



Future cereal production in China: The interaction of climate change, water availability and socio-economic scenarios

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ABSTRACT

Food production in China is a fundamental component of the national economy and driver of agricultural policy. Sustaining and increasing output to meet growing demand faces significant challenges including climate change, increasing population, agricultural land loss and competing demands for water. Recent warming in China is projected to accelerate by climate models with associated changes in precipitation and frequency of extreme events. How changes in cereal production and water availability due to climate change will interact with other socio-economic pressures is poorly understood. By linking crop and water simulation models and two scenarios of climate (derived from the Regional Climate Model PRECIS) and socio-economic change (downscaled from IPCC SRES A2 and B2) we demonstrate that by the 2040s the absolute effects of climate change are relatively modest. The interactive effects of other drivers are negative, leading to decreases in total production of –18% (A2) and –9% (B2). Outcomes are highly dependent on climate scenario, socio-economic development pathway and the effects of CO₂ fertilization on crop yields which may almost totally offset the decreases in production. We find that water availability plays a significant limiting role on future cereal production, due to the combined effects of higher crop water requirements (due to climate change) and increasing demand for non-agricultural use of water (due to socio-economic development). Without adaptation, per capita cereal production falls in all cases, by up to 40% of the current baseline.

By simulating the effects of three adaptation scenarios we show that for these future scenarios China is able to maintain per capita cereal production, given reasonable assumptions about policies on land and water management and progress in agricultural technology. Our results are optimistic because PRECIS simulates much wetter conditions than a multi-model average, the CO₂ crop yield response function is highly uncertain and the effects of extreme events on crop growth and water availability are likely to be underestimated.

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1. Introduction

Food production in China is a fundamental component of the national economy and driver of agricultural policy. Its global importance is measured by the fact that Chinese agriculture supports staple food supply for most of its population (~20% of global population) and produces 30, 15, and 17% of global production of rice, wheat and maize, respectively (as of 2003; Winters and Yusef,

2007). Sustaining and increasing this output to meet growing demand faces significant challenges including, land degradation, maintaining yield gains through agricultural technology, changing patterns of food consumption (per capita increase and changes in dietary preference), increasing population, pressure to use agricultural land for other purposes, and competing demands for water currently used for irrigation (Gale, 2002; Zhao et al., 2008). In the face of these challenges there is increasing concern about the impacts of future climate change, and the interaction of climate change, water availability, land use change, and socio-economic development with food security (Gregory and Ingram, 2000; Parry et al., 2001; Rosegrant and Cline, 2003; Gregory et al., 2005).

Water availability is critical for agricultural production (Fischer et al., 2007) and is already a major stress factor for China's grain

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production, particularly in northern parts of the country (Li, 2006). In China, irrigated agriculture is the primary consumer of water and accounts for over 70% of total use. More than 75% of grain production in China is from irrigated land. Irrigation plays a major role in food security and poverty alleviation in China, and even in stabilizing the world grain market due to the significance of China's grain imports (Jin and Yong, 2001).

Studies of climate change impacts on crops in China show conflicting results and uncertainties primarily relating to differences between crop models (empirical, econometric, biophysical), differences between GCM scenarios and whether the effects of CO₂ fertilization are included. CO₂ fertilization tends to increase yields and offset the negative effects of higher temperatures. Recent reviews (e.g. IPCC, 2007) conclude that simulations of CO₂ effects on crop yields are still within the range observed in experimental trials (Kimball et al., 2002). Econometric studies using Ricardian analysis show both negative (Wang, 2008) and positive effects on average farm net revenues (Liu et al., 2001). Lobell et al. (2008) presented empirical relationships between observed harvests and monthly temperature and precipitation for seven crops in China. Only two of the relationships were statistically significant ($P < 0.05$). They modelled probability distributions of crop production changes using multi-model output (20 GCMs) for 2030 and found moderate (<5%) increases in five cases (including wheat) and decreases for rice and maize.

Crop modelling studies without CO₂ fertilization tend to show negative impacts on crop production. Tao et al. (2008) made a probabilistic assessment of changes in rice yield (based on 20 different climate scenarios) and found that rice yield would decrease with a probability of 90%. Similar results have been reported by Jin et al. (1995) and Yao et al. (2007) for rice and by Jiang et al. (1998) and Ju et al. (2005) for wheat. Fischer et al. (2005) inferred that generally higher precipitation projected by GCMs for China will benefit future national food production. Lin et al. (2005) also found the effects of higher CO₂ concentrations offset the negative effects of higher temperatures, resulting in average increases in yield of 13% for rice, 18% for maize, and 28% for wheat.

The interactions between climate change, crop production, land use and water availability have been largely neglected until recently (Betts, 2005). The drivers of agricultural responses to climate change are direct biophysical effects and their mediation through socio-economic processes. The relentless pressure of increasing population and per capita food consumption on land and water use are major factors in determining the characteristics of future scenarios of food security and are likely to be key factors in increasing the risk of famine in the future (Slingo et al., 2005). Recent studies have used a variety of models and climate scenarios to analyze the integrated impacts of climate change on food production. Several integrated assessments have incorporated water availability (e.g. Rosenbeg et al., 2003; Rosenzweig et al., 2004) and others have considered different socio-economic development pathways (e.g. Parry et al., 2004; Fischer et al., 2005). Although most of the integrated assessments have been done in developed countries (e.g. Izaurrealde et al., 2003; Holman et al., 2005, 2008; etc.), results for China have been referred to in global studies such as Parry et al. (2005). They simulated modest changes in China's national potential grain yield by the 2080s (range of 0–2.5%) which would be indistinguishable from the effects of background climate variability.

This paper sets out a framework to assess the direct effects of climate change (using high resolution regional scenarios) on cereal crop yields (using detailed simulation of rice, maize and wheat) and the indirect effects of changes in water availability (as it affects irrigation water supply). Other factors considered include the direct effects of CO₂ fertilization and changes in arable land and demand for water due to population increase and economic

development based on socio-economic scenarios (downscaled from the IPCC SRES, Gaffin et al., 2004). Changes in crop yields and water availability are presented and, using areas of crops sown across China, converted into estimates of cereal production, expressed as a national total or per capita. The analysis explores projections of the future for the 2020s and 2040s using two emissions scenarios (A2 and B2), with and without the direct effects of CO₂. Results are presented in a stepwise manner to demonstrate the relative impacts of climate change and other drivers on cereal production. Our objective is to quantify the influence of different drivers of change on future cereal production in China and to examine the effectiveness of three adaptation scenarios, which reflect national level agricultural policy objectives, in relation to maintaining national grain production. The adaptation scenarios consider: prioritizing water allocation for cereal production; successful implementation of controls on agricultural land conversion and sustained improvements in agricultural technology in the future.

The next section introduces the modelling framework and the scenarios. Section 3 presents the impacts models and methods. Section 4 presents the results in a stepwise manner, before introducing the overall integrated results and the effects of adaptation scenarios. The final section discusses the main assumptions and factors not included in the analysis and the wider research and policy implications of the results, before identifying our main conclusions.

2. Generating scenarios

Fig. 1 shows the components of the analysis and their linkages. Expert judgement was used to ensure that as far as possible the climate scenarios, socio-economic scenarios (SES) and adaptations were internally consistent and underpinned by similar assumptions about the future guided by relevant storylines.

Climate impacts were simulated using process-based models with high resolution climate scenarios (50 km × 50 km, Fig. 2). In brief, the overall process can be described in five steps. First, climate change and SES were constructed for China; second, crop models and a hydrological model were used to simulate the impacts of climate change on crop production and water

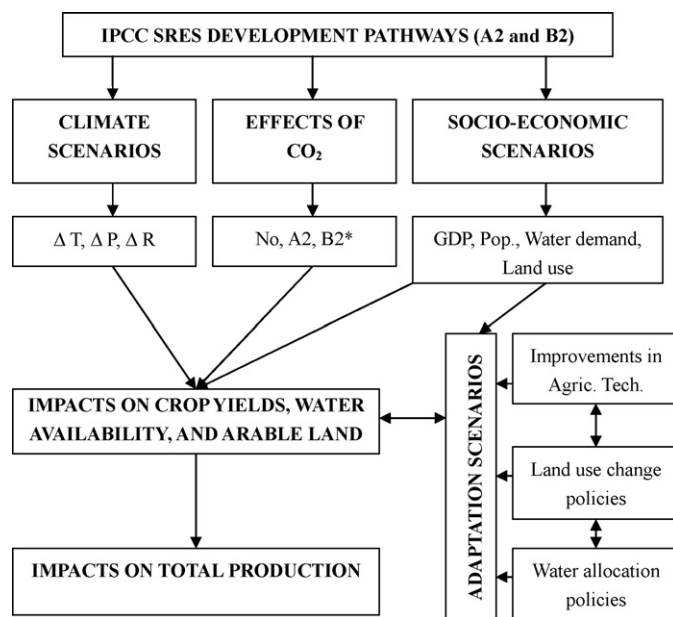


Fig. 1. The main steps and linkages between different components in the analysis. Δ , changes in: T, temperature, P, precipitation and R, radiation. A2 and B2 are the IPCC SRES emissions scenarios.



Fig. 2. The main river basins of China and resolution of climate scenarios and impacts simulation (50 km × 50 km).

availability; third, total national rainfed and irrigated cereal production was calculated; fourth, the effects of the drivers were combined and compared; and finally, the effects of three policy related adaptation scenarios were assessed.

2.1. Climate change scenarios for China

Regional climate scenarios were generated using a high resolution (~50 km grid interval) atmospheric regional model (PRECIS—Providing Regional Climates for Impacts Studies, Jones et al., 2004; Xu, 2004; Xu et al., 2007). Two scenarios of CO₂ concentrations (based on the IPCC SRES A2 and B2 storylines) were used with PRECIS to simulate changes in daily temperature, radiation, and precipitation. A2 represents medium-high emissions and B2 medium-low, together they encompass a wide range of future emissions pathways (Nakicenovic and Swart, 2000). It is important to note that the CO₂ concentration scenarios used to drive PRECIS (Table 1) were derived from the SRES emissions scenarios using a simple carbon cycle model which does not account for a potential acceleration in CO₂ concentrations due to climate–carbon cycle feedbacks. This uncertainty has received limited attention but is potentially very important (Meehl et al., 2007) and means that the standard concentrations scenarios used here (A2 and B2) will not necessarily be associated with their corresponding socio-economic scenarios. However, to avoid confusion in our analysis we kept the respective CO₂ concentrations and socio-economic scenarios together. PRECIS projections of future temperature, precipitation and radiation in China are summarized in Table 1 for three future 30-year time slices.

As different climate models (global and regional) simulate different patterns of response in temperature and particularly precipitation it is important to assess how PRECIS results compare with those from other climate models to reflect this source of potential uncertainty. Results are presented from 17 climate models made available through the Program for Climate Model Diagnosis and Intercomparison (PCMDI) for the IPCC Fourth Assessment Report (Meehl et al., 2007). Forty years of temperature and precipitation data were used from the 20th Century model runs (1961–2000) and 99 years of data were extracted from the SRES A2 and SRES B1 scenarios (2001–2099, see Xiong et al., 2008a for detail). Fig. 3 shows the results for A2 emissions, with 30-year average changes in temperature plotted against changes in precipitation for all models, including PRECIS, and three time slices. Climate scenarios from PRECIS produce warming similar to the all-model average for China but PRECIS produces wetter conditions than the multi-model average for China (q.v. for the 2020s A2 PRECIS increases by 5% and the all-model average increases by 0.5%). PRECIS therefore gives a reasonable mid-range projection of warming but a wetter projection of precipitation than the multi-model average.

2.2. Socio-economic scenarios for China

To be consistent with the high resolution climate scenarios available from PRECIS we developed socio-economic scenarios at provincial level for A2 and B2 out to 2050. The methods are based broadly around those used in Nakicenovic and Swart (2000) and Gaffin et al. (2004) and guided by relevant literature on agricultural

Table 1
Average changes in surface air temperature, precipitation and radiation relative to a baseline period (1961–1990) under SRES A2 and B2 emissions scenarios simulated by PRECIS. Corresponding CO₂ concentrations are also given.

Timescale	A2 emissions scenario				B2 emissions scenario			
	Temperature change (°C)	Precipitation change (%)	Radiation change (%)	CO ₂ (ppmv)	Temperature change (°C)	Precipitation change (%)	Radiation change (%)	CO ₂ (ppmv)
2020s (2011–2040)	+1.3	+5	+0.5	440	+1.5	+4	+0.5	429
2050s (2041–2070)	+2.6	+10	+0.7	599	+2.4	+6	+0.7	492
2080s (2071–2100)	+4.5	+17	+1.1	721	+3.4	+9	+0.9	561

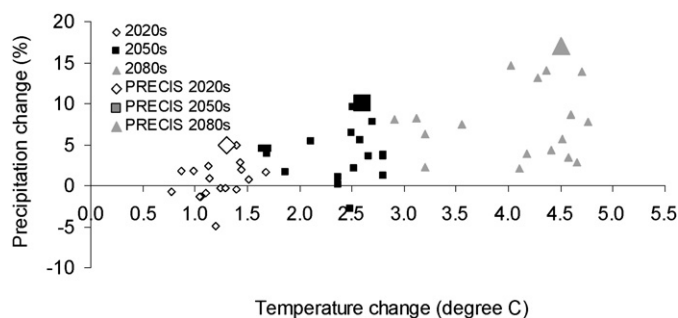


Fig. 3. Annual changes in temperature and precipitation averaged for the whole of China for the 2020s, 2050s, and 2080s with 17 GCMs from IPCC AR4 and PRECIS (all simulations with A2 emissions scenario).

and other trends in China (e.g. Yang and Li, 2000; Zhao et al., 2008). The IPCC SRES B2 storyline fits broadly with China's national social and economic development plans over the medium to long term and is taken here as an optimistic or desired socio-economic scenario. The 'A2 family' represents the higher range of likely CO₂ emissions under the development of business as usual, and is chosen here to represent an environmentally pessimistic development pathway.

Based on SRES GDP and population projections we changed the base year from 1990 to 2005 according to more recent statistics (China Statistical YearBook, 2006) and assumed a linear relationship between global and country scale. National annual population and GDP growth rates were set equal to the SRES rates for southeastern Asia.

Scenarios of future water demand were based on four sectors; agricultural (AW), industrial (IW), domestic (DW), and municipal (MW). A combination of recent trends in water use, other research and expert judgement were used to calculate water demand in each sector. Irrigation water use in all provinces was projected to decrease based on the assumption that technology advancements in irrigation and water management, and implementation of water sector reform and new policies will continue. For the IW and DW sectors per capita water consumption was based on economic development and technological advances. The proportion of demand from the municipal sector was assumed to increase.

Since China's Reform period began in the late 1970s arable land has declined substantially (Yang and Li, 2000; Zhao et al., 2008) although not evenly over time and space. Coastal and central provinces lost arable land and northern and western provinces have tended to gain arable land. During 1986–1995 arable land

was lost to capital construction, conversion to higher value production and natural hazards (Yan et al., 2006 as cited in Zhao et al., 2008), whilst in the north land was reclaimed from forests and pasture (Song et al., 1998 as cited in Yang and Li, 2000). Concern about land degradation resulted in the 'Grain-for-Green' Programme in 1998, intended to convert marginal arable land to grasslands and forest (Feng et al., 2005) which became a significant regional source of arable land loss. Pressures on agricultural land are counter-balanced by government policies such as the Basic Farmland Protection Regulation. For this study relationships were derived between provincial scale GDP and change in arable land area, using the hypothesis that urbanization and industrial growth are the main drivers in national arable land area conversion (Yang and Li, 2000). Conversion of arable land in the future was projected using the provincial level relationships, interpolated to the 50 km × 50 km grid. For A2 the future rate of change was consistent with recent trends (between 1990 and 2005) and for B2 the area of arable land was kept for B2 the area of arable land was kept consistent to the desired area identified in the national policy on protection of agricultural land.

2.3. Adaptation scenarios for the agricultural sector

Differing trajectories of population growth and economic development will affect the level of future climate change and, simultaneously, the responses of agriculture and water to changing climate conditions (Parry et al., 2005). A large number of studies have examined the consequences of adaptation at agronomic level, for example, modification of sowing dates (e.g. Matthews et al., 1997; Trnka et al., 2004; Mall et al., 2004), change of crop cultivars (e.g. Southworth et al., 2000; Ortiz et al., 2008), optimization of water and nitrogen management (e.g. Holden and Brereton, 2005), and shifts of crop production areas (e.g. Iglesias and Minguez, 1997). Here we identify three broad policy level adaptation strategies; adaptation in water allocation policy (WP), in arable land policy (LP), and improvements in agricultural technology (AT). The three have been chosen as illustrative of likely/realistic responses and relate to an overarching national policy objective to maintain self-sufficiency in staple cereal production in China. Table 2 summarizes the main assumptions underpinning the adaptation scenarios. These assumptions can have a significant effect on the final results and there is potential to greatly expand the number of scenarios to reflect the full range of uncertainty and possibilities. In reality each scenario would be comprised of many actions but for our purposes their detail can be assumed to be incorporated implicitly by the overall effects of the policy.

Table 2

The three adaptation scenarios and their assumptions.

Adaptation policy	No adaptation	Adaptation policy assumptions
1. WP—Water Policy; prioritizing water for agriculture	Without adaptation we assume all sectors have equal access to water according to the proportion of their demands to projected total demand. If demand exceeds supply all sectors experience water shortage.	In the future national food self-sufficiency is prioritized (congruent with current policy and water allocation practice in northwest China). Agriculture is given the highest priority for water use, after domestic demand has been satisfied in A2 and B2 scenarios.
2. LP—Conservation of arable land	The current decline in cultivated land is assumed to continue in the future based on observed rates of change during the last decade.	We assumed successful implementation of policies to limit loss of arable land. For A2, the current rate of change is halved. For B2 (assumed a society with more attention to environmental considerations), the area of arable land is held constant (2005 levels).
3. AT—Continued improvement in agricultural technology	No assumption is made about increases in crop yields due to improvements in agricultural technology.	For A2 we assumed a linear growth rate in yield equivalent to the global average during the period 1961–2000 (53 kg ha ⁻¹ yr ⁻¹ for the three crops, Hafner, 2003), which partially reflects the demands implicit in A2's higher population growth and more rapid decrease of arable land. The rate of increase in yield in China from 1961–1998 was around 95 kg ha ⁻¹ yr ⁻¹ (Tong et al., 2003), but this but slowed considerably during 1991–2000 (31 kg ha ⁻¹ yr ⁻¹ ; 1% per year, based on FAOSTAT 5-year moving average). This slower rate during 1991–2000 was fairly consistent with projections in national planning policies (Xiong et al., 2007a) and so was used for scenario B2.

WP gives highest priority to agricultural water use after satisfaction of domestic demand, although increasing demand from other sectors will intensify competition for water in the future. Other opportunities exist for adaptation through improvements in water use efficiency, which is currently relatively low in China, water demand management and large scale infrastructure, such as the South to North water transfer scheme. Such developments will have major impacts on future water availability for agriculture. Key influences on agricultural land conversion are outlined in the previous section. For the future (LP) we assumed that conversion rates are slowed to half current levels (A2) and halted (B2).

The AT scenario represents future crop yield increases due to progress in agricultural technology. Such changes are extremely difficult to quantify and project (Hafner, 2003) and so our scenario should be treated as illustrative. Historical trends in crop yield increase were used with the assumption that considerable potential remains to increase crop yields globally, particularly in developing countries (Herdt, 2006), and in China (see Table 2 for detail).

3. Modelling impacts

3.1. The crop and hydrological models

Three CERES crop models (Ritchie et al., 1989) were modified to simulate yields and potential irrigation demand across China at the same resolution as the regional climate model (50 km × 50 km): Rice, maize and wheat. Full details of the models are presented in Xiong et al. (2007a,b) and details of recent improvements in their calibration and validation in Xiong et al. (2008b,c). The simulated yields were assumed to represent observed yields obtained in the field assuming technological levels from 2000. Crops are simulated for rainfed and irrigated conditions using areas of crops sown across China based on the distribution in 2000 (obtained from county census data).

For irrigated crops water was applied periodically throughout the growing season and the total irrigation water requirement for each grid and crop was obtained by multiplying by the total irrigation area. Crop response to CO₂ was based on results from FACE experiments from (Kimball et al., 2002); an 850 ppm CO₂ concentration causes a roughly 40% increase in photosynthesis for wheat and rice, and 15% for maize. Higher CO₂ levels tend to decrease the evapotranspiration rates of crops and improve their water use efficiency.

The Variable Infiltration Capacity (VIC) hydrologic model was used to simulate runoff, water yield (surface flow + groundwater flow + lateral flow – loss from evapotranspiration) at 50 km × 50 km grid resolution across China. Previous studies have validated VIC simulation of runoff in China and streamflow simulation in some catchments (Su and Xie, 2003). Daily water yield was calculated from each grid cell and annual total water yield series were calculated for ten main river basins in China (Fig. 2). These volumes were used to provide estimates of annual renewable internal water resources in each basin (WRI).

3.2. Agriculture water use and irrigation area

Water available for agriculture (WAA_{*i*}) in province *i* was calculated as (1)

$$WAA_i = \left(\sum_{j=1}^n (WRI_j \times R_j \times P_{ij}) \right) \times \left(\frac{AW_i}{AW_i + DW_i + IW_i + MW_i} \right) \quad (1)$$

where R_j was the water exploitation proportion in basin *j* (an average value of the observed exploitation proportion for each basin from 1994 to 2005 which is assumed to remain constant in the future), P_{ij} represents the proportion of water used in province *i* that comes from basin *j* (based on the average value from historical data for 1994–2005). For any given grid *k* in *i* province, the Available Irrigation Water, AIW_k was computed as (2)

$$AIW_k = WAA_i \times \left(\frac{IA_k}{IA_i} \right) \quad (2)$$

where IA_k is the irrigation area in grid *k* and IA_i is total irrigation area in *k* province.

The balance between AIW and potential crop irrigation demand (Section 3.1) in each grid cell was used to limit irrigation and estimate the irrigated area of each crop at the grid cell. Because most of the rice planted in China is irrigated paddy rice, we assumed that rice takes highest priority for water withdrawal, with the objective of irrigating as much of the present area of rice as available water permits. The remaining water was allocated to maize and wheat.

3.3. National cereal production

Estimates of national total cereal production incorporated scenarios of land use change based on the SES (Section 2.2). The future area of crop land in each grid was calculated as a function of current arable land, multiplied by projected arable land conversion rate. The conversion rate was set to the rate of the province in which the grid lies. These estimates, together with an assumption of constant patterns of crop-planting and crop mix, were used to calculate total production, by multiplying the area of irrigated or rainfed crops by the yield per unit of land area.

3.4. Combinations of driving forces and simulation runs

In order to determine the contributions of different driving forces to the overall impacts on total crop production and per capita productivity, a series of simulations were performed with different combinations of scenarios and drivers. The combinations were: climate change scenarios only (CC), climate change scenarios + CO₂ fertilization effects (CC + CO₂), climate change scenarios + water availability (CC + WA), climate change scenarios + CO₂ effects + water availability (CC + CO₂ + WA), climate change scenarios + water availability + arable land loss (CC + WA + LA), and climate change scenarios + CO₂ effects + water availability + arable land loss (ALL). The annual total and per capita cereal production was calculated for each combination from 2011 to 2050 and compared with simulated current production (climate for 1961–1990 and agricultural technology and cultivated area for 2000). Averages were calculated for the periods 2011–2030 (2020s) and 2031–2050 (2040s).

4. Results

4.1. Main results of the socio-economic scenarios

Table 3 lists the main components of the SES. Agricultural land use was projected based on extrapolation of recent trends across China. The rates of change and areal estimates are subject to large uncertainty due to problems with observed data and the important role of policy interventions (Yang and Li, 2000; Liu, 2005). Changes range from large decreases with A2 (due to high contemporary rates) and moderate change with B2 (reflecting national policy interventions to slow decline in agricultural land area).

Table 3

Population and GDP projections for China in the two SES, plus the general characteristics of the scenarios.

	2000	2005	A2		B2	
			2020	2050	2020	2050
GDP	99,200	156,000	301,000	837,000	481,000	1,450,000
Population	1.27	1.31	1.53	1.94	1.44	1.51
GDP per capita (\$)	950	1,700	2,400	5,200	4,050	11,650
Water demand	5,497	5,633	6,161	7,470	6,194	6,910
Arable land	128,250	121,500	113,950	107,700	121,500	117,550
Characteristics	Rapid regional economic growth, materialist; low GDP growth rate; high population growth; rapid decrease of arable land; and rapid growth of water demand.				Local emphasis and environmental priority; moderate GDP growth rate and population growth; conservation of arable land; and steady growth of water demand.	

Notes: GDP in 100 M RMB at comparable price in 2000; population: billion persons; GDP per capita Unit: USD in 2000 (100 USD = 828 RMB); arable land: 1000 ha; water demand: 100 M m³. Figures are rounded to nearest thousand (50 for per capita GDP).

Water demand was projected to increase from 5633 (2005) to 7470 (A2), and 6910 (B2) in 2050 (100 M m³). This was accompanied by a shift in the proportional use of water by sector; primarily away from agriculture in response to greater demand from industrial, urban and municipal users. The proportion of water used for agriculture decreased from 63.6% in 2005 to 37.5% (A2), 46.2% (B2) in 2050.

4.2. Impacts of climate change on crop production

In 2000, the total cereal production in China was 395.7 million metric tones (MT), with 189.8, 99.6 and 106.2 MT for rice, wheat, and maize, respectively (FAOSTAT). The corresponding planting acreages for the three crops were 30.3, 26.7, and 23.1 million ha. The projected cereal production for the current conditions was 429.8 MT (rice, wheat and maize comprise 216.6, 104.6, and 108.6 MT, respectively, without limitation from water).

Fig. 4 shows that without CO₂ fertilization climate change decreased cereal production in China under B2, but increased it under A2, in both the 2020s and 2040s. The production of rice increased a little under the A2, but decreased under B2. Wheat production increased in all cases and maize decreased in all. CO₂ fertilization effects caused increases in production in all cases (production increased by 14.2% (2020s) and 13.9% (2040s) under A2, and 5.5%, 6.6% under B2, respectively). The largest change occurred for wheat, and the smallest for maize. The differences between the effects of A2 and B2 are modest, within roughly 10%,

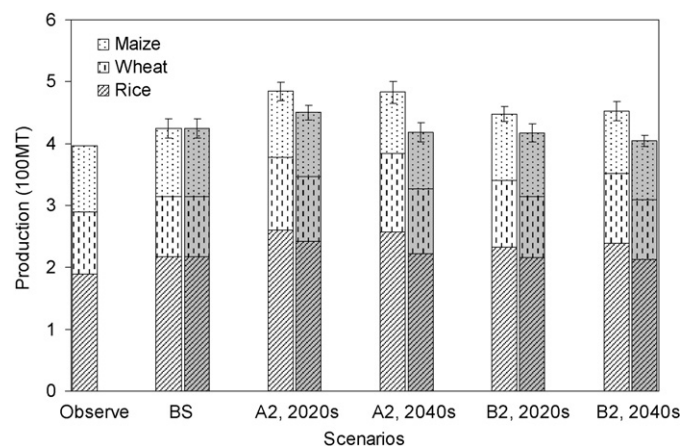


Fig. 4. Changes in total cereal production for China with present (2000) cultivation areas and maximum irrigation area. Observed production (from FAO), BS, baseline simulation 1961–1990. White (grey) background with (without) the effects of CO₂ fertilization. The vertical lines indicate the Standard Deviation (SD) of the data set.

and very small between the 2020s and 2040s (<5%). Spatial patterns of change in total crop production by the 2040s exhibit marked differences across China (not shown). The general pattern shows increases in the northeast and north and decreases in the central, eastern and southern provinces.

4.3. Impacts of climate change and water availability on the area of irrigated land

Water availability is critical for agriculture production (Fischer et al., 2007). In China, irrigated agriculture is the primary consumer of water. More than 75% of grain production in China is from irrigated land (Jin and Yong, 2001). Results from simulations with VIC showed an overall increase in water resources in the future as precipitation increases offset greater losses to evaporation (roughly 10% in all cases). However, due to increases in demand in other sectors (domestic, municipal and industrial) captured in the SES the water available for agriculture decreased. This resulted in substantial decreases of irrigated land in all cases, under the assumption of current irrigation practice.

Fig. 5 shows changes in the area of irrigated land with climate change after irrigation was limited according to water availability for agriculture. In this estimation, the available water was assumed to first meet the irrigation demand of the current area of cereal production. For paddy rice the baseline area was 29.9 M ha. This showed a large decrease with A2, and moderate decrease with B2. For the area of irrigated wheat/maize the decreases were generally quite small under A2 and B2. With CO₂ fertilization effects included the changes became smaller in most cases. Changes in the area of irrigation for wheat and maize were generally small because increased water use efficiency, caused by higher CO₂ concentrations, reduced the irrigation water requirements. The different changes of water availability imposed on rice and wheat/maize were related to the different geographic distribution of the crops; rice is largely distributed in the humid southern and northeastern China, and wheat/maize mainly located in semi-humid or semi-arid northern and western China.

4.4. Integrated results for national cereal production

Fig. 6 shows the percentage change in total cereal production in China under different combinations of drivers. A2 and B2 increase average production moderately in the 2020s, but only slightly in the 2040s (first cluster of bars in Fig. 6). Including CO₂ effects led to large increases in production ranging from 12% to 18% due to stimulated photosynthesis and improved water use efficiency. A2 produced a larger increase in production than B2 primarily because of its higher CO₂ concentrations. Including the effects of water

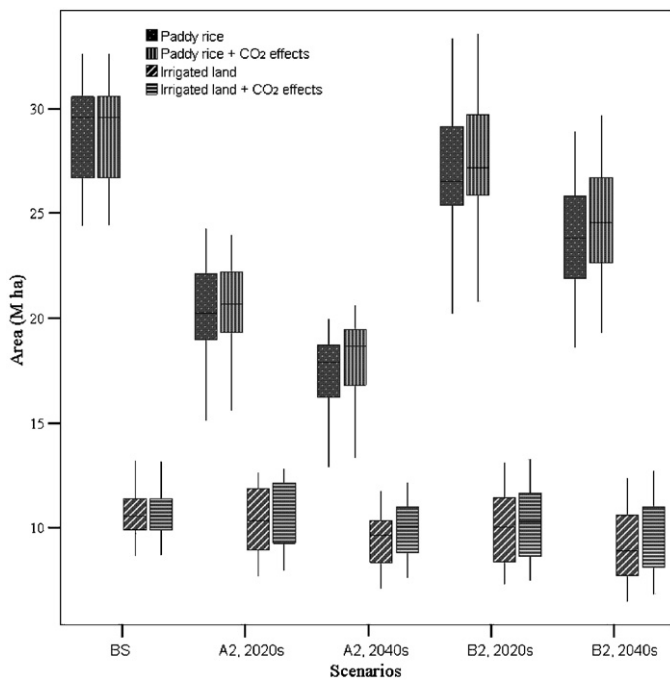


Fig. 5. The total annual irrigated area (including paddy rice area and other irrigated land, wheat/maize) due to changes in future water availability (resulting from climate change and socio-economic change). The upper and lower hinge of the box indicates the 75th percentile and 25th percentile of the data set (20-year), respectively. The line in the box indicates the median value of the data set. The ends of the vertical lines indicate the minimum and maximum values.

availability with and without CO₂ fertilization led to increases and decreases in total production, respectively. The fifth cluster of bars shows the additional effects of decreases in arable land which further reduced total production under A2 due to its higher rate of land conversion. The overall effects of climate change, water availability and agricultural land conversion reduced production in the 2040s by 9% (B2) and 18% (A2). The final cluster of bars in Fig. 6 shows the integrated effects of all drivers and highlights the counter-balancing effects of CO₂ fertilization, such that slight increases in production occur in all cases except the 2040s under A2.

Production per capita can be used as an indicator of food security and driver of agricultural policy in the context of national priorities for self-sufficiency in staple food production (e.g. Xiong et al., 2007a). Fig. 7 shows production per capita without taking into account international trade and other crops for selected combinations of drivers (the results without CO₂ fertilization effects are not included). In most cases production per capita was projected to decline, particularly the cases with A2 population, but the declines were significantly different between combinations of drivers and population scenarios. The beneficial effects of higher CO₂ maintained a small increase by the 2020s (with A2 population, Fig. 7), but these benefits were offset by other stressors (reduced water for agriculture, and decrease in area of arable land) under both A2 and B2 population scenarios. In contrast, B2 produced much smaller changes in per capita cereal production particularly due to its lower population growth.

4.5. The effects of adaptation scenarios

Fig. 8 shows future total cereal production for all drivers with and without adaptation. Prioritizing water for agriculture (WP) led to moderate increases in production, ranging from 2.6% to 3.9%. The combined effects of adaptation in water and land use policy

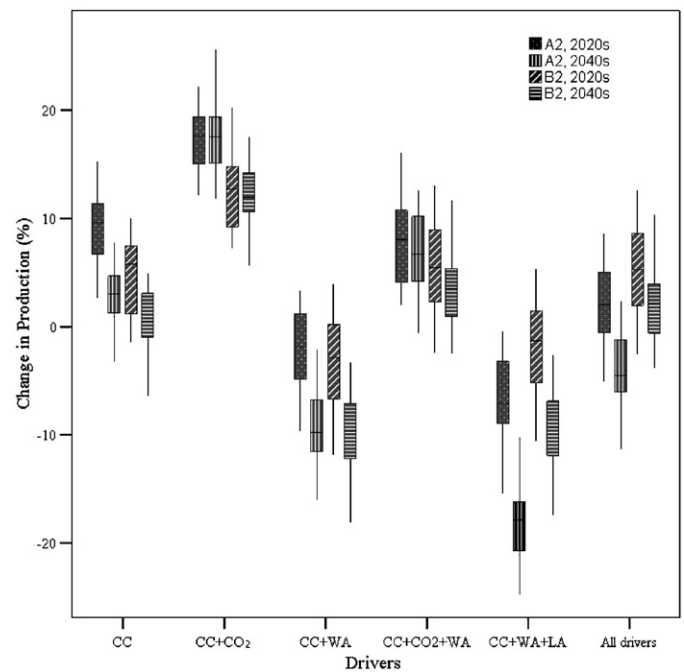


Fig. 6. Change in total cereal production under different combinations of drivers (CC: climate change; CO₂: CO₂ fertilization effects; WA: water availability; LA: agricultural land conversion; ALL: climate change, CO₂ fertilization effects, water availability, and agricultural land conversion). The upper and lower hinge of the box indicates the 75th percentile and 25th percentile of the data set (20-year), respectively. The line in the box indicates the median value of the data set. The ends of the vertical lines indicate the minimum and maximum values.

(WP and LP) resulted in higher production (from 3% to 12%, higher values with A2). LP policy on its own produced substantial increases, particularly with A2 in the 2040s. Improvements in agricultural technology produce the largest benefits in production. The accumulated improvements in yield were 32% and 55% by the 2040s (compared to the actual yield in 2000), respectively, under A2 and B2. This led to increased total national production of 18.7% and 10.1% respectively under A2 and B2 in the 2020s, and corresponding values of 37.4% and 22.3% in the 2040s.

Fig. 9 shows the effects of adaptation on production per capita and it is only with adaptation scenario AT (plus LP and WP) that

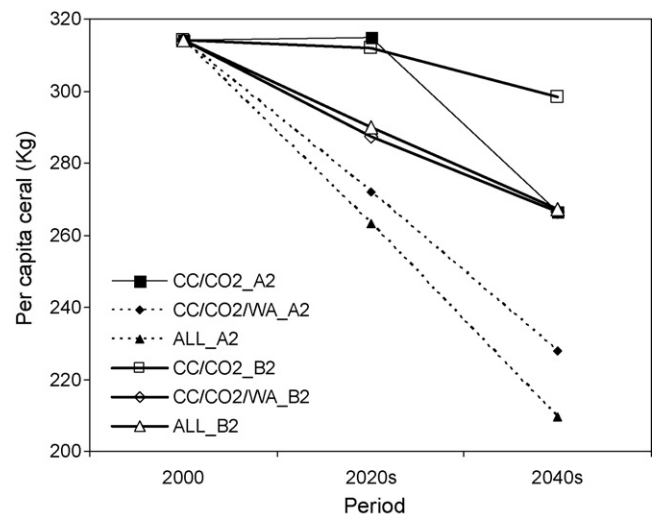


Fig. 7. Changes in per capita cereal production under selected combinations of drivers. See Fig. 6 for explanation of acronyms.

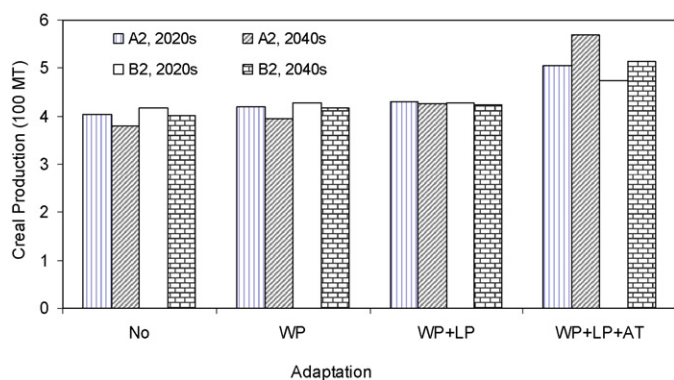


Fig. 8. National potential cereal production with and without adaptation (WP: water policies; LP: arable land conservation policies; AT: sustained improvements in agricultural technology).

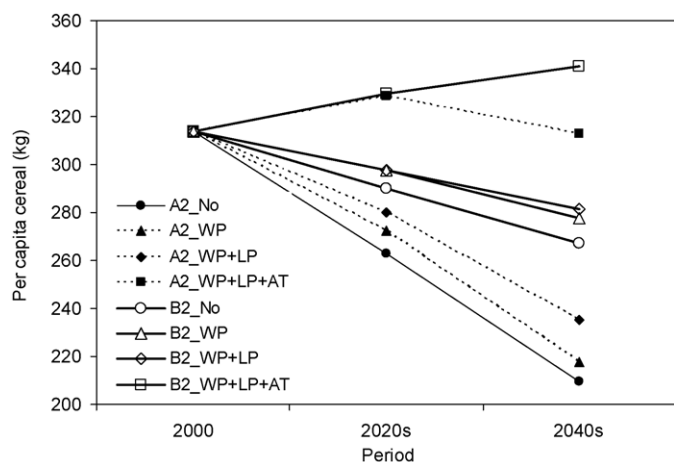


Fig. 9. The effect of adaptation strategies on per capita cereal production. See Fig. 8 for explanation of acronyms. No represents no adaptation scenarios.

production increases. For all adaptation strategies, the effects on total production were larger with A2 than with B2, indicating the larger scope for adaptation within a more pessimistic development pathway. Yield improvements with scenario AT had the greatest effects and, together with WP and LP, more than compensated for the decreases due to all drivers.

5. Discussion

We have presented the first detailed attempt for China to link the interactions of climate change, crop production, water availability and socio-economic development. Our results highlight in terms of cereal production, key challenges and sensitivities, however, it is important to examine the main uncertainties and assumptions and their relative significance to the results.

5.1. Key uncertainties and assumptions

5.1.1. The main scientific uncertainties

Standard concentration scenarios for A2 and B2 (based on emissions pathways) were used to drive PRECIS and these do not account for possible acceleration of the CO₂ concentrations due to climate–carbon cycle feedbacks (Meehl et al., 2007). This means that A2 and B2 SES might not necessarily be associated with their corresponding climate scenarios. Differences in the spatial patterns and magnitude of future precipitation between climate

models have a large bearing on future yields of rainfed crops and irrigation water availability. Differences in the daily characteristics of climate variables and differences between ensemble experiments will also influence the overall results. The multi-model average precipitation change is much lower than PRECIS but due to the data requirements of the crop models it has not been possible to simulate impacts with other climate models. This is a key requirement for future analysis and our results should be understood as just one realization of future climate impacts and probably optimistic due to PRECIS' large precipitation increases.

The effects of CO₂ on crop yields are critical to the overall results, but they remain highly uncertain. CERES simulates the effects of CO₂ on photosynthesis and on crop water use efficiency broadly in line with current experimental and modelling results. Given present state of knowledge it is not possible to attribute different levels of confidence to results either with or without CO₂ effects and therefore we present both with equal weight with the expectation that the reality should lie within this range and not beyond it.

5.1.2. The significance of extreme events

China's vulnerability to climatic hazards is high; because of its size and geographical extent it experiences many types of hazard and because of its transitional economy, production and employment in sectors such as agriculture remain very important, such that millions of livelihoods are exposed to climate related risks. The annual average crop area affected by meteorological hazards is around 50 million ha and economic losses amount to over 200 billion RMB per annum (Wang, 2007). Drought in 2004–2006 in Ningxia (Northwest China) led to crop failure, increased need for local people to purchase water and significant economic impacts (Yue et al., 2008). China's high exposure and sensitivity were clearly highlighted by the events during January and February 2008 when unusually low temperatures and heavy snowfalls (the heaviest in ~50 years) in southern China brought massive disruption to transport networks during the peak travel period of the Spring Festival. By mid-February the impacts had spread to 21 provinces, caused 129 deaths, destroyed crop harvests across 1.68 M ha, and led to direct economic losses of 152 billion RMB (Wang, 2008).

Climate models, either global or regional, are unlikely to capture fully the spatial and temporal detail of many extreme events across China. This is due to the imperfect understanding of their physical causes and limitations related to model structure. Crop models may also fail to simulate the total impact of events such as temperature peaks and soil moisture deficits during critical stages in crop growth cycles.

5.1.3. Assumptions related to the impacts modelling

The simulation of crop production did not incorporate the effects of changes in distribution and impact of pests and diseases, changes in management practice, crop variety and type, and the multiple cropping index. Farmers were assumed to apply optimum inputs. Water management and efficiency of use were also assumed to continue at current levels and the observed planting and irrigation area were used to calculate future potential production. Water use did not consider non-grain production and livestock requirements, both of which are growing rapidly in China, the ratio of arable farming output value to total agricultural output value fell from 89% (1949) to 49.7% (2005, Zhao et al., 2008). Also, whilst agricultural water availability was constrained within the simulations, it was assumed that all of the agricultural water is available at the correct times for irrigation. Decreasing groundwater levels due to abstractions for irrigation and urban water use (e.g. North China Plain) and declining soil fertility were not incorporated in the modelling work.

5.1.4. Assumptions in the SES and adaptation scenarios

We downscaled IPCC SRES storylines to China and sub-national scales, however, large uncertainties exist in the SRES SES and it is quite possible that China will follow different pathways to the world and Asia. Indeed, the A2 population is much higher than other projections and given current national policies on population probably unrealistic. Farmers and agricultural policies will respond to many signals and drivers but we have made no assumptions in the SES about their roles in affecting production. The SES do not incorporate incremental responses or anticipatory actions in response to change as it occurs; i.e. there are no feedbacks in the scenarios: they are not co-evolutionary. Our results do not include the effects of extreme events and adaptation related to agronomic practices.

We have made no assumptions about the role of crop prices and international trade in affecting production. Other important trends not included here are rapid changes in food consumption patterns in China. For example, average per capita meat consumption increased from 8.2 kg to 25.3 kg between 1978 and 2000 (Zhao et al., 2008).

The three adaptation policies are based on current practice and regulation as summarized in Table 2: prioritizing water allocation for cereal production (WP); successful implementation of controls on agricultural land conversion (LP) and improvements in agricultural technology in the future (AT). The adaptation scenarios encapsulate implicitly many types of responses across different scales, national or local programs, policies and new technologies, etc. and the outcome of many counter-acting drivers and policies (e.g. Zhao et al., 2008). All the scenarios are underpinned by a set of implicit and explicit assumptions to which the final outcomes are quite sensitive.

5.2. The wider implications of the results

To provide some traction to the results of this impact analysis we set them in the context of maintaining national food (staple grains) sufficiency in China. This is an important current policy goal for China and is likely to remain a major influence on agricultural policy and practice over the timescales considered in our study. Nevertheless, this production oriented policy goal ignores issues of sustainability, such as land degradation and over-application of inputs, all of which need to be addressed to maintain and increase future production.

In relation to climate change the results demonstrate the importance of improving our understanding of the effects of CO₂ fertilization in real world situations. Water availability is a critical factor for agricultural production in China and so effective linkages between agriculture and water management/policy will be vital for successful adaptation. Improved projections of future water availability will require better surface and groundwater modelling and simulation of soil moisture dynamics and evapotranspiration. In terms of adaptation we have identified three broad-level scenarios; there is a need to develop more detailed and grounded policies based on understanding of existing decision-making and management practice which are highly context specific.

6. Conclusions

The effects and interactions of multiple drivers of change (climate, CO₂ fertilization, water availability, population and land use change) have been considered in relation to their impacts on staple cereal production in the 2020s and 2040s. Two standard IPCC SRES emission scenarios and SES storylines provided the quantitative inputs and qualitative context for the future drivers of

change and adaptation scenarios. The main conclusions are as follows.

- Scenarios of future climate change project continued warming in all seasons over the whole of China, and consistent but modest increases in mean annual precipitation. The regional climate model PRECIS produced warming similar to a multi-model average for China but precipitation higher than a multi-model average for China.

6.1. Results without adaptation

- By the 2040s climate change alone produced small to moderate effects on China's potential cereal production. The largest changes in production occurred with wheat (increases) and the smallest with maize (decreases).
- The combined effects of CO₂ fertilization and climate change produced increases in cereal production with both A2 and B2 climate scenarios. The increases were larger with A2.
- Water availability acted as a significant limitation to national production in the future with or without CO₂ fertilization effects. A decrease in water availability for agriculture reduced the irrigation area in all cases, particularly under A2 for the area of paddy rice.
- The absolute effects of climate change by the 2040s were modest relative to the other drivers. The interactive effects of all drivers together led to significant decreases in total production by the 2040s (−18%, A2 and −9%, B2).
- In most cases production per capita was projected to decrease, particularly the cases with A2 population, but the decreases were significantly different between combinations of drivers and population scenarios.
- Outcomes were highly dependent on socio-economic development pathways and their underlying assumptions and the effects of CO₂ fertilization which, assuming sustained positive effects, offset most of the negative effects of the other drivers.

We judge our results on climate change and water availability impacts on cereal production to be near the upper limits to the potential range in response because PRECIS gives much wetter conditions than the multi-model average, the CO₂ crop yield response function may not be sustained and the negative effects of extreme events on crop growth and water availability are likely to be underestimated. By concentrating on results for the 2020s and 2040s, aggregated for three crops at national scale, we omit some of the more significant effects of higher temperatures on crop yield and the existence of significant differences at provincial scale and between crops. The general patterns show production increases in the northeast and north and decreases in the central, eastern and southern provinces. Such patterns could create adaptation opportunities in the north, subject to constraints from water availability, and food production risk hotspots in the central, eastern and southern provinces.

6.2. Results with adaptation

- The effects of three broad-level adaptation scenarios (in water, land and agricultural technology) were explored. Adaptation in water allocation policy produced modest benefits to total cereal production.
- Adaptation to limit conversion of arable land offset the negative impacts on production (particularly with A2) and produced increases in total cereal production.
- Adaptation based on sustained improvements in agricultural technology resulted in significant increases in national total

cereal production. In terms of per capita cereal production only improvements in agricultural technology enabled production to keep pace with population growth.

The results demonstrate the importance of integrating climate change with other socio-economic drivers of change in order to generate a system understanding of how climate and socio-economic drivers affect cereal production in China. Other studies that incorporate multiple drivers of change tend to obtain similar results: increasing demand due to economic and demographic growth leads to large changes in per capita food and water availability, often outweighing climatically induced changes (Conway et al., 1996; Vorosmarty et al., 2000; Alcamo et al., 2007). Future development pathways will play the major role in determining which of our scenarios is most accurate. Critical scientific uncertainties exist around the future effects of CO₂ fertilization and differences between GCM results. The relative magnitude and direction of change in the results are therefore more important than the absolute values. Access to additional climate model scenarios and consideration of ranges across the major uncertainties and assumptions would generate a more complete representation of future conditions. We believe, however, that this would be unlikely to alter our overall conclusion that, inter alia, climate change represents a potentially major additional stress on China's future agricultural production. This conclusion reinforces the need for China to achieve sustainable agricultural production and support adaptive management and appropriate investment levels in agricultural technology.

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