duration observations. These coefficients were then computed at each of the 756 NSSs based on the nearest 3 stations from the 122 NSSs, using triangular irregular network interpolation. Finally, SR_D at each of 756 NSSs was computed from sunshine duration observations using the estimated coefficients a and b .

At the county level, daily Tmean and SR_D in each county was computed from its nearest 3 NSSs, using the triangular irregular network interpolation. Because spatial interpolation of daily precipitation might cause greater uncertainties than daily Tmean and SR_D, daily precipitation in each county used observations from its nearest NSS to avoid such uncertainties. The meteorological and agro-meteorological experimental stations are dense enough to represent climate and crop phenology for each county, particularly in the major production regions. Fig. S1 (in the supplement) shows the spatial pattern of crop cultiva-

tion fraction, locations of the 756 meteorological stations and the agro-meteorological experimental stations for rice, wheat, maize and soybean, together with a map of county boundaries. We used 321, 288, 258, and 80 agro-meteorological experimental stations for rice, wheat, maize and soybean, respectively.

2.2. Methods

Datasets on crop locations, crop phenology, crop yields, and climate were combined in a panel analysis of 4 major crops (rice, wheat, maize and soybeans) for all counties across their major production regions. Linear trends in climate variables were investigated by applying a linear regression analysis to time series of measured climate variables.

To investigate climate–yield relationships and further quantify the effect of climate trends over the past few decades on crop yield by county, we used an approach based on the first-difference time series for yield (ΔYield) and climate (ΔTmean , ΔP , and ΔSR_D) (i.e. year-to-year changes) (Nicholls 1997, Lobell & Field 2007, Tao et al. 2008). This approach avoids the confounding influence of long-term variations, such as changes in crop management (Nicholls 1997, Lobell & Field 2007, Tao et al. 2008). We initially computed the ΔYield , ΔTmean , ΔP and ΔSR_D during the crop growing period (from planting to maturity). A stepwise regression model was then developed (with ΔYield as dependent variable, and ΔTmean , ΔP , and ΔSR_D as independent variables) in which a specific independent variable was entered into the model if the probability (p) was ≤ 0.05 , and removed from the model if p was > 0.05 . The model is of the form

$$\Delta\text{Yield}_{i,t} = \beta_{i,0} + \beta_{i,1}\Delta\text{Tmean}_{i,t} + \beta_{i,2}\Delta\text{P}_{i,t} + \beta_{i,3}\Delta\text{SR}_{D,i,t} + \varepsilon_{i,t} \quad (2)$$

where $\Delta\text{Yield}_{i,t}$ is the first-difference of yield at county i in year t ; $\Delta\text{Tmean}_{i,t}$, $\Delta\text{P}_{i,t}$ and $\Delta\text{SR}_{D,i,t}$ represent the first-difference of Tmean, precipitation, and SR_D in county i in year t , respectively; $\beta_{i,0}$ is the average yearly change caused by management in a county; $\beta_{i,1}$, $\beta_{i,2}$ and $\beta_{i,3}$ are model coefficients to be fit and ε_{it} is an error term.

Owing to the limited historical sample size, a bootstrap resampling approach was used to estimate sampling uncertainty associated with the derived regression coefficients, in which the historical data were resampled and a new regression model fit to the data. In each case, 1000 bootstrap samples were used and median estimates were used in further analyses. Estimate uncertainties were represented

by a 5 to 95 % confidence interval from bootstrap resampling with 1000 replicates.

For each crop in a county, the sensitivity of yield change (ΔYield) to Tmean, precipitation, and SR_D was represented by the median estimates of model coefficients $\beta_{i,1}$, $\beta_{i,2}$ and $\beta_{i,3}$ in Eq. (2), respectively, divided by mean crop yield during 1980–2008 and expressed as a percentage. The impact of trends in a climate variable (i.e. Tmean, precipitation, and SR_D) on crop yields during 1980–2008 (as a percentage) was estimated by multiplying the sensitivity of yield change to the climate variable by change of that climate variable during the period estimated by a linear trend. The impact of all climate trends on crop yields during 1980–2008 (as a percentage) was computed by summing the effects of trends in Tmean, precipitation and SR_D on crop yields over the period.

The planting area weighted average of the effect of climate variable trends across China was computed based on estimated effects of climate variable trends on crop yields during 1980–2008, and planting area of the crop in each county in 2008. For each crop in a county, the effect of climate trends on total crop production (in tons) was computed by multiplying the climate trend effect on crop yields during 1980–2008 by total crop production in the county in 2008. The effect of climate trends on total production of the crop across the entire country was the sum of estimated effects for all counties.

3. RESULTS

3.1. Climate trends during the crop growing period

The spatial distribution of climate trends shows patterns over the crop growing period from 1980 to 2008, presented in Fig. 1. During the rice growing period, Tmean generally increased across the major cultivation areas, except portions of southwestern China (Fig. 1A). In particular, it increased by more than $0.6^\circ\text{C decade}^{-1}$ in portions of the northeast and east. Precipitation decreased in some major rice production areas, including the middle and lower reaches of the Yangtze River and northeast China (Fig. 1B). SR_D decreased in large areas across the major production regions such as the the North China Plain (NCP) and portions of southern China (Fig. 1C). During the wheat growing period, Tmean increased more dramatically, particularly in northern, northeast and eastern China (Fig. 1D). Precipitation increased in the middle and lower reaches of the Yangtze River

(Fig. 1E), and SR_D decreased slightly in the NCP (Fig. 1F). During the maize growing period, T_{mean} also generally increased, with the greatest increase in northern China and middle and lower reaches of the Yangtze River (Fig. 1G). Precipitation decreased over large areas, particularly in the lower reaches of the Yangtze River (Fig. 1H). During the soybean growing period, T_{mean} increased by as much as 0.6°C decade⁻¹ (Fig. 1J). Precipitation decreased over large areas, and increased in the NCP (Fig. 1K). SR_D decreased substantially in the NCP during the growing periods of both maize (Fig. 1I) and soybean (Fig. 1L).

3.2. Sensitivity of crop yield to climate change

We analyzed sensitivity of crop yield to climate change during 1980–2008 based on the median estimates. The 5 to 95% confidence interval of the estimates is represented in Fig. S2 (in the supplement at www.int-res.com/articles/suppl/c054p233_supp.pdf). The sensitivity of crop yield to climate change has a distinct spatial pattern (Fig. 2). For each 1°C increase in T_{mean} , rice yield is estimated to decrease by 10% or more in portions of southwest and east China (Fig. 2A). There the mid-season *Indica* hybrid rice, which takes up nearly 40% of planting area, is more susceptible to climate warming and heat stress (Tian et al. 2009). Wheat yield is estimated to decrease by 20% or more in portions of northern and northeast China, where spring wheat dominates. Spring wheat is more susceptible because climate warming can cause acceleration of the development rate which can lead to a reduction in the growing period (Wang et al. 2011, Tao et al. 2012). In contrast, wheat yield is estimated to increase in portions of eastern China (Fig. 2D), where T_{mean} is currently below the optimal temperature for winter wheat production (Tao & Zhang in press). Maize and soybean yield are estimated to decrease by 20% or more in portions of northern and northeast China (Fig. 2G,J).

If precipitation during the crop growing period increases by 10%, rice yield will likely decrease by up to 5% in portions of northeast and south China (Fig. 2B); wheat yield will likely decrease (increase) by $\geq 5\%$ in southeast China (other regions) (Fig. 2E). Maize and soybean yield will likely increase by $\geq 5\%$ (decrease) in north and northeast China (portions of southeast China) (Fig. 2H,K). Generally, in the south and southeast, low SR_D is the major limiting factor for crop production (Tao et al. 2008, Zhang et al. 2010). Continuous precipitation usually causes decreases in SR_D , increases pests and diseases, and reduces crop

yield indirectly (Tao et al. 2008). Additionally, floods and the associated waterlogging could also be possible factors that decrease crop yield in southeast China. In arid and semi-arid areas of north and northeast China, drought is the major limiting factor for crop production; more precipitation and less evapotranspiration in these regions would substantially increase crop yields (Tao et al. 2008).

If SR_D during the crop growing period increased by 10%, rice yield is likely to increase by up to 10% in portions of eastern and northeastern China, but decrease by 10% or more in portions of the south (Fig. 2C). The areas with negative effects of SR_D coincided with the areas with negative effects of T_{mean} or positive effects of precipitation, suggesting the negative impacts of SR_D on rice yields could be ascribed to coincident high T_{mean} or droughts. Wheat yield is likely to increase by $\geq 20\%$ (decrease) in the southeast (in other regions) (Fig. 2F). Maize yield is likely to increase (decrease) in portions of the southeast and northeast (in other regions) (Fig. 2I). Soybean yield is likely to increase (decrease) in portions of the southeast (in the north and northeast) (Fig. 2L). An increase in SR_D can increase evapotranspiration, which aggravates drought and reduces rain-fed crop yields in the arid and semi-arid regions of north and northeast China (Tao et al. 2003).

3.3. Impact of climate trends on crop yields during 1980–2008

Climate trends during 1980–2008 measurably affected major crop yields in China, with a distinct spatial pattern. This was comprehensively determined by both the sensitivity of crop yields to climate variables (Fig. 2) and changes of those variables over the period (Fig. 1). We address climate effects on crop yields during the period based on median estimates. The 5 to 95% confidence interval of the estimates is represented in Fig. S3 (in the supplement at www.int-res.com/articles/suppl/c054p233_supp.pdf).

Rice yield decreased by up to 20% in portions of the southwest and east, because of a warming trend during the period (Fig. 3A). In contrast, it increased by up to 10% in portions of the northeast and middle and lower reaches of the Yangtze, owing to a decrease in precipitation (Fig. 3B). Rice yield declined in portions of the east, and increased in portions of the south, because of the trend in SR_D (Fig. 3C). Climate trends as a whole increased rice yield in portions of the northeast and south, but yield changes were patchy in the south, with both increases and decreases in yield (Fig. 3D).

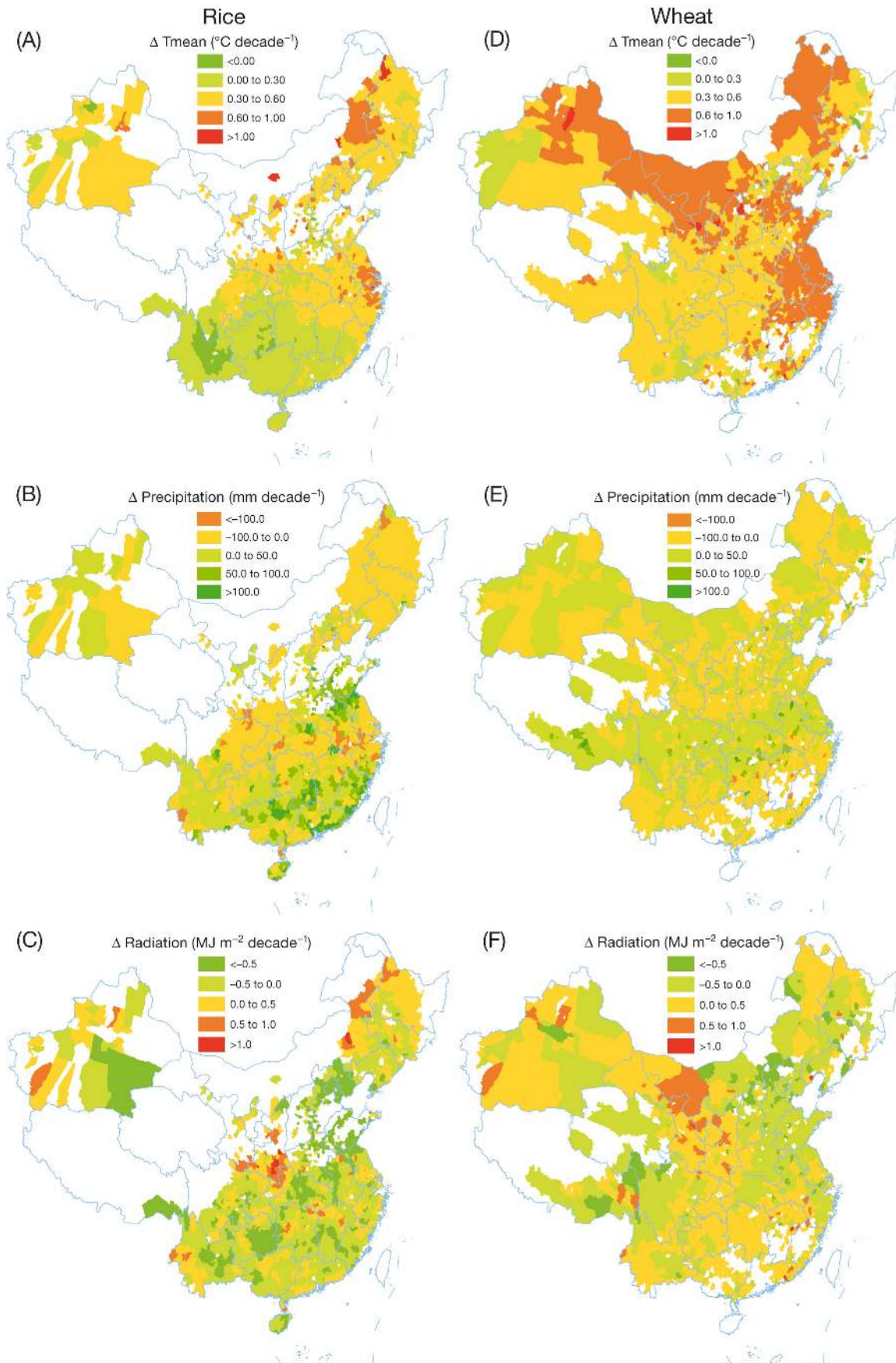


Fig. 1. (Above and following page.) Trends in mean temperature (Tmean), total precipitation and solar radiation for (A–C) rice, (D–F) wheat, (G–I) maize and (J–L) soybean growing periods, during the period 1980–2008

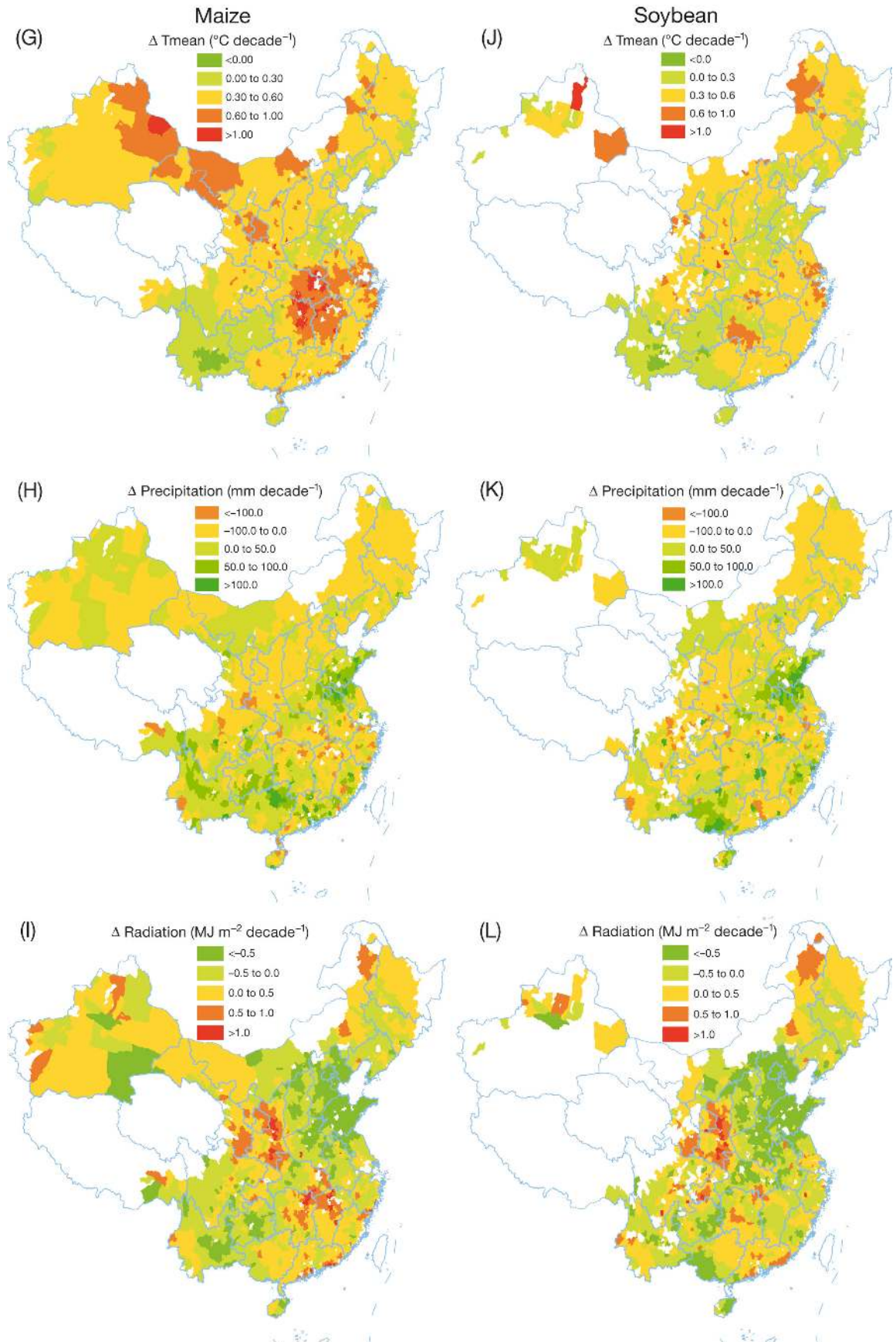


Fig. 1 (continued)

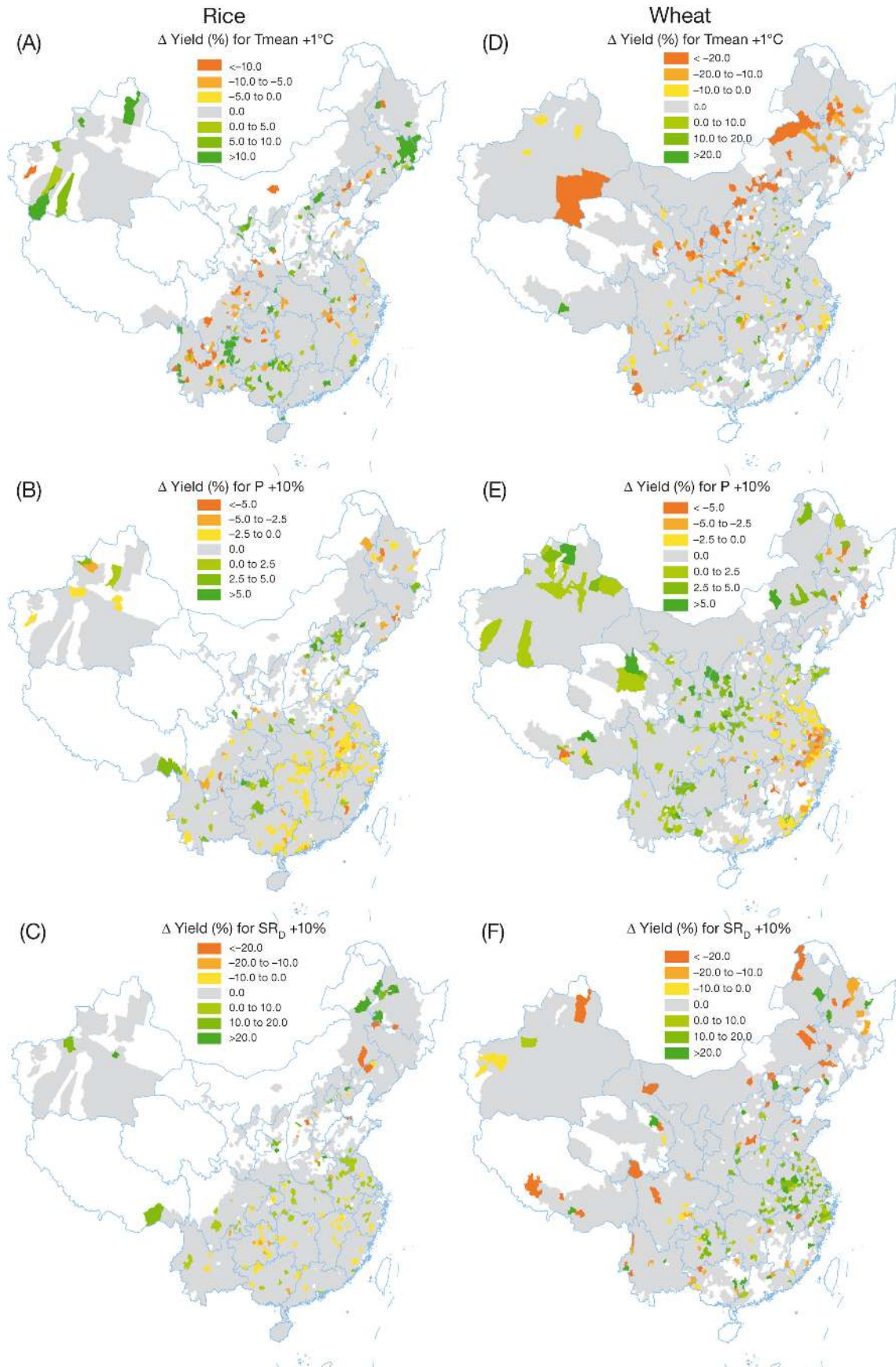


Fig. 2. (Above and following page.) Change of (A–C) rice, (D–F) wheat, (G–I) maize and (J–L) soybean yields for mean temperature (Tmean) increase of 1°C, precipitation (P) increase of 10%, solar radiation (SR_D) increase of 10% during growing periods, based on median estimate

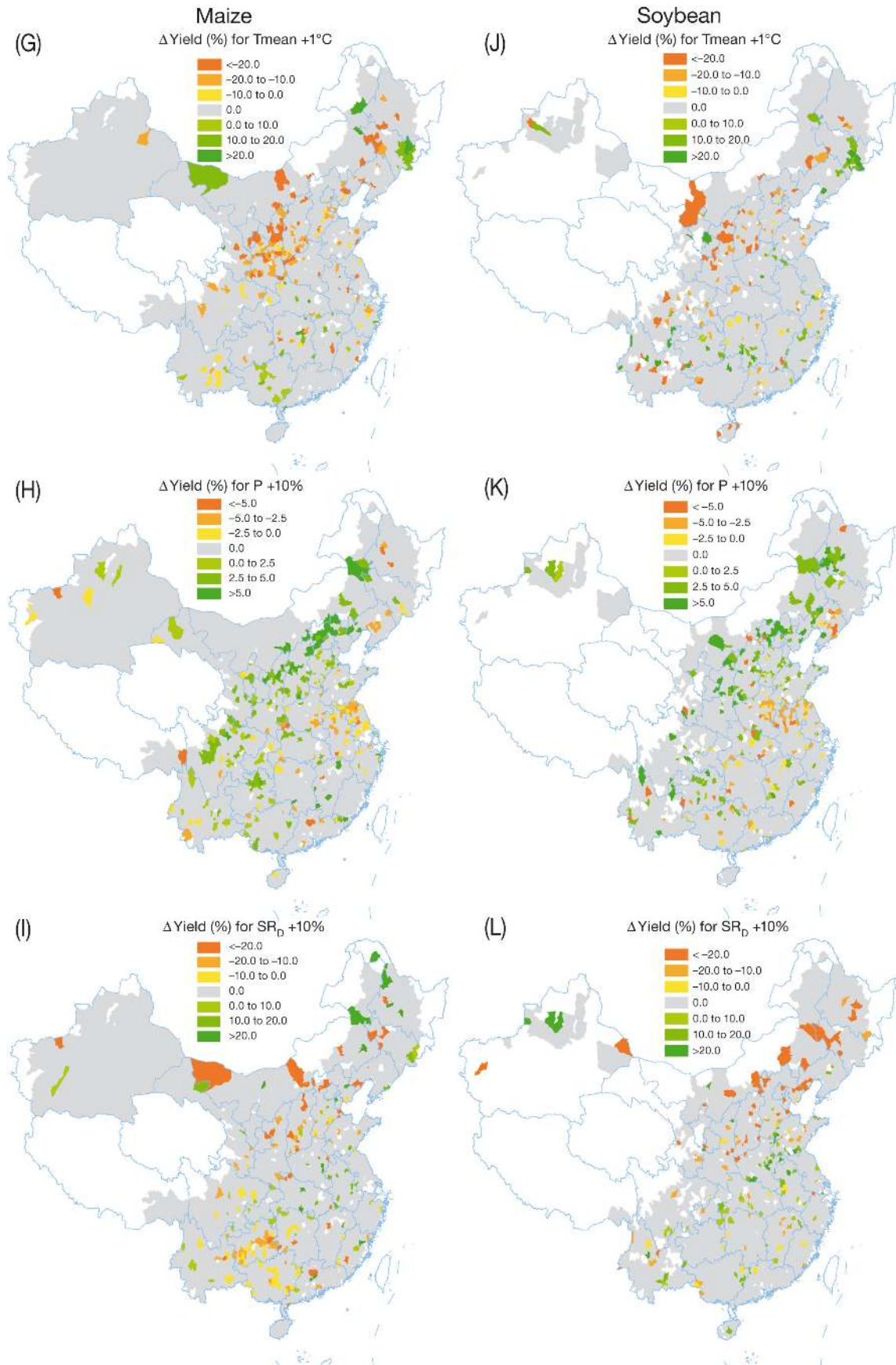


Fig. 2 (continued)

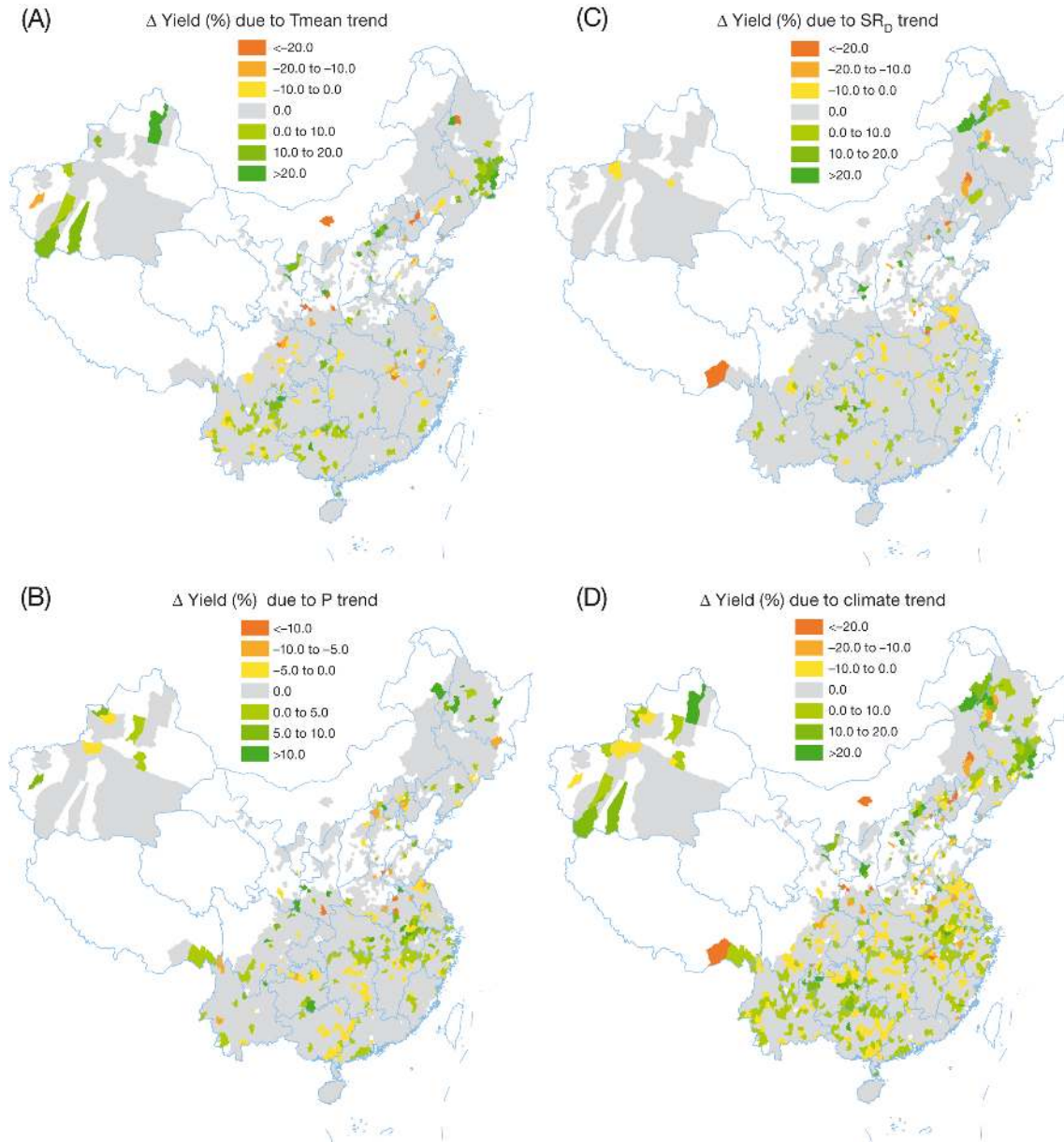


Fig. 3. Rice yield change due to trends in (A) mean temperature (Tmean), (B) precipitation (P), (C) solar radiation (SR_D), and (D) climate overall during 1980–2008, based on median estimate

Wheat yield increased by up to 20% in portions of the NCP and the southwest, but declined substantially in other regions because of a warming trend over the period (Fig. 4A). Yield declined in parts of central and eastern China, owing to a precipitation increase during the period (Fig. 4B). Wheat yield declined in portions of the east because of a decreasing trend in SR_D (Fig. 4C). Climate trends overall reduced wheat yield in eastern, northern and northeastern China (albeit patchily) by 20% or more (Fig. 4D).

Maize yield declined by $\geq 20\%$, particularly in the north and northeast, owing to a warming trend dur-

ing 1980–2008 (Fig. 5A). The yield dropped, albeit patchily, in parts of the north and northeast, because of a decrease in precipitation during the period (Fig. 5B). Increasing trends in SR_D raised maize yield in the northeast, but reduced it in parts of the north by aggravating drought. Decreases in SR_D caused some reduction in maize yield in the NCP (Fig. 5C). Climate trends overall reduced maize yield in parts of the east, north and northeast by $\geq 20\%$ (Fig. 5D).

The response of soybean yield to climate trends was similar to that of maize, but to a more moderate degree (Fig. 6).

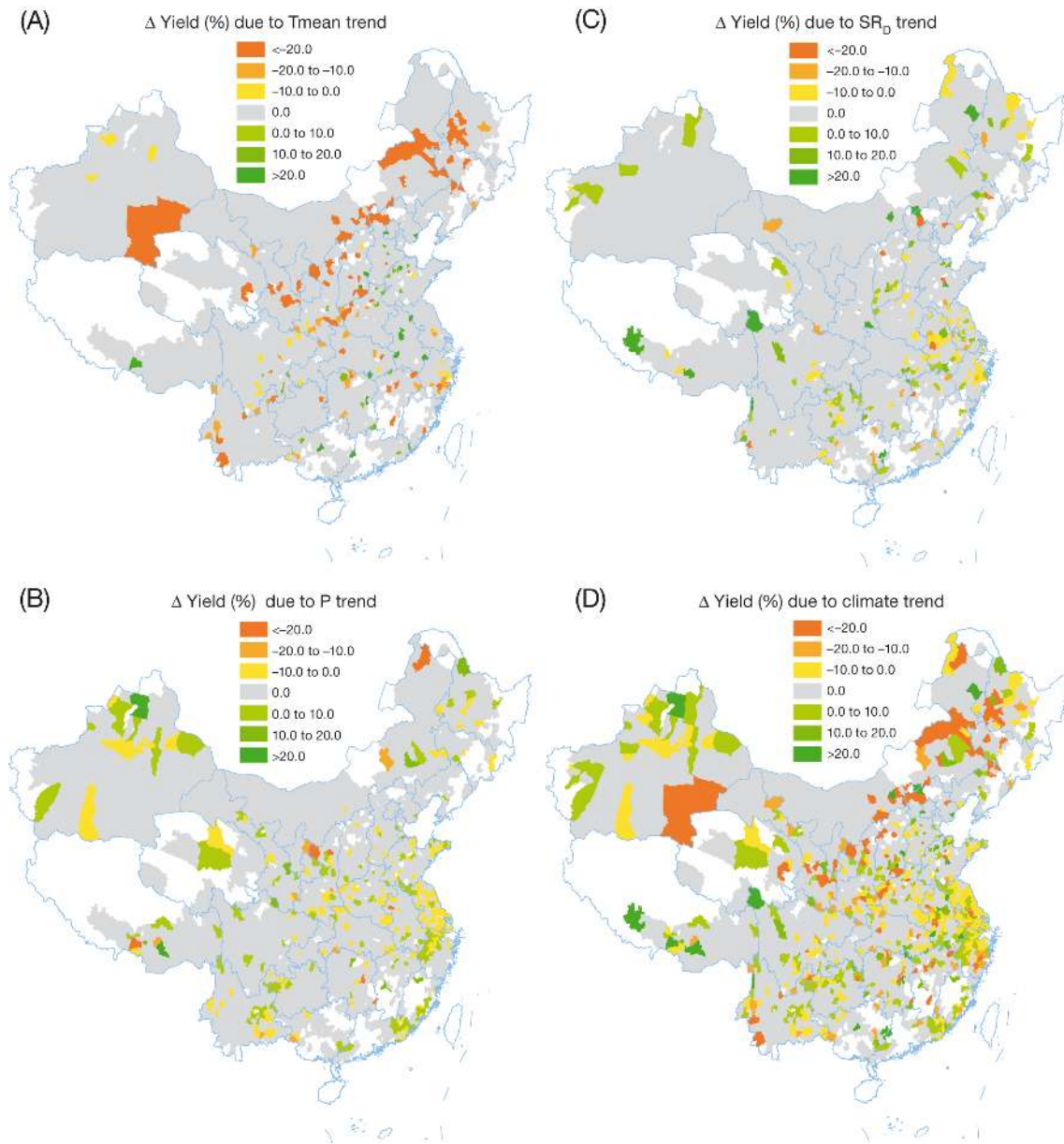


Fig. 4. Wheat yield change due to trends in (A) mean temperature (Tmean), (B) precipitation (P), (C) solar radiation (SR_D), and (D) climate overall during 1980–2008, based on median estimate

3.4. Impact of climate trends on crop yields and production for all China

Climate trends during 1980–2008 have had measurable effects on crop yields, although with large spatial differences. For all China, based on crop planting area and total production by county in 2008, planting area weighted averages across the country showed that temperature trends during the period reduced wheat and maize yields by 1.23 and 1.55%, respectively, while increasing rice and soybean yields

by 0.31 and 0.88%, respectively, albeit with a large uncertainty range (Fig. 7A). Climate trends overall reduced wheat, maize and soybean yields by 1.27, 1.73 and 0.41%, respectively, while increasing rice yield by 0.56% (Fig. 7D). The seemingly small impact on average crop yields resulted in a major impact on total production. Total production loss was by 1.87×10^5 , 2.74×10^5 and 1.58×10^6 t for rice, wheat and maize, respectively; however, soybean production increased by 5.07×10^4 t, owing to the Tmean trend during the period (Fig. 8A). Climate

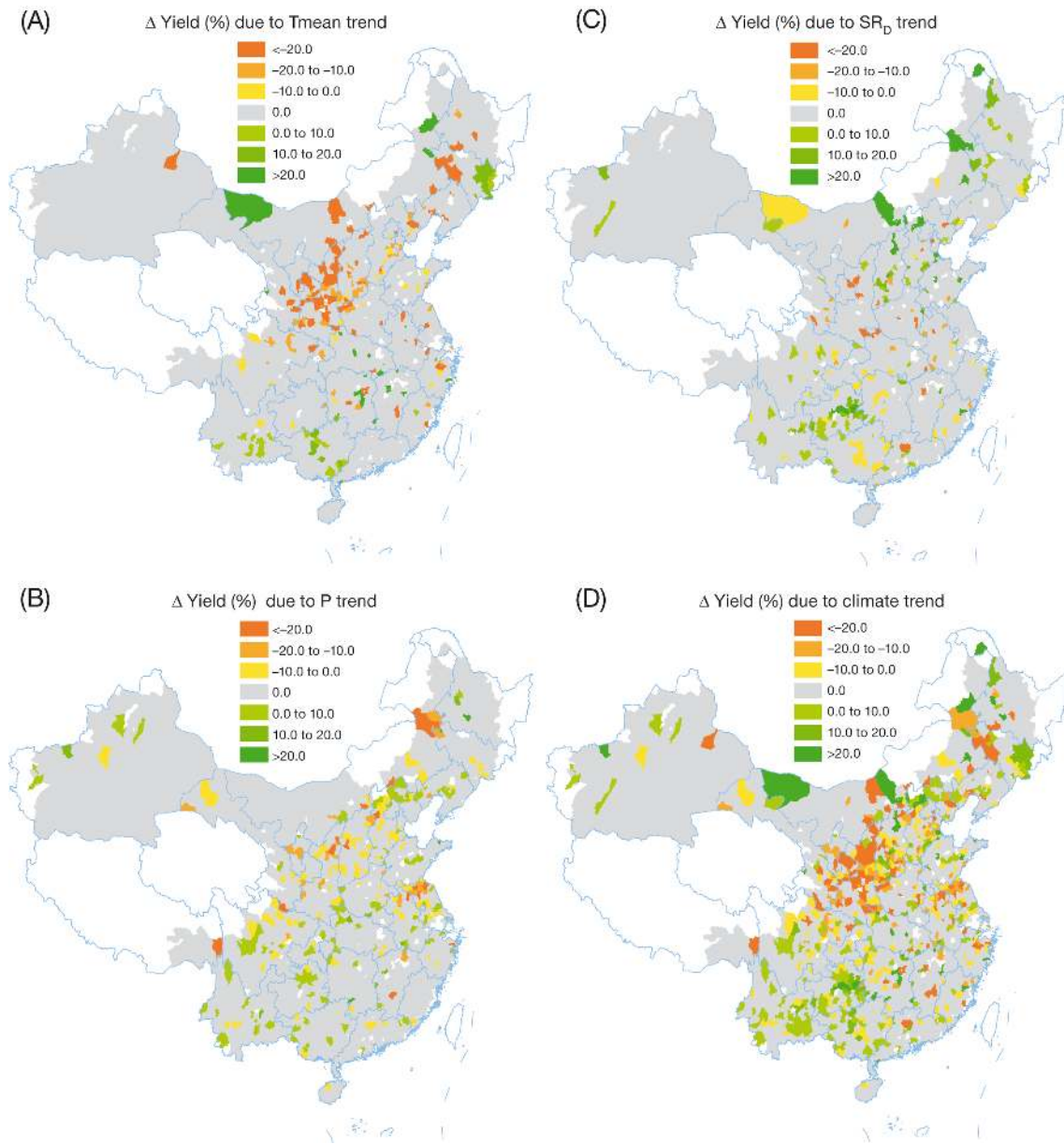


Fig. 5. Maize yield change due to trends in (A) mean temperature (Tmean), (B) precipitation (P), (C) solar radiation (SR_D), and (D) climate overall during 1980–2008, based on median estimate

trends as a whole reduced wheat and maize production by 3.60×10^5 and 1.53×10^6 t, while increasing rice and soybean production by 7.44×10^4 t and 4.16×10^3 t, respectively (Fig. 8D). For soybean, there were relatively large low-yield cropland areas where yield was negatively affected. In contrast, there were relatively few high-yield cropland areas where yield was positively affected. As a result, mean yield change (weighted by planting area) was negative, but the total production change was positive.

4. DISCUSSION

4.1. Response pattern and mechanism of crop yields to climate change

The sensitivity of major crop yields to Tmean, precipitation and SR_D is shown in Fig. 2. In portions of southwestern and eastern China, rice was more sensitive to climate warming, and in areas of the east and south, it was more sensitive to changes in precipitation and SR_D (Fig. 2A–C). As a result, in parts of

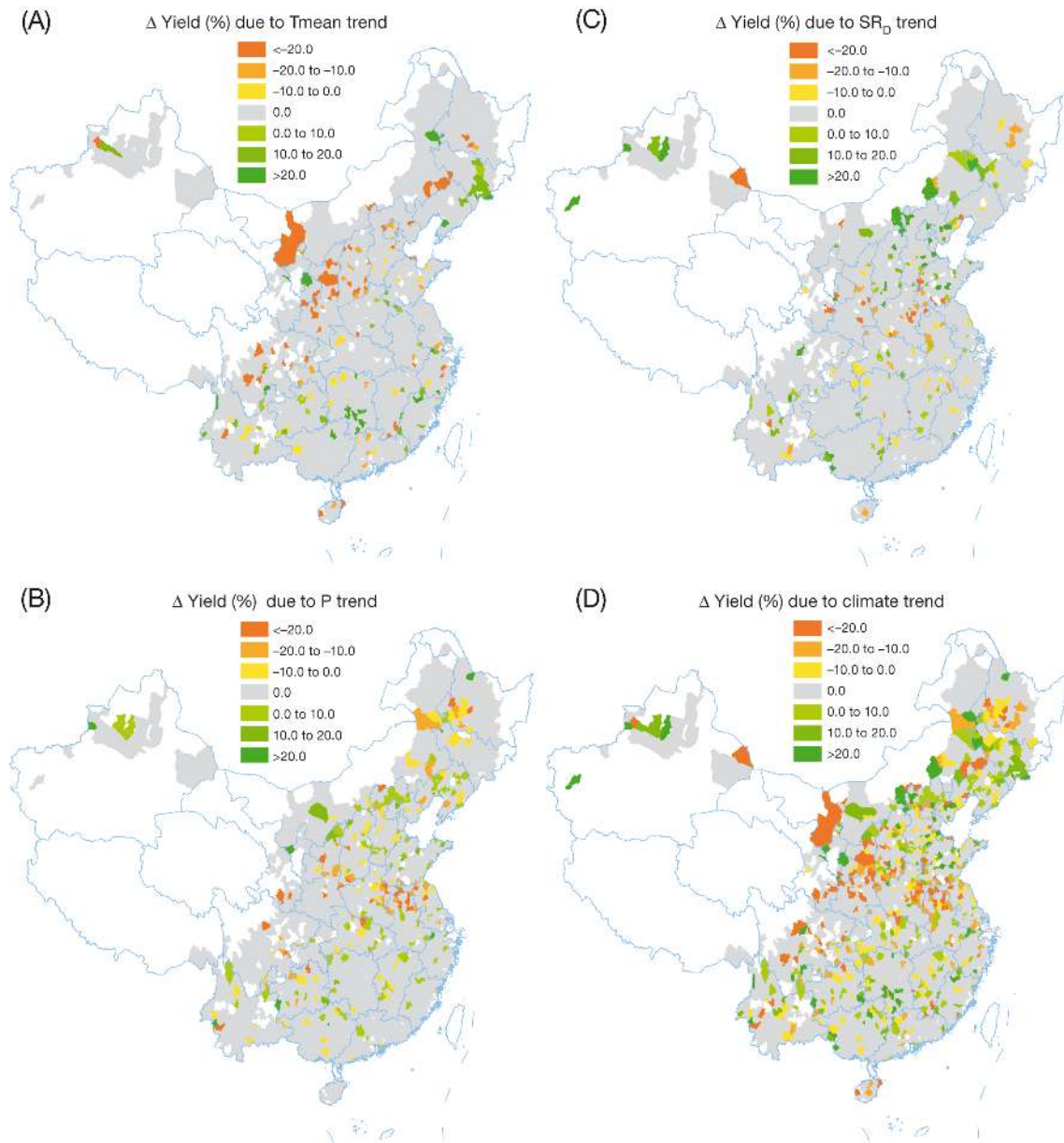


Fig. 6. Soybean yield change due to trends in (A) mean temperature (Tmean), (B) precipitation (P), (C) solar radiation (SR_D), and (D) climate overall during 1980–2008, based on median estimate

the southwest and east, rice yields decreased owing to a warming trend (Fig. 3). Climate warming decreases crop yield by hastening crop development rate, and reducing crop growth period and yield accumulation. Moreover, heat stress, which increases with climate warming, induces crop floret sterility and reduces crop yields (Tian et al. 2009). In eastern and southern China, trends in precipitation and SR_D , and their effects on rice yields during 1980–2008, were diverse. Generally, rice yields increased in the east and south because of decreased precipitation and increased SR_D ; however, at some local areas of

southern China where SR_D was negatively related to rice yields (Zhang et al. 2010), rice yields increased due to a decrease in SR_D during 1980–2008 (Figs. 1, 2 & 3). Wheat production in the southeast was stressed by excess precipitation and low SR_D . In contrast, in the arid and semi-arid areas of the north, northwest and northeast, wheat production was stressed by low precipitation (Fig. 2). Besides the role of increased Tmean in reducing crop growing duration and increased heat stress in inducing crop floret sterility, we found that response patterns of wheat yield to Tmean and precipitation were opposite (Fig. 2D,E),

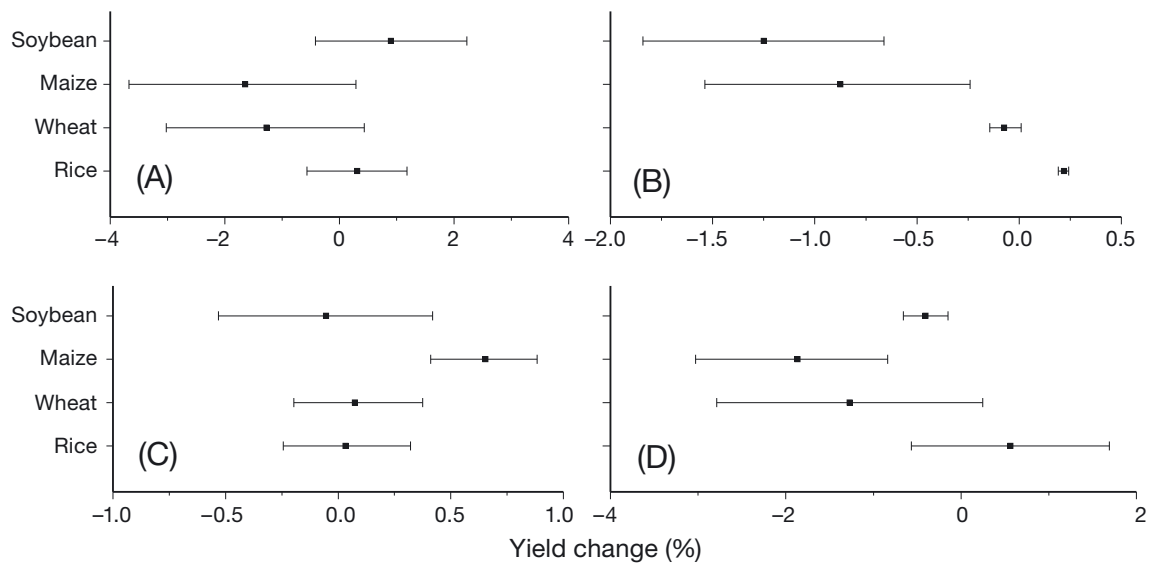


Fig. 7. Estimated net impact of all trends in (A) mean temperature, (B) precipitation, (C) solar radiation, and (D) climate overall during 1980–2008 on crop yields for all China. Values are area-weighted planting averages. Lines extend from 5 to 95% confidence interval from bootstrap resampling, with 1000 replicates. ■: median estimate

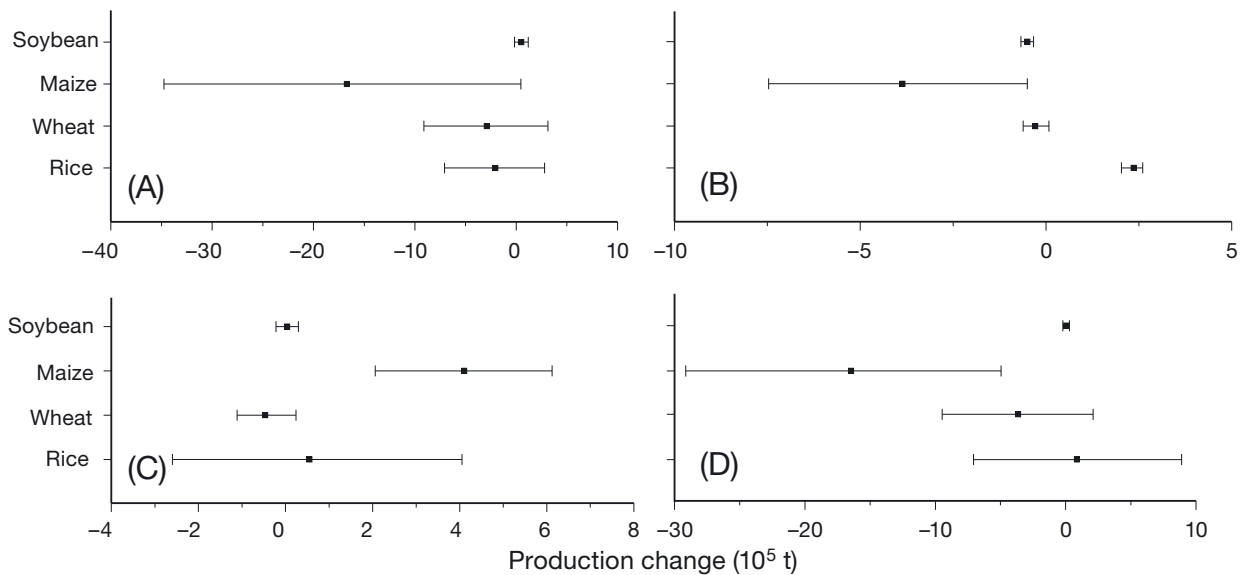


Fig. 8. Estimated net impact of trends in (A) mean temperature, (B) precipitation, (C) solar radiation, and (D) climate overall during 1980–2008 on crop total production for all China. Lines extend from 5 to 95% confidence interval from bootstrap resampling, with 1000 replicates. ■: median estimate

which suggests that a warming trend should also affect wheat production indirectly, via temperature-induced droughts. Likewise, negative effects on crop yields from increased SR_D were also observed in parts of these regions, suggesting the indirect effects of SR_D -induced droughts. These results are consistent with our previous study (Tao et al. 2003). The response and mechanisms of maize and soybeans were similar to those of wheat (Fig. 2). As a result, cli-

mate trends during the period reduced crop yields, particularly in aforementioned arid and semi-arid areas (Figs. 4, 5 & 6).

It is generally believed that crop yield in mid and high latitude regions can benefit from climate warming (IPCC 2007), and that improved thermal conditions permit extensions of the area suitable for double cropping, as well as northward cropland extension (Dong et al. 2009). Our results, however,

suggest that the particular crops and regions that have been most affected and should be prioritized for adaptation are maize and wheat in the arid and semi-arid areas of northern and northeastern China. These are where climate-warming-induced droughts could limit the benefits of improved thermal conditions. In fact, the wheat planting area in the northeast has continued to decrease over the last few decades (Tong et al. 2003), which could be partly ascribed to the effects of climate trends. Adaptation options—such as adoption of cultivars with longer growing periods or those that are drought-resistant and tolerant of high temperatures—can be very effective in coping with ongoing climate change. Further, advanced water-saving technologies for agricultural irrigation, and soil and water conservation techniques for rain-fed agriculture, should be encouraged by agricultural extension authorities.

4.2. Uncertainties in estimating effects of climate trends on crop yield

The present study represents several important advances in estimating the effect of climate trends on crop yield in China. Our estimates are based on improved datasets of crop yield by county, crop phenology, and the updated homogenized temperature series (Li & Yan 2009). Estimates of climate effects on crop yields for China, based on planting-area weighted averages and using different datasets and methods, are smaller than previous estimates at county, provincial and national scales (e.g. Tao et al. 2008, You et al. 2009, Lobell et al. 2011a, Zhang & Huang 2012). For example, using country-level FAO data on production quantity, as well as different climate data and analysis methods, the median estimates of Lobell et al. (2011a) show that net effects in China of Tmean trends from 1980 to 2008 on crop yields were approximately 1.0, –2.0, –7.0, and –1.0% for rice, wheat, maize and soybeans, respectively. Using provincial crop yield data from 1979 to 2000, the CRU TS 2.0 monthly climate datasets (Mitchell & Jones 2005) and a Cobb-Douglas form of wheat yield function, You et al. (2009) showed that rising temperature during the period accounted for a 4.5% decline in Chinese wheat yield. Recently, Zhang & Huang (2012) showed that Tmean trends during 1980–2008 had positive effects in northern China based on county level data, which offset losses from warming in other areas and improved national production by up to 1.6% relative to the mean over the study period. For maize, approximately 5.8% of production was lost from increases in Tmean. How-

ever, in the present study, positive effects of Tmean trends on wheat production were only for winter wheat, mainly in the NCP. These uncertainties may originate from climate and crop production datasets, analysis methods, and spatial scales.

The uncertainties of our estimates were represented by a 5 to 95% confidence interval from bootstrap resampling, with 1000 replicates. The confidence intervals varied by county and climate variable (Figs. 7 & 8 and Figs. S2 & S3 in the supplement), and were large for some counties. Nevertheless, climate effects on crop yields were significantly different from zero in many counties, which warrants the promotion of adaptation measures.

As in many previous studies, we did not fully incorporate long-term adaptation possibilities or effects of extreme temperature or precipitation events. Direct effects of elevated atmospheric CO₂ concentration on crop yield were also not considered, which could have increased C₃ crop yield (rice, wheat, soybeans) by approximately 3% with CO₂ concentration increasing from 339 ppm in 1980 to 386 ppm in 2008 (Lobell et al. 2011a).

5. CONCLUSIONS

The present study, based on improved crop yield datasets by county, crop phenology and the updated homogenized temperature series, represents several important advances in estimating the effects of climate trends on crop yields in China.

We found clear regional climate trends during the period 1980–2008, particularly for temperature. Such climate trends have had measurable effects on major crop yields, with a distinct spatial pattern. For the entire country, the area-weighted planting mean showed that climate trends during the period reduced wheat, maize and soybean yields by 1.27, 1.73 and 0.41%, respectively, while it increased rice yield by 0.56%. As a result, overall climate trends reduced wheat and maize production by 3.60×10^5 and 1.53×10^6 t, respectively, while increasing rice and soybean production by 7.44×10^4 and 4.16×10^3 t, respectively. Our estimates of climate impacts were smaller than in previous studies, which used different scales, datasets and methods. The particular crops and regions that have been most affected and should be prioritized for adaptation are maize and wheat in arid and semi-arid areas of north and northeast China. Climate warming decreases crop yields by accelerating the crop development rate, reducing crop growth duration and yield accumulation, as well as by increasing tempera-

ture extremes and heat stress. In addition, droughts induced by climate warming and increased SR_D are among the major mechanisms for yield loss.

Adaptation options—such as adoption of cultivars with longer growth duration, that are tolerant to high temperatures and resistant to drought—can be very effective in coping with ongoing climate change. In addition, advanced water-saving technologies in agricultural irrigation, and soil and water conservation techniques in rain-fed agriculture, should be encouraged by agricultural extension authorities. However, this study did not fully incorporate long-term adaptation possibilities. Adaptation experiences of the past few decades should be further investigated for designing effective adaptation strategies.

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