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Untangling relative contributions of recent climate and CO₂ trends to national cereal production in China

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Abstract

There is increasing evidence of crop yield response to recent global warming, yet there is poor understanding of the relative contributions of different climatic variables to changes in crop production. Using a spatially calibrated crop model with cultivars and crop inputs held constant for the year 2000, we simulate idealized national cereal production during the period 1961–2010 under different combinations of observed climate and CO₂ forcings. With increasing CO₂ and all climate forcings, production shows a slight and insignificant change (−0.9% between 1961 and 2010); however, without CO₂ the combined climate forcings decrease production (−8.6%). Changing one climate variable at a time, whilst holding the other variables constant at 1961 values, observed warming has virtually no overall effect on production (0.01%), precipitation decreases it by 1.2% and radiation decreases it by 7.0%. The effects are management and crop dependent, with decreasing radiation responsible for reduced irrigated crop production, and precipitation for variability in rain-fed crop production. Rice is the most sensitive crop, with the largest decline (−12.4%) in simulated production. Wheat shows reduced yield (−9.7%) owing to climate factors, whilst offset by CO₂ fertilization (overall change 0.9%). Maize shows insignificant change (−1.2%) and moderate increase in production (2.6%), respectively. These model results suggest that decreasing radiation due to increasing aerosol concentration and other atmospheric pollutants has had a greater effect on crop production than warming trends in China. This underscores the need for crop–climate studies to resolve better the effects of radiation on crop yield and examine climate model projections of radiation in greater detail.

Keywords: climate change, relative contribution, cereal production, China

1. Introduction

Advances in technology and changing agronomic practices have been responsible for significant increases in agricultural production in China, however, production remains weather



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dependent and shows high interannual variability and susceptibility to extreme events (Yang 1999, Editorial board 2007). Recent climate variability in China is characterized by increases in mean temperature, complex spatial and temporal patterns in precipitation and decreases in solar irradiance (Ding *et al* 2007, Liu *et al* 2004, Zhang *et al* 2011). Changes in these climatic variables drive changes in overall crop production through interacting effects on crop yields and harvest areas. Recent climate trends have been shown to affect crop yields and production in other parts of the world, but to date the net impacts of these trends on food production in China is still unclear (Piao *et al* 2010, Welch *et al* 2010, Lobell and Asner 2003, Nicholls 1997).

Empirical assessments (statistical and observed) of crop yield–climate relationships in China show inconsistent results and may be difficult to aggregate to the national level (Zhang and Huang 2012, Zhang *et al* 2010, You *et al* 2009, Tao *et al* 2008, Li *et al* 2011). Differences in assessment scale (site, provincial or national level), selection of empirical models (such as methods for yield de-trending) or predictor variables and data reliability prevent direct comparisons and generalizations. In addition, empirical models are limited in their application at a regional scale in China due to the availability of agronomic data, for example, county level yields are only available from 1980 onwards.

Crop simulation models are computer programs that represent the growth and development of crops as a function of environmental conditions (weather and soil), crop genetics and agronomic management strategies. They are widely used in climate change-related agricultural impact assessment (White *et al* 2011). Such models allow crop varieties and management practices to be kept constant, so that the effects of climate can be explored without the confounding effects of changing agronomic management. At some specific sites, they have been used to identify the impacts of recent climate change and have produced consistent results (Chen *et al* 2010a, 2010b, Liu *et al* 2010, Song *et al* 2006).

We investigate the impacts of observed climate change on cereal production in China at the national scale using a regional simulation method. The objectives of the study are to (1) determine the net effects of recent climate change and increased CO₂ concentration on cereal production; (2) untangle the relative contributions of climatic variables, and (3) examine the sensitivity of crops and cropping systems to recent climate change.

2. Materials and methods

Rice, wheat and maize, which together provide over 85% of the cereal production in China, are simulated using CERES-Rice, CERES-Wheat and CERES-Maize, all part of the Cropping System Model in DSSAT 4 (version 4.0.2). These models have been relatively well tested in a range of environments including China (Jones *et al* 2003). To estimate national crop production, the models were operated at a 0.5° × 0.5° grid scale across China, using a set of regionalized input parameters including crop cultivars and management (such as sowing date, fertilizer use) based on

previous calibration studies that represent locally dominant practices in the year 2000 (Xiong *et al* 2007, 2008a, 2008b)

Gridded daily weather data (maximum and minimum temperature, precipitation and sunshine hours) for 1961–2010 were used from the Chinese Meteorology Administration, interpolated from around 2400 meteorological observations by altitude corrected Inverse Distance Weighted (IDW) method. Daily solar radiation is required for CERES-crop models and was calculated from an empirical global radiation model, using a linear relationship with h/H (actual daily hours of sunshine/maximum daily hours of sunshine), which has been validated in China (Chen *et al* 2006, Pohlert 2004). Gridded soil information, including texture, bulk density, pH, organic carbon, total nitrogen, was derived from the Chinese soil database and 1:1 M scale soil map of China (Chinese National Soil Survey Office 1998). Soil water characteristics, including water-holding capacity at drained lower and upper limits, and at saturation, were calculated from soil texture, organic carbon and bulk density (Rawls *et al* 1982). One dominant soil type was selected for each grid based on the geographical location of the soil types and its area in the grid. Crop areas in each county were available from 1981 to 2010 from the China Agricultural Yearbook (Chinese Agriculture Press), converted to the grid scale using an area-weight method (Xiong *et al* 2007). Observed atmospheric CO₂ concentrations were taken to increase from 318 ppm in 1961 to 388 ppm in 2010, according to IPCC online datasets.

To isolate the effects of climate variables and rising CO₂ six simulations of national cereal production were performed. Each simulation used the observed 50-year time series of one or more selected climatic variable (named as follows; temperature [T], precipitation [P], radiation [R], $T + P + R$, CO₂ concentration [CO₂], and all [$T + P + R + CO_2$]), with the remaining variables held constant (using repeated series of the daily observed values from 1961). For example, for the simulation with varying temperature (T), we used the observed 1961–2010 daily maximum and minimum temperatures and held CO₂ constant at the observed 1961 concentration and continuously repeated the 1961 time series for the other climatic variables (precipitation and radiation). In each simulation rice was assumed to be fully irrigated (a 30 mm irrigation was applied whenever the value of soil water content in the top 30 cm falls below 80% of the field capacity), and wheat and maize were under fully irrigated and rain-fed conditions. Nutrient availability, pests and diseases were not incorporated in the analysis. To calculate total change in cereal production, simulated yields, excluding the effects of management changes, were multiplied by the reported average crop area for 1981–2010. The simulations were idealized in that they represent potential production under the management practices of 2000, such that the difference between simulations depends only on the combination of specific climatic factors.

Linear regression analysis was used to identify trends in the simulated production time series. The slope of the linear regression line against time was calculated using Student's t -test at 95% confidence levels. The change in production was estimated by taking the sum of the slope of the linear

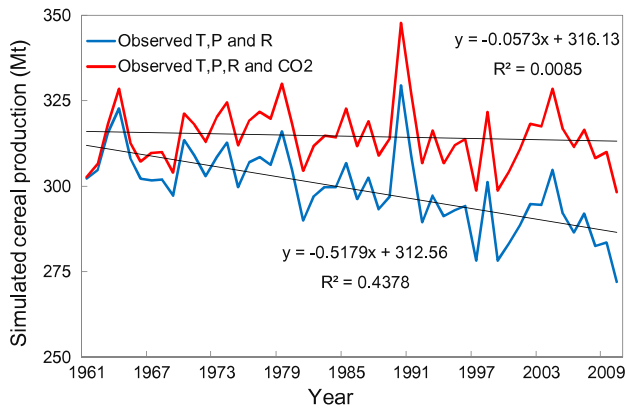


Figure 1. Simulated national cereal production in 1961–2010, with drivers of $T + P + R$ and all.

regression from 1961 to 2010 and expressing this as a per cent change in production from the 1961 value. The results may be dependent on the reference climate (here defined as 1961), the assessment period (1961–2010) and the harvest area used to aggregate the national production (the average area for the period 1981–2010), therefore, a sensitivity analysis was conducted using different values of these inputs.

3. Results

3.1. Impacts of recent climate and CO₂ trends

With cultivars and management practices held constant at year 2000 values, recent climate trends (represented by the simulation $T + P + R$) caused a negative impact on simulated yields, resulting in a simulated decline in national cereal production of 25.9 Mt over the past five decades, or a decrease of 8.6% between 1961 and 2010 (figure 1). Simulated production with constant climate and observed atmospheric CO₂ concentrations increased by 26.1 Mt (data not shown), suggesting that according to the simulation methodology a 70 ppm increase in atmospheric CO₂ since 1960 could increase national production by roughly 8.7%. The simulation combining the effects of recent climate trends and increasing CO₂ produced a small but insignificant decrease in production of 2.9 Mt (0.9% between 1961 and 2010) (figure 1), showing that CO₂ fertilization offset the simulated negative effects of recent climate trends on crop production.

3.2. Relative contributions of climatic variables

To understand how the separate climatic variables contributed to the decline in simulated production of 25.9 Mt over the past five decades shown in figure 1, figure 2 shows how cereal yields varied between the three simulations in which observed 50 yr time series were used for one climate variable each (T , P or R) and all others used repeated series of the observed values from 1961 (as described in section 2). The yield responses are averaged according to latitude. The national cereal production, computed based upon the simulated crop

yields and the reported crop areas for 1981–2010, is shown in figure 3.

The simulation suggests that the warming trend from 1961 to 2010 would result in negative yield impacts at low latitudes but positive impacts at higher latitudes (figure 2). However, the aggregated national cereal production with varying T only had a small change over the past five decades (figure 3). Based on the crop area of 1981–2010, simulated cereal production exhibited a slight decline (−0.02 Mt or −0.01% compared to the simulated production in 1961), which is not significant at the 95% confidence level (figure 3(a)). Simulated production with observed P showed a slight decreasing trend, of −3.7 Mt over the five decades, or −1.2% compared to the production in 1961 (figure 3(b)), with larger yield reductions for wheat and maize (figure 2). This trend is also not significant at the 95% confidence level. Varying R reduced yields of rice and wheat (figure 2), leading to a substantial decrease in simulated national cereal production of −21 Mt over the period, or −7.0% relative to the simulated production in 1961 (figure 3(c)).

Climate change not only affects crop yields, but also production area. Because the historical change of crop area was not included in our simulation, we conducted a sensitivity analysis in which the reported crop area of the different decades (1980s, 1990s and 2000s) was used to aggregate the production, to investigate the possible impacts of crop area change on estimated contributions (figure 4). This had small impacts on estimated contributions, for example, the impact of warming on production exhibiting a small decrease using the crop area of 1980s (−0.47%) and 1990s (−0.17%), and a slight increase with the area in the 2000s (0.69%).

3.3. Changes in production for different crops and management

Figure 5 and table 1 show the estimated net loss or gain in simulated production under different climatic drivers. The production is summarized for irrigated and rain-fed cereals (figure 5) and by crop (table 1).

The effects of recent climate change produced clear differences in production response between irrigated and rain-fed crops. Recent climate change trends caused negative effects of −10.9% on production for irrigated cereals (figure 5(a)). This decrease was mainly due to the effects of reducing radiation, as production with varying R showed a substantial reduction of −9.6%. The estimated yield promotion by elevated CO₂ was 7.8% for crops under optimal irrigation conditions, which led to an overall moderate negative change (−3.5%) in production under $T + P + R + CO_2$ (all). In contrast, recent climate change tended to decrease the production for rain-fed cereals, although the changes were not greater than the interannual variability, with relatively modest changes under T , P and R separately.

Estimated losses in production under $T + P + R$ were substantial for rice (−12.4%) and wheat (−9.7%), but only −1.2% for maize. Reduction in radiation caused a 12.4% decrease in production for rice, representing over 90% of the overall production reduction in $T + P + R$, while the

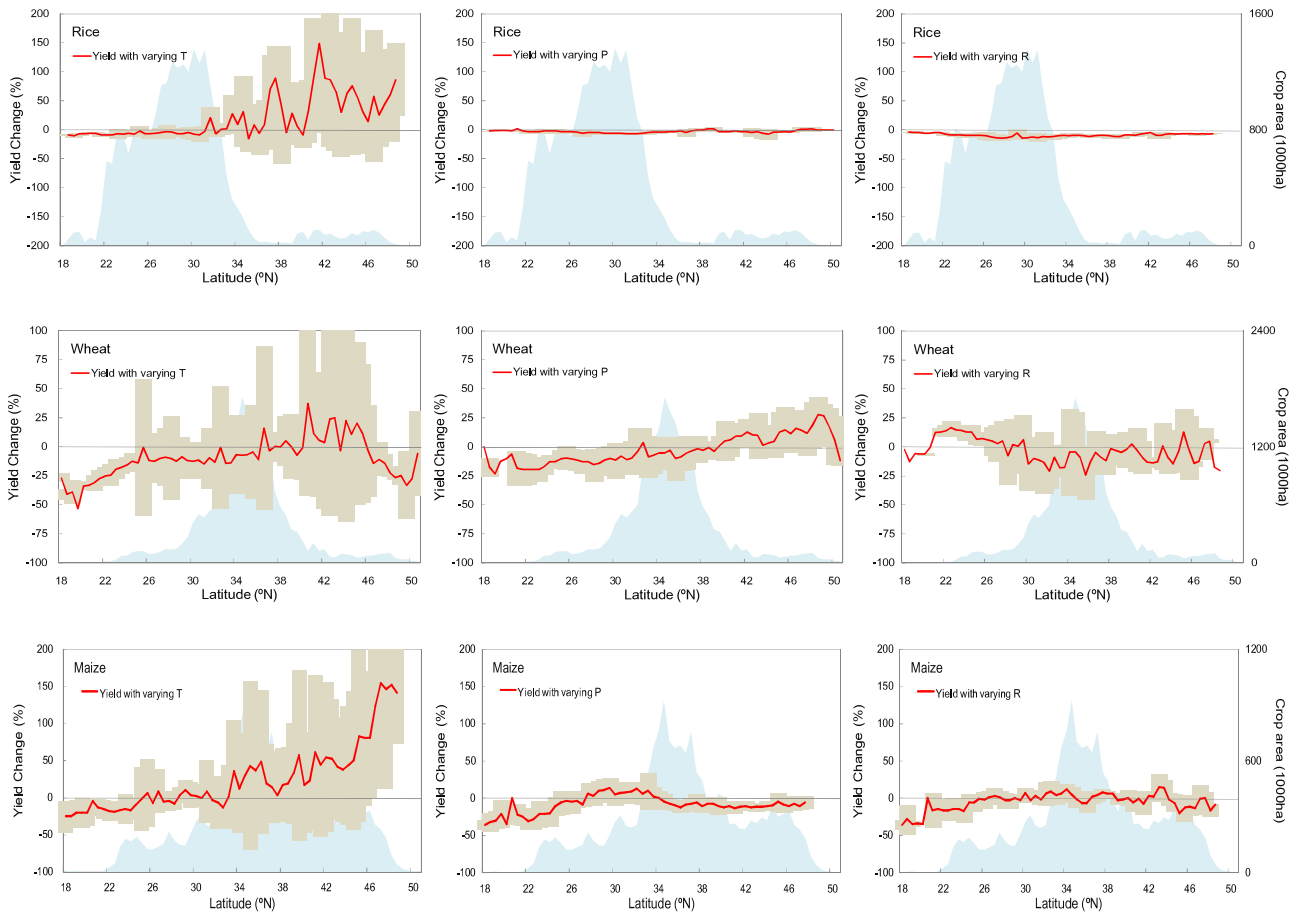


Figure 2. Yield changes (compared with the simulated yields with 1961 climate) according to latitude and crops, driven by separate climatic variables of temperature (*T*), precipitation (*P*) and radiation (*R*). Red lines are latitudinal mean values of all of the simulation grids. The shaded band indicates standard deviation across grids of each latitude. The pale blue histogram indicates the latitudinal distribution of the crop area in 1981–2010.

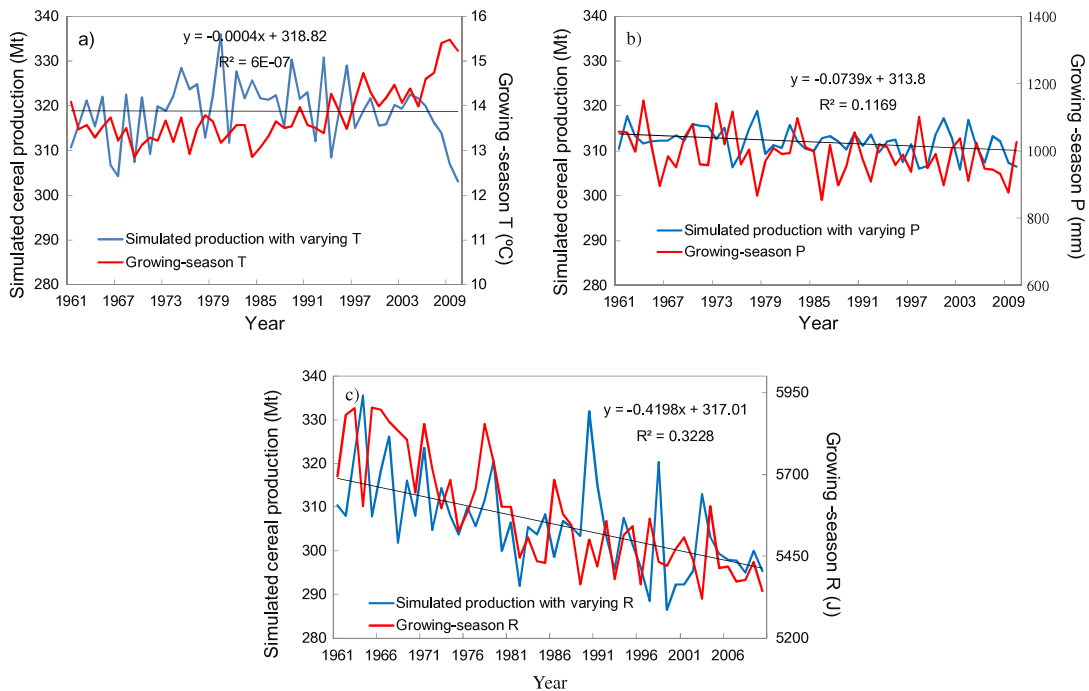


Figure 3. Simulated national cereal production in 1961–2010, with (a) varying *T*, (b) varying *P* and (c) varying *R*, along with best-fit lines of the production changes, and annual changes of associated climatic variables. Other climate variables are kept at 1961 values.

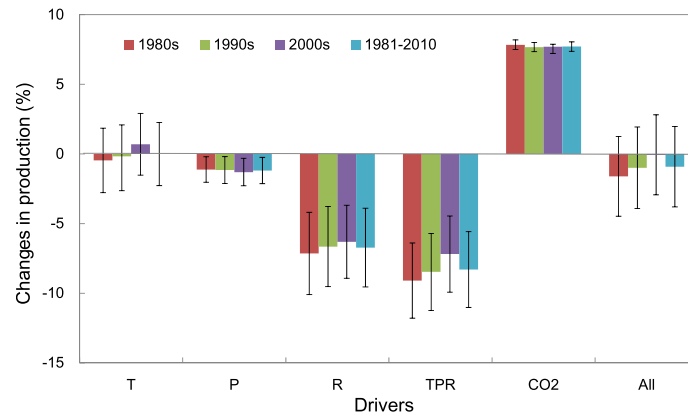


Figure 4. Relative contributions to national cereal production by different climatic drivers, using different decadal average crop areas.

Table 1. Simulated changes in production (%) under different climatic drivers, for different crops.

Crops	Simulated production in 1961 (Mt)	Changes in production (%), compared to production with 1961 climate					
		T	P	R	TPR	CO ₂	All
Rice	140	0.4	-0.4	-12.4 ^a	-12.4 ^a	8.7 ^a	-4.2 ^a
Wheat	75	-4.6 ^a	0.3	-3.9	-9.7 ^a	11.7 ^a	0.9
Maize	96	3.1	-3.5 ^a	-0.6	-1.2	3.2 ^a	2.6

^a Significant at 95% confidence level.

growing season warming provided relatively weak impacts, with an insignificant increase (0.4%) in production. Warming and reducing radiation were the main causes for the decrease in simulated production for wheat, with production reductions of -4.6% and -3.9%, respectively. Maize showed a slight and insignificant decrease in production (-1.2%) under climate change ($T + P + R$), with the change of P resulting in a moderate decrease (-3.5%), while warming produced a small increase (3.1%). Elevated CO₂ significantly boosted production for all crops, with ranges between 3.2% and 11.7%, with largest promotion for wheat (11.7%), and smallest for maize (3.2%). Changes in production with full complement of climate variables and elevated CO₂ (All) were negative for rice (-4.2%), and positive and insignificant for both wheat (0.9%) and maize (2.6%).

4. Discussion

4.1. Yield response to recent climate trends and possible mechanisms

A general yield pattern responding to recent warming trend is that crops exhibit yield losses in areas at low latitudes, while experiencing gains at high latitudes. Wheat and maize appear to have more negative effects from warming than rice in low latitude regions (figure 2). Accelerated growth rates and increased heat stress explain the yield decreases at low latitudes. These findings are consistent with prior empirical studies for China and at the global scale (Zhang and Huang 2012, Lobell and Field 2007). In crop areas at high latitudes, the reported yield gains are much larger

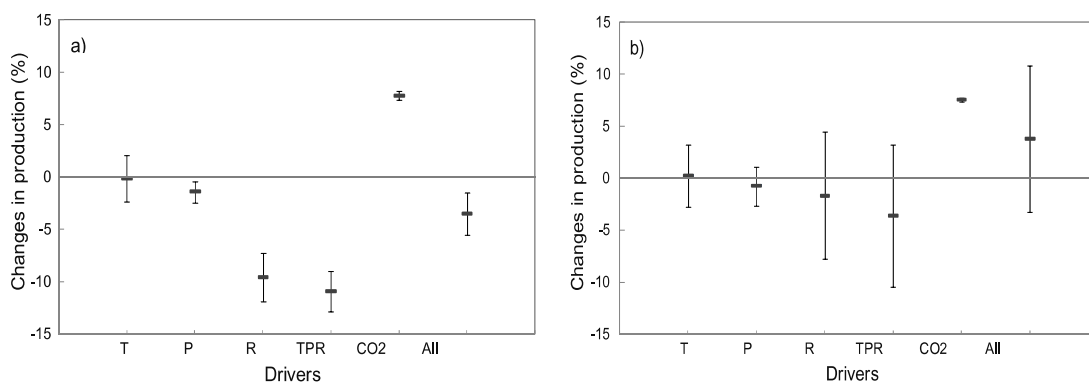


Figure 5. Estimated changes (compared to the simulated production with climate of 1961) in simulated national production under different climatic drivers for (a) irrigated cereals and (b) rain-fed cereals. Error bars show an estimate of the 95% confidence interval.

than previous estimations except for wheat. These larger yield gains in high latitude regions are in part because the simulation systemically produced lower yields in the pre-warming period (before 1980s) due to the shorter growing seasons as we used current (2000) warming-adapted crop varieties, and in part because of a large yield promotion, in particular after the 1980s, caused by the decrease in cold stress events. These simulation results are supported by observed expansion in the area of rice and maize in northeast China and successive good harvests since 2000 in north China (Yang *et al* 2007). Spring sown wheat is the only crop to exhibit depressed yields in high latitude regions due to an accelerated growth rate under warmer spring and summer conditions, leading to substantial decreases of yield in areas at latitudes greater than 45°N.

Rainfall is considered an important factor in influencing crop yield variability, particularly in countries with monsoon climate (Challinor *et al* 2003). But in China, precipitation produces less climate induced yield changes than warming at most latitude bands because: first, there are no pronounced trends in precipitation during the growing season in most of the crop areas, and any precipitation effects in individual regions are often canceled out when averaged over latitude bands; and second, because the majority of the cereal planting area in China is irrigated (over 70% in 2000) so that yields are relatively insensitive to changes in precipitation. However, precipitation appears to have large detrimental effects for some crops at some latitudes, for example, wheat at low and middle latitudes (18–38°N) and maize at low latitudes (18–26°N) exhibit substantial yield decreases (figure 2) due to increased soil water stress. In the model, as the soil dries, a greater proportion of biomass is partitioned to roots and thereafter the potential biomass production rate is reduced; this decreases crop yield, even for irrigated crops because a soil water deficit factor (80%) is used to trigger the operation of irrigation in the simulations. The significant negative effects of precipitation at some latitudes suggest that soil water stress has increased from 1961 to 2010, which is in agreement with observed increases of drought events in some regions (Piao *et al* 2010).

Decreased solar radiation has been observed globally since the 1960s due to increasing aerosol concentration and other air pollutants (Liepert 2002, Stanhill and Cohen 2001). This so-called global dimming reduces the total amount of photosynthetically active radiation (PAR, 400–700 nm) and therefore potentially reduces crop yields through decreased photosynthesis (Chameides *et al* 1999). Substantial decreases in yields are simulated in the main crop areas (i.e. eastern China with latitude spans 20–40°N) (figure 2) and with crops under better management (i.e. irrigated crops) (figure 3). In these main crop areas, air pollution is usually more serious due to their faster rates of urbanization and larger populations, and because agriculture in these areas is generally more intensive and under better management (Chameides *et al* 1999). Due to the unavailability of detailed radiation observations, the solar radiation used in our study was based on an empirical model and only considered the extra-terrestrial radiation and the sunshine hours (Pohlert 2004). It neglects the possible

increase in the fraction of diffuse PAR due to the changes in cloud and aerosol, which might increase crop yields by allowing more PAR to reach shaded leaves. However, previous CERES simulations revealed that increased diffuse fraction due to aerosol loading tends to increase crop yields in clear sky days, but decrease yields in overcast days, with a consequential negative influence for much of the current climate (Greenwald *et al* 2006). In reality, the influence of aerosols is projected to be more negative on yields, given the decreased clear sky visibility and increased precipitation days over the past decades (Li *et al* 2011, Wang *et al* 2009).

4.2. Relative contribution of climatic variables to simulated production change

Increased atmospheric CO₂ has the largest positive contribution to the estimated change in production (figure 4) (8.7%) and counteracts most of the climate-related yield reductions. We recognize that the CO₂ fertilization effects may be overestimated in the models, because the simulated yield promotion of elevated CO₂ is much higher than the observations in the FACE studies, but the magnitudes of these effects are still under debate (Tubiello *et al* 2007, Long *et al* 2006). However, the increased production caused by elevated CO₂ was still around 5% when the CO₂ yield promotion in the crop models was reduced by 50% roughly in accordance with the FACE experimental observations (Ainsworth *et al* 2008). This is still larger than the simulated production decline caused by varying *T* (−0.01%) or varying *P* (−1.2%). The yield effects caused by elevated CO₂ concentration are often neglected for climate–yield analysis in China, possibly due to the difficulty in separating the confounding effects of elevated CO₂ concentrations and technology on yields. This result indicates a significant role of CO₂, and that change in CO₂ concentration should be taken into account in evaluating recent and future crop–climate interactions.

The effects of recent warming trends in our simulation are benign compared to most empirical estimations. Based on climate–yield relationships, previous studies in China reported past warming reduced production of maize (~−10%) and wheat (−3%~−10%), and increased for rice (~1%) (Zhang *et al* 2010, You *et al* 2009, Tao *et al* 2008). Whereas in this study, these impacts are estimated to be negative but less severe for wheat (−4.6%), moderately positive for maize (3.1%), and slightly positive for rice (0.4%). One reason for the differences is the time period used; 1961–2010 here and 1979–2002 in Tao *et al* (2008). As warming is more pronounced since 1980, adjusting our time period to 1981–2010 led to larger negative effects for all crops (−7.2% for wheat, −2.0% for maize and −1.1% for rice), but these changes are still smaller than previous estimations. A possible reason for the larger climate impacts in other studies is likely to be the covariance of climatic variables; warming is often associated with decreasing radiation (Zhang and Huang 2012). This correlation between climatic variables has been recognized as a source of uncertainty in separating the effects of warming in empirical models and has biased some estimates of rice yield impacts in Asia (Sheehy *et al* 2006).

In addition, the contributions of the individual climate variables depend to some extent on the data used, such as the reference period (1961) and average harvest area (1981–2010). Sensitivity analysis (not reported here) demonstrates that using the long-term mean daily values (1961–2010) rather than 1961 as the reference climate has very little effect on the results. However, changes in crop area, such as the expansion of crops in northern areas, movement in the main crop production areas and switches between crops in certain areas, which were not considered in our simulations, could outweigh the effects of climate change on yields (Auffhammer *et al* 2006). Production aggregated by various reported crop areas (figure 4) demonstrates its effects on warming contributions. Recent warming trends generally cause positive effects in cooler areas and negative effects in warmer areas and expansion of cropping in northern areas (Yang *et al* 2007) and movement of some crops to cooler areas (Liu *et al* 2010) has occurred since the 1980s, when warming trends have been strongest. Thus, production estimates based on recent cropping areas and distributions may exhibit less negative and more positive effects from warming.

Overall, our simulation suggests that, with cultivars and management practices held constant at year 2000 values, recent climate trends caused a pronounced decline in production of 8.6%, in which the relative contributions of T , P , R are 0.1%, 14% and 81.4%, respectively, with the remainder likely attributed to interactions between the variables. Decreasing radiation plays a major role in the production decline, in contrast to current understanding that warming is the main cause of yield decline. The moderate negative contribution of P on production (−1.2%) supports prior findings that soil moisture deficit has increased during recent decades in China with negative consequences for food production in China (Tao *et al* 2003).

4.3. Uncertainties

Site-specific models have been used widely to estimate impacts of past and future climate change. More rigorous calibration methods have improved the agreement between simulated and census/observed yields across different temperature conditions, but using them to the estimate of climate contribution to yield variability over time remains highly challenging (Li *et al* 2011). Crop models are generally unable to simulate the effects of most pests (insects, diseases, weeds) and some of the yield damage caused by extreme events (heat stress, waterlogging, etc) is often underestimated (Xiong *et al* 2008a, 2008b, Yao *et al* 2007). As the yield losses due to pests and extreme events are often reported to increase during warmer conditions (e.g. during recent decades), neglect of these stresses may under estimate the effects of recent climate patterns (Li *et al* 2011). Further, the assumption of unlimited fertilizer application and full satisfaction of crop water requirements for irrigated crops means simulated yields are over optimal and likely to be higher than yields achieved by farmers (Lobell *et al* 2011).

Not with standing these uncertainties, our results offer a first-order estimation of the relative contributions of separate climate variables on crop production, with important conclusions which provide greater insight to crop–climate interactions in China. First, the negative effects of recent warming on yields in China are less severe than previously understood, and over the short-term continued warming may be less harmful than currently anticipated by some studies. Second, as decreasing radiation is associated in part with human activities (e.g. land degradation and anthropogenic aerosol emissions), some of which are on the increase (Liang and Xia 2005, Lu *et al* 2010, Zhuang *et al* 2011, Mukai *et al* 2004), there is potential for policy interventions to mitigate impacts on production. Support for breeding crop cultivars with higher photosynthesis use efficiency could form part of future adaptation strategies in agricultural technology.

5. Conclusion

Recent climate trends produce a discernible negative impact on simulated cereal production in China with cultivars and management practices held constant at year 2000 values. The largest contribution is caused by decreasing radiation during the growing season. These conclusions are supported by other results from empirical models which show that decreased solar radiation negatively contributes to crop yields in a number of specific sites, but it was usually accounted as the warming effects due to the covariation of rising temperatures and reduced radiation (Zhang *et al* 2010, Sheehy *et al* 2006). However, the present study provides a more precise estimation of the relative contributions, and demonstrates that the negative impacts on China's simulated food production caused by reduced solar radiation greatly exceeds the impacts caused by temperature and precipitation. There are considerable differences in spatial patterns of response to observed climate between the three crops and between the three climate variables. Although the crop models are sensitive to changes in growing season temperature, the simulated effects of recent warming alone are small and insignificant. These conclusions question some findings that past warming has been the dominant contribution to decline in yields.

The simulation methodology requires assumptions about which periods are used to define baseline conditions and how changes are calculated. We have not considered changes in agricultural management and crop types during the simulation period, or indirect, but possibly important, effects of warming on crop production, such as a warming-induced increase in pests and diseases and heat stress due to their poorly understood mechanisms and limited observational data. Our simulations of the negative effects of recent warming on production in China are smaller than those found in empirical studies. Our results indicate that, at the national scale, decreasing radiation may have had a more important effect on national cereal production than other climatic variables. The identification of the individual contributions of observed trends in climatic variables and CO₂ concentration to yield variability provides important insights for understanding

recent observations. These results highlight the importance of radiation and research to understand its effects on crop yield and its representation in global climate model projections would enable better assessment of climate change impacts.

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