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The impacts of climate change on water resources and agriculture in China

Shilong Piao[1], Philippe Ciais[2], Yao Huang[3], Zehao Shen[1], Shushi Peng[1], Junsheng Li[4], Liping Zhou[1], Hongyan Liu[1], Yuecun Ma[1], Yihui Ding[5], Pierre Friedlingstein[2,6], Chunzhen Liu[7], Kun Tan[1], Yongqiang Yu[3], Tianyi Zhang[3] & Jingyun Fang[1]

China is the world's most populous country and a major emitter of greenhouse gases. Consequently, much research has focused on China's influence on climate change but somewhat less has been written about the impact of climate change on China. China experienced explosive economic growth in recent decades, but with only 7% of the world's arable land available to feed 22% of the world's population, China's economy may be vulnerable to climate change itself. We find, however, that notwithstanding the clear warming that has occurred in China in recent decades, current understanding does not allow a clear assessment of the impact of anthropogenic climate change on China's water resources and agriculture and therefore China's ability to feed its people. To reach a more definitive conclusion, future work must improve regional climate simulations—especially of precipitation—and develop a better understanding of the managed and unmanaged responses of crops to changes in climate, diseases, pests and atmospheric constituents.

Climate change and its impacts on water resources and crop production is a major force with which China and the rest of the world will have to cope in the twenty-first century[1,2]. In China, despite the growing importance of industry, agriculture has a central role in ensuring the food security and welfare of 1.3 billion people. At first glance, a map of China's climate and ecosystems (Fig. 1) reveals an uneven distribution of water resources between the south, where water is abundant, and the drier north. Many regions lie in transitional zones where water resources, and hence agricultural production, could be affected positively or negatively by changes in climate.

Over the past several decades, China has already experienced some devastating climate extremes[2]. For instance, the great flood of 1998 inundated 21×10^6 hectares (21 Mha) of land and destroyed five million houses in the Yangtze basin, causing an economic loss of over US\$20 billion (ref. 3). Despite the enormous importance of the subject and the growing number of specific studies, multidisciplinary synthesis of the knowledge of climate impacts in China is scarce[2].

Our primary goal here is to review observations of climate, hydrology and agricultural production trends in China, and associate these observations with likely future changes. We highlight the main areas of vulnerability and sources of uncertainty based on recent literature and published data. We present an analysis progressing from well-observed recent trends to more uncertain model projections and mechanisms. The first section deals with recent climate change observations and projections from climate models. Particular attention is given to drought and flood extremes. The second section addresses past and projected future trends in water resources, investigates whether the recent changes are unusual or within the bounds of normal climatic variability, and assesses the contribution of human withdrawals of water versus climate forcing. In this context, we review changes in glacier mass balance and their impact on hydrosystems. The last section integrates climate and atmospheric composition impacts on agricultural production, and the role of agricultural adaptation potentials, within a more conceptual and speculative framework.

Through this analysis, we show that China's climate has clearly warmed since 1960, with an increased frequency of heatwaves, and that glaciers are in retreat. But the geographic and interannual variability in water resources is so large, and the improvements of crop management have been so important, that they prevent a clear conclusion on the net

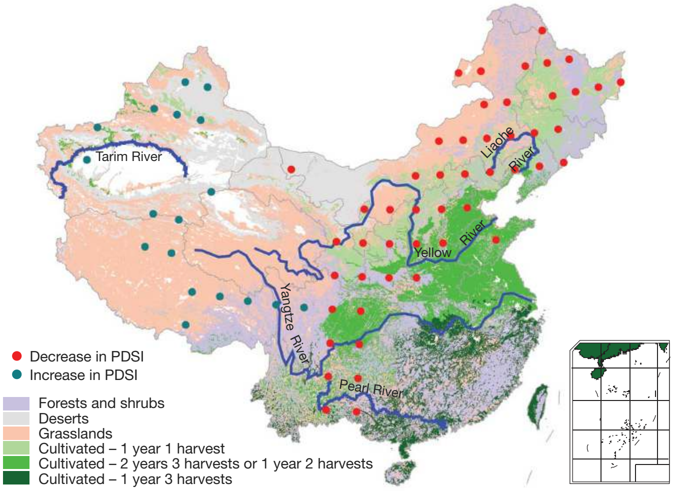

Figure 1 | Distribution of vegetation across China. **The vegetation distribution reflects present-day climate gradients. The vast area covered by agriculture and regions with different crop rotations are given in green. The red dots represent the areas with a significant ($P < 0.05$) increase in drought expressed by the Palmer Drought Severity Index (PDSI; the higher the index the less drought) during the period 1960–2005 (see text). The green dots indicate the areas where a decrease in drought was observed. Annual PDSI at spatial resolution of 2.5° is from ref. 20. Inset, islands in area below map.**

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[1]Department of Ecology, Department of Geography, College of Urban and Environmental Science, Key Laboratory for Earth Surface Processes of the Ministry of Education, and Center of Climate Research, Peking University, Beijing 100871, China. [2]Laboratoire des Sciences du Climat et de l'Environnement, UMR CEA-CNRS-UVSQ, Batiment 709, CE L'Orme des Merisiers, Gif-sur-Yvette, F-91191, France. [3]State Key Laboratory of Atmospheric Boundary Layer Physics and Atmospheric Chemistry, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing 100029, China. [4]Chinese Research Academy of Environmental Sciences, Beijing 100012, China. [5]Laboratory of Climate Studies, National Climate Center, China Meteorological Administration, No. 46 Zhongguancun Na Da Jie, Beijing 100081, China. [6]QUEST, Department of Earth Sciences, University of Bristol, Bristol, BS8 1RJ, UK. [7]China Water Information Center (Hydrological Bureau), Lane 2 Baiguang Road, Beijing 100053, China.

impact of historical climate change on agriculture. Climate simulations point to serious potential vulnerabilities in China's future agricultural security, but extensive uncertainties prevent a definitive conclusion.

Evidence and projection of climate trends

Stronger warming in the north. A strong warming[4,5] of China over the past five decades is firmly supported by continuous measurements from 412 meteorological stations. The temperature has increased by 1.2 °C since 1960. The seven warmest years all occurred during the last decade (see Box 1). Winter warming (0.04 °C per year) is about four times the rate of summer warming (0.01 °C per year), and thus the temperature seasonal cycle amplitude has decreased by 0.03 °C per year (see Box 1). Moreover, northern China is warming faster than southern China[4]. Temperatures reconstructed over the past thousand years using tree-ring width confirm that the last century was the warmest period since 1600, although its temperatures are comparable to temperatures from the Medieval Warm Period[2,6].

As for future projections, IPCC global climate models tell us unambiguously that the warming trend will continue, but uncertainties about its extent and pace are large[1] (see Box 1). China's average temperature is estimated to increase further by 1–5 °C by 2100 (ref. 1). This 4 °C range reflects not only uncertainty in IPCC greenhouse gas emission economic scenarios[7] (a range of 2 °C), but also the spread among climate models when forced by the same scenario[1] (a range of 3 °C). Beyond mean annual values, impact studies need projections of seasonal temperature change. In looking at the output of 24 IPCC models[1], we found a much stronger future warming rate in summer (from 0.021 ± 0.008 °C per year in the IPCC B1 scenario[7] to 0.049 ± 0.009 °C per year in the IPCC A2 scenario[7]) than is currently observed[1]. Such a pronounced summer warming would inevitably enhance evapo-transpiration, increasing the risk of water shortage for agriculture.

Increased rainfall contrast between northeastern and southern China. Precipitation in eastern China exhibits decadal-scale variability, forced by the East Asian and Indian monsoons[8]. We analysed data from 355 rain gauge stations and observed no significant long-term trend in country-average precipitation since 1960 (see Box 1). However, there are significant regional precipitation trends (see Box 1). The drier regions of northeastern China (including North China and Northeast China) are receiving less and less precipitation in summer and autumn (a 12% decline since 1960). By contrast, the wetter region of southern China is experiencing more rainfall during both summer and winter. Similar regional summer precipitation trends are expected from the probable weakening of the summer monsoon since the late 1970s[9,10]. So far, the changes appear to fall within the bounds of normal decadal variability of rainfall (see Box 1).

Future projections of precipitation by IPCC climate models[1] are highly uncertain (see Box 1). For instance, in northern China, where a decrease in precipitation is observed today (see above) the models surprisingly project an increase in summer precipitation of $7 \pm 7\%$ above 2000–2006 levels by 2100 (ref. 1) (under the IPCC A1B scenario[7]). Models logically simulate a globally more intense hydrological cycle when forced by increasing greenhouse gases[11], but over a region like northern China, they may not accurately reflect synoptic and orographic rainfall processes[12], nor regional climate forcing by dust and pollution aerosols[4].

In the light of this case study, one can appreciate that to reconcile the observed temperature and precipitation trends with future projections for China remains a major scientific challenge. This can be addressed by using regional models fitted with aerosol and chemistry effects on climate and improved description of land–atmosphere feedback processes, to enable improved impact studies and to design cost-effective adaptation measures[4].

A country of drought and floods. China is at risk from heavy rainfalls, heatwaves and drought[5,13,14]. Heatwaves have occurred more frequently during the past 50 years, except over central China[15]. A significant reduction of cold days in winter has also been observed[16]. Trends in heavy rainfall events causing floods show high spatial heterogeneity[13,14]. These extreme events seem to become more frequent over northwestern China and the mid- to lower reaches of the Yangtze River, but less frequent in northeastern China and the northwestern Yangtze River[13]. Meanwhile, a general decrease in the number of rainy days has been observed across the entire country (see Box 1). According to regional climate models, the frequency of heatwaves and rainfall extremes in the future may increase over most of the country[17].

Drought is one of the most severe manifestations of climate variability in China. It is a source of concern for agriculture and human life, given that the country is already quite dry[18] (3.32×10^6 km^2 of drylands). Over the past six decades, very severe droughts hit China in the 1960s, in the late 1970s and early 1980s, and in the late 1990s[19]. Recently, northeastern China has suffered particularly from drought[20,21] while, surprisingly, arid regions of northwestern China have enjoyed less-severe droughts (Fig. 1), as indicated by rising lake levels and increased vegetation cover on desert margins[22].

A key question is whether northeastern China will continue to suffer from drought in the future. Here again, results from climate models and scenarios indicate a large range of uncertainty. Under the IPCC A1B scenario[7], it is predicted that the recently observed dipole of drier northeast China and wetter northwest China may further intensify[23]. In contrast, under the IPCC B1 scenario[7], a decrease of drought in northeast China is projected[24]. To understand and project drought occurrences better, we need to pay more attention to the effects of soil moisture feedbacks on climate[25]. Analysing the big droughts of the twentieth century[26] should further help researchers to identify key drought traits such as duration, intensity and extent, the processes that affect ecosystems and water resources most adversely, and the differences in regional responses.

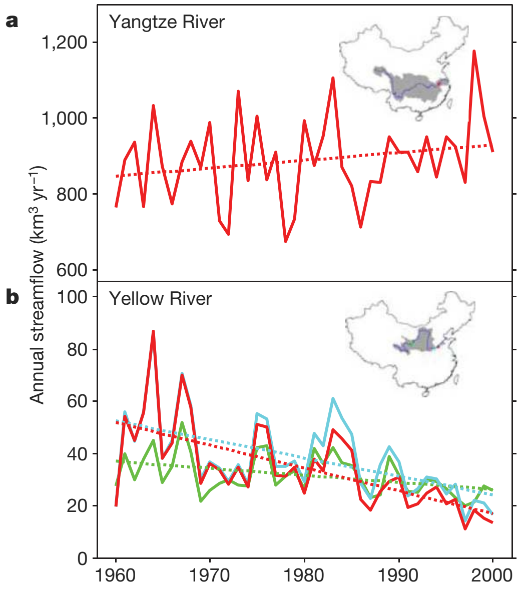


Figure 2 · Observed inter-annual variation in annual runoff in two major Chinese rivers. **a, Observed inter-annual variation in the Yangtze River annual runoff at the Datong station (red dot on China map in inset; grey shading indicates the area of the Yangtze River basin) from 1960 to 2000. The red dotted line is the fit to the Datong data: $y = 2.05x - 3{,}172$ ($R^2 = 0.05$, $P = 0.16$). b, Observed inter-annual variation in the Yellow River annual runoff at the Lanzhou (upper basin), Huayuankou (lower basin), and Gaocun (lower basin) stations (green, blue and red dots on China map in inset; grey shading indicates the area of the Yellow River basin) from 1960 to 2000. The green dotted line is the fit to the Lanzhou data: $y = -0.27x + 560$ ($R^2 = 0.19$, $P < 0.01$). The blue dotted line is the fit to the Huayuankou data: $y = -0.7x + 1{,}434$ ($R^2 = 0.31$, $P < 0.01$). The red dotted line is the fit to the Gaocun data: $y = -0.87x + 1{,}764$ ($R^2 = 0.44$, $P < 0.01$). The decreasing trend in Yellow River annual runoff is at least partially induced by climate change (see text). A linear regression *t*-test was conducted to determine whether the slope of the regression line differed significantly from zero.**

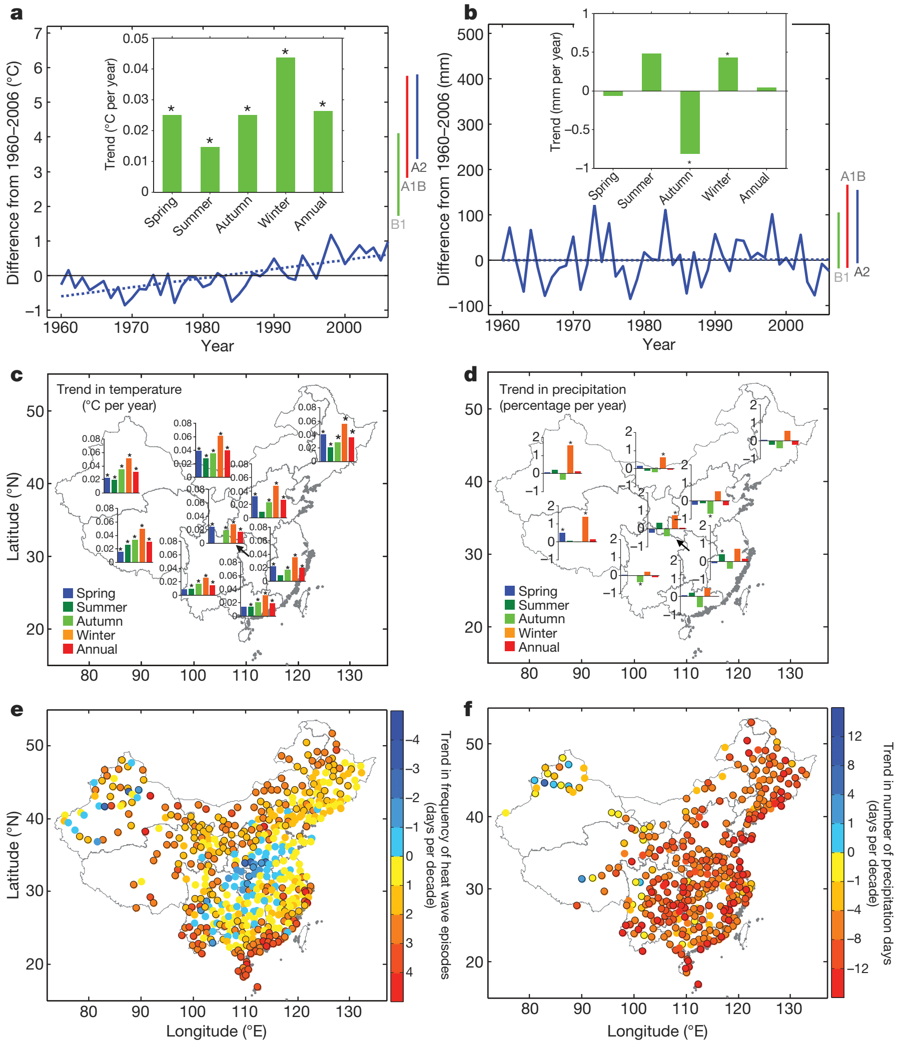
Box 1 - Climate change in China

Although China's overall mean annual temperature has significantly increased over the past five decades (Box 1 Figure a), there are remarkable regional contrasts (Box 1 Figure c). The largest warming is found in northeast China, with a trend of 0.36 uC per decade, and Inner Mongolia, with 0.4 uC per decade. The smallest warming trend is found over southwest China with a trend of 0.15 uC per decade (possibly related to the cooling effects of increasing aerosol content[100]).

Annual precipitation trends in China for the period 1960–2006 show strong differences between northeastern (decrease), northwestern (increase) and southeastern China (increase). The northeastern decrease is mostly caused by the decrease in summer and autumn precipitation, while the southeastern increase mainly results from an increase in summer and winter precipitation (Box 1 Figure d). Seasonal changes in precipitation patterns are also apparent. In autumn, most regions except the Qinghai–Xizang Plateau show a decrease in precipitation. In stark contrast, winter has experienced an increase in precipitation across China, particularly in northwestern China (16% per decade) and Qinghai–Xizang Plateau (14% per decade).

We have analysed past trends in heatwaves from long-term meteorological observations. We defined heatwaves as June–August days with temperatures exceeding the 90th percentile with respect to the 1960–2006 reference period[15]. An increase in frequency of heatwave events occurred across most of China, except in central China. The Qinghai–Xizang Plateau and coastal regions of southern China show the largest increase in frequency of heatwave events (over two days per decade).

Most of China has experienced a decrease in the annual number of raindays, particularly in the southwest and northeastern part. In southeastern China, the decrease in the annual number of raindays is coincident with an increase in annual precipitation, implying an increase in rainfall intensity[13].



Box 1 Figure · Observed trends and future projections of climate in China. a, Observed mean annual temperature variations between 1960 and 2006 across the country, expressed as deviation from the mean during that period (blue line). The blue dotted line is a fit to the data: $y = 0.0263x - 52.13$ ($R^2 = 0.54$, $P = 0.001$). The inset shows trends in seasonal temperature (°C per year) during the period 1960–2006. The data come from the climate records of 412 meteorological stations. The three coloured bars on the right-hand side show the projected temperature range by 2100 for the three IPCC marker scenarios A1B, A2 and B1. Model output comes from ref. 1 and uses an ensemble of 24 models. **b**, As for **a** but for precipitation variations, but the data come from climate records at 355 meteorological stations where all daily precipitation data are available during the period of 1960–2006. The blue dotted line is a fit to the data: $y = 0.0454x - 90.03$ ($R^2 = 0.00$, $P = 0.93$). **c**, Spatial patterns of the trend in seasonal temperature (°C per year, shown as bar graphs) from 1960 to 2006. **d**, Spatial patterns of the trend in seasonal precipitation (percentage per year, shown as bar graphs) from 1960 to 2006. **e**, Spatial patterns of the trend in frequency of summer heatwave episodes (days per decade, shown as colour scale) from 1960 to 2006. Heatwave episodes were defined as hot summer (June–August) days with temperatures exceeding the 90th percentile with respect to the reference period (1960–2006). **f**, Spatial patterns of the trend in rainfall days with precipitation exceeding 0 mm (days per decade, shown as colour scale) from 1960 to 2006. A linear regression *t*-test was conducted to determine whether the slope of the regression line differed significantly from zero. Asterisks and black-edged circles indicates that the trend is statistically significant ($P < 0.05$).

River runoff and water resources

As the demand by agriculture, industry and households for water increases, its availability is becoming a key factor in China's development[27,28]. China's total fresh water volume is 2.81×10^{12} m^3, with 2.7×10^{12} m^3 of surface water and 0.83×10^{12} m^3 of groundwater[29]. Although this water resource is large in absolute value, ranking sixth in the world, the per capita water resource is only 25% of the world average[30]. Moreover, the distribution of water resources is spatially and seasonally uneven. The north of the country, similar in land area and population to the south, holds only 18% of the total water despite having 65% of the total arable land. By contrast, the south receives water from summer rainfalls, which is often 'wasted' through flooding.

Observed trends. In this context, a key question is how the drying of northeastern regions coupled to the warming trend across China has affected water resources. This question is difficult to answer, because one must disentangle the effects of climate change from those of increased human withdrawal. We reviewed runoff changes in the two largest river basins of China: the Yangtze River and the Yellow River (Fig. 1). The Yellow river is a perfect example of a large northern catchment sensitive to drying trends, conjugated with intense human withdrawal (109 million people concerned). The Yangtze River, on the other hand, is frequently flooded by monsoon rains in its central and middle reach (487 million people concerned). In addition, we selected the Tarim River (Fig. 1), the largest inland river in China, as a case study of the effect of glacier retreat on river runoff.

Many influences on variable trends in runoff. The Yangtze River shows only a small and statistically insignificant increase in annual runoff[31,32] since 1960 (Fig. 2a). In autumn, many gauged headwater catchments even record decreasing runoff, an observation explained partly by declining regional precipitation[33]. In summer, the middle and lower Yangtze reaches show a positive runoff trend[33] driven by increasing precipitation. About 50% of the summer precipitation is received as rainstorms, bringing an increased risk of summer flooding in the Yangtze over the past 40 years (ref. 34). In the lower reaches of the Pearl River further south, a trend similar to that of the lower Yangtze River is observed. The runoff has increased by 12% since the 1960s, owing to an increase in precipitation[35].

In stark contrast, the Yellow River shows a persistent decline in runoff (Fig. 2b). This decline is more pronounced from the upper to the lower basin[36]. Daily drying-up of the river is observed more frequently at the Lijin hydrological station at the Yellow River mouth over the last 40 years, especially during the 1990s[37]. The onset of daily

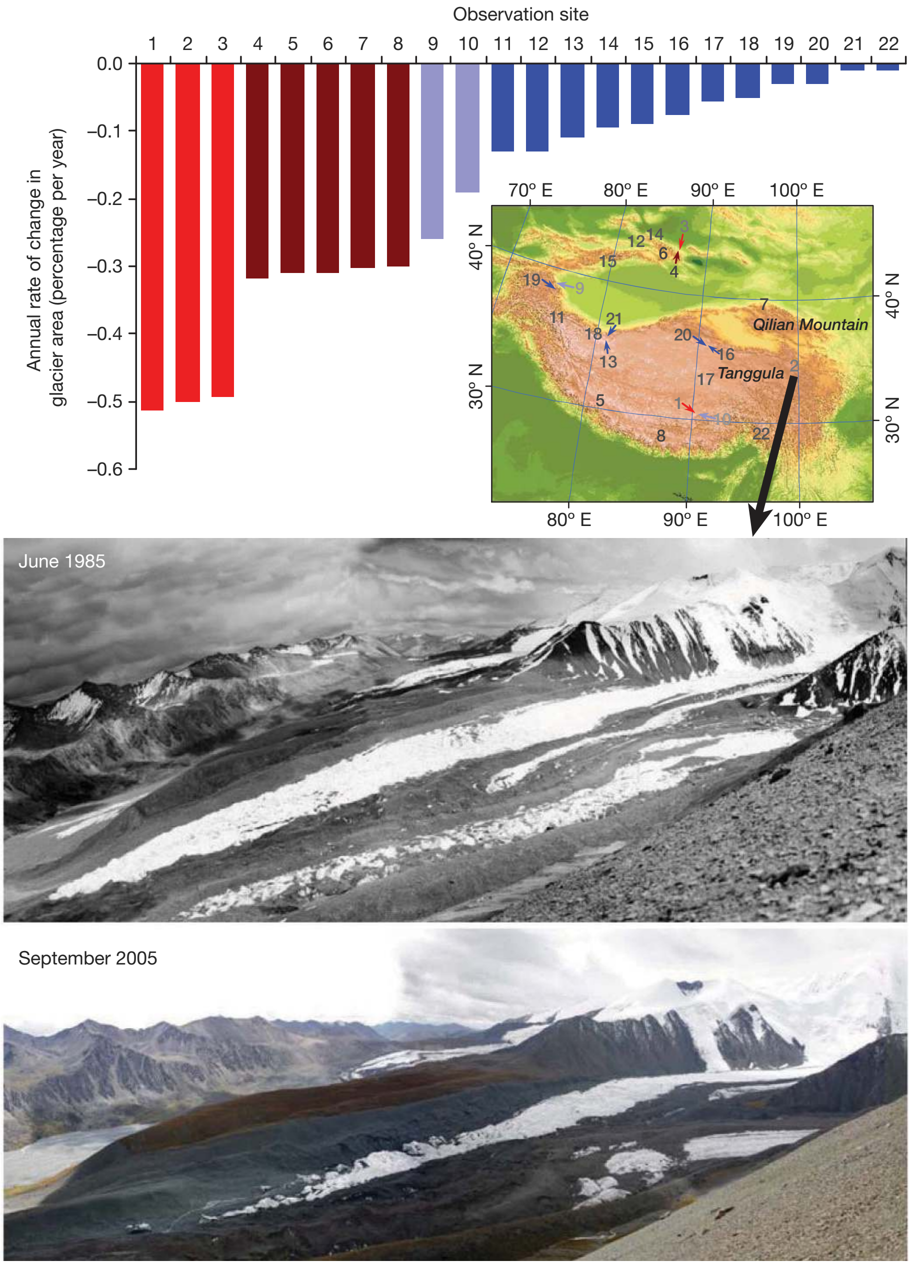


Figure 3 · Observed annual rate of change in glacier area at 22 monitoring stations in western China over the past 30–40 years. A negative rate indicates a shrinking glacier[42,98]. Each glacier location is shown on the map inset. The photographs show examples of glacier retreat between 1985 and 2005 due to increased melting at Mount Anyemaqen, Qinghai (one of the sacred mountains in the Tibetan ethnic area of China). Top image by Matthias Kuhle; bottom image by John Vovis for Greenpeace (reproduced with permission).

drying-up is occurring earlier in the year and the period of zero flow has lengthened[37]. The observed decrease in the runoff of the Yellow River is interesting because it reflects both climate change impacts and over-extraction of water for irrigation, industry and domestic usage[38]. Increased withdrawals can explain about 35% of the declining runoff observed at the Huayuankou station in the lower reaches (see Fig. 2b) over the last half-century[39]. This case study shows that, even for such a heavily managed river, climate is dominant in controlling runoff. When projecting the future of both the Yangtze and the Yellow River, however, not only precipitation trends, but also glacier melt come into the picture. These changes are analysed below.

Waning glaciers. Changes in glacier mass balance critically affect river runoff and agricultural development in China and south Asian countries. China has 46,377 glaciers, covering an area of 59,425 km^2 (refs 40 and 41). Owing to the current pronounced warming, more than 80% of the glaciers in western China are currently in a state of retreat[42–45] (Fig. 3). Temperature reconstruction suggests that the last five decades were the warmest in the past 500 years over the Qinghai–Xizang Plateau[46]. In the Qinghai–Xizang Plateau, glaciers shrank by 7% (3,790 km^2) over the past four decades[45], with an average decrease in thickness of 200 mm yr^{-1}. Although long-term mass balance observations are scarce, several lines of evidence support a mass loss by Chinese glaciers[43,44,47,48]. For instance, the mass balance of the Hailuogou valley glacier (26 km^2) shifted from an accumulation of 109 mm yr^{-1} during 1971–1985 to a net loss[47] of 538 mm yr^{-1} during 1986–2004. The Urumqi Glacier No.1, the glacier in China with the longest observation history and the one studied in most detail, has lost mass at the rate of 234 mm yr^{-1} over the past five decades[49].

The Tarim glacial meltflow case study. There is little doubt that the current loss of glacier mass in China is affecting river runoff, which also affects neighbouring countries (60% of glacier runoff flows out of China[40]). The annual glacier meltwater runoff in China increased from 62 km^3 in 1980 to 66–68 km^3 in 2000 (ref. 41). In the Tarim River basin[50], increased runoff was observed in nearly every headstream, a phenomenon which cannot be explained by precipitation alone and suggests a significant contribution from decreasing glaciers[22]. For example, mass loss from the upstream Tailan Glacier (-287 mm yr^{-1}), which feeds the Tarim River, increased local runoff[51] by 15% between 1957 and 2000. Increased glacier melting is also causing a rise in the level of glacial lakes[44], which in turn provokes more frequent lake outbursts and floods in the Tarim basin[52] (from 0.4 floods per year in the 1950s up to one flood a year in the 1990s). Yet, despite having more water flowing into its upper basin, the Tarim River is experiencing decreased runoff in its mainstream basin because of the rapid development of oases[53]. This example shows that increased human withdrawals in arid regions are not compensated by increased supply from glaciers, a disequilibrium that limits sustainable agriculture.

Future river runoff and water resources

Uncertain water supply and growing demand. The large uncertainties of projected precipitation changes[1] prevent us from making firm statements about how river flow in China will respond to climate change. Hydrological models driven by climate simulations predict an overall increase of river runoff over China[27] (7.5% in the IPCC B1 scenario[7] by 2100, and 9.7% in the A1 scenario[7]). In the Yellow River basin studied above, annual runoff is modelled to increase by 11% (ref. 54) in the IPCC A2 scenario[7] and by 5% in the IPCC B2 scenario[7]. This result is clearly sensitive to biases of global climate projections. For instance, a high-resolution regional climate model predicts decreasing or unchanged precipitation[12]. This implies that there is also a worst possible scenario in which water resources in the Yellow River region will decrease, owing to the rising temperatures increasing evapotranspiration. The key issue is that seasonal change in precipitation is more important for agriculture than annual changes. If it occurs in winter, out of phase with the cropping season[27,55], a future increase in rainfall in the Yellow River basin will not be beneficial to agriculture unless water managers can save water for the growing season. Observed recent trends since 1960 (see Box 1) indeed show that winter rainfall increased (46±35%), while summer rainfall slightly decreased ($-1\pm11\%$) over the Yellow River, which empirically suggests a potential risk for the future. Unfortunately, this risk cannot be confirmed by climate models, the uncertainties of which are much too large, as seen above.

A growing and increasingly wealthy population, coupled with agricultural and industrial development, is bound to push up the future demand for water in China. According to the IPCC A2 scenario[7], which posits a rapid population increase, parts of northern China, including the Yellow River, will experience decreasing per capita amounts of

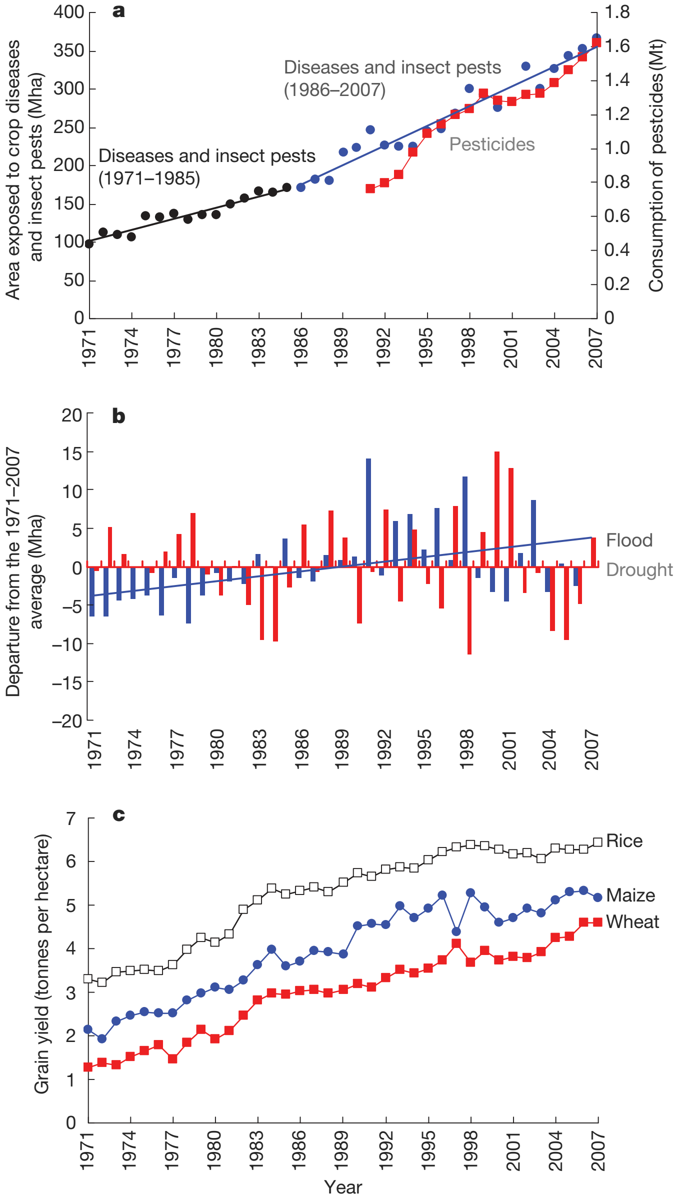


Figure 4 · Observed expansion of crop pests and diseases, and changes in flooding and droughts during the period 1971-2007. a, **Arable land area exposed to crop pests and diseases during the period 1971–2007. The increase is partially induced by climate warming (see text). The consequences of pesticide use are shown by the red curve. The black line is a fit to the 1971–1985 data: $y = 4.9x - 9{,}495$ ($R^2 = 0.92$, $P < 0.001$). The blue line is a fit to the 1986–2007 data: $y = 8.6x - 16{,}918$ ($R^2 = 0.94$, $P < 0.001$). b, Changes in cropland areas affected by flooding and droughts, expressed as a deviation from the 1971–2007 average. The blue line is a fit to the flood data: $y = 0.208x - 3.95$ ($R^2 = 0.20$, $P = 0.006$). The red line is a fit to the drought data: $y = -0.030x + 0.58$ ($R^2 = 0.00$, $P = 0.759$). c, Changes in cereal yields during the period 1971–2007, expressed as grain yield per unit area rather than total grain production because of interannual variation in the planted area. These data come from China's agricultural statistics[72,99].**

available fresh water[2]. In this context, it is foreseeable that the gap between water scarcity in the north and abundance in the south will widen even further[56]. Yet, uncertainties in regional climate projections and in river management plans hinder a more quantitative assessment.

Possible exhaustion of glacial runoff. Obviously, glaciers will play a key role in determining river runoff in the future. Despite the importance of this subject, we found surprisingly few studies addressing it. In the coming decades, a continuing increase in glacial runoff can reasonably be expected in response to warming, especially in spring and early summer[57,58]. But uncertainties are large. In the short term, this would be beneficial for irrigated agriculture in arid western China, although runoff may be reduced in late summer and autumn[58]. But in the long term, if a large fraction of the glaciers melt[59], water shortage may return and become the norm.

Most of the uncertainty lies in the vulnerability of Chinese glaciers to future warming. It has been suggested that most glaciers could suffer substantial reductions in volume over the next 50 years, with small glaciers ($<1\,\mathrm{km}^2$) at risk of disappearing[60]. Overall, 5–27% of glacial area is projected to disappear by 2050, and 10–67% by 2100 (refs 2, 61 and 62). Several studies[41,62,63] converge on the conclusion that glacier melt runoff may peak during 2030–2050, and could gradually decline afterwards. Even though the exact timing and magnitude of the 'tipping point' of each glacier is still uncertain, the projected long-term exhaustion of glacial water supply should have a considerable impact on the availability of water for both agricultural and human consumption[59]. We expect that such a critical issue would prompt a complete redesign of water management systems for the vast areas of western China.

Agriculture

Agriculture in China feeds some 22% of the global population with only 7% of the world's arable lands[64]. It is one of the most important economic sectors, contributing 11% to GDP in 2007 (ref. 64). Arable lands (130 Mha) span temperate, subtropical and tropical climates (Fig. 1). Single cropping is common in northern China, while multi-cropping rotations dominate south of 40 °N (Fig. 1). Rice, wheat and maize are the main crops, together accounting for 54% of the total sown area and 89% of the grain yield in 2007. We review below the impacts of recent climate trends on China's agriculture[65–67] by joint analysis of yield data, cropping areas affected, climate-sensitive pests and diseases, and occurrence of extreme events.

Effect of recent climate trends on crops. Depending on regional conditions and crop varieties, climate variability may produce either positive or negative effects on crop yield per unit area. In China, warming is believed to be harmful to rainfed crops but beneficial to irrigated agriculture[68]. For instance, rice yields in the northeast appear to have increased by 4.5–14.6% per °C in response to night-time warming during 1951–2002 (ref. 66). By contrast, warmer day-time temperatures are likely to have decreased wheat yield[66] (6–20% per °C). This shows the value of regional and crop-specific studies, and the need to incorporate a probabilistic approach to uncertainties. Countrywide, a 4.5% reduction in wheat yields is attributed to rising temperatures over the period 1979–2000 (ref. 67). Maize yields may also have been sensitive to recent warming[66], with data from eight Chinese provinces showing a negative response to rising temperature during the period 1979–2002 (ref. 66).

Regional warming has extended the length of the potential growing season for crops, allowing both earlier planting and later harvesting[69], and northward expansion of rice planting. For instance, the growing season of cotton in northwest China was lengthened by nine days during 1983–2004 (ref. 70). In parallel, the number of frost days shows a decline across most cropland regions[71]. Data from the Chinese National Bureau of Statistics[72] suggest that warming has already enabled a significant northward expansion of rice planting in Heilongjiang Province (the northernmost region of China) from 0.22 Mha in the early 1980s to 2.25 Mha in 2007, that is, a northward shift from ~48 °N to ~52 °N. In parallel, rice yield in this province has increased from 0.7 Mt to 14.2 Mt over the same period, owing mainly to improved practice[72]. All these changes suggested that crop yield in the temperate climate zones of north China has benefited from the increased temperature.

Unfortunately, pests and diseases may also expand their geographic ranges as the climate warms, increasing stress on crops. The cropland area exposed to diseases and pest infestations rose dramatically from ~100 Mha in the early 1970s to ~345 Mha in the mid-2000s (Fig. 4a). The annual grain harvest loss due to pests and diseases increased from ~6 Mt in the early 1970s to ~13 Mt in the mid-2000s (2.7% loss of total grain harvest). In addition, drought and floods adversely affect crop production. Drought, however, is affecting a larger cropland area (25 ± 7 Mha per year; 17 ± 5% of sown area) than floods. A non-significant increasing trend in drought affected cropland areas has been observed since 1971 (Fig. 4b) even though the Palmer Drought Severity Index decreased on average over cultivated areas[20] (Fig. 1). The area affected by flooding increased by 88% from ~5 Mha per year in the 1970s up to 10 Mha per year in the 2000s (Fig. 4b). Drought and flood together caused harvest failure of ~4 Mha of sown area per year in the 1980s, a number which climbed up to ~5 Mha per year during 2000–2007. This observed change remains within the bounds of year-to-year harvest variability.

Together, these agricultural data indicate that climate-sensitive pests and extreme events have a negative impact on crop production, but that these impacts remain small at country scale. The key observation is that climate effects have so far been dwarfed by the huge production gains from modernization of agriculture[73–76]. Rice, maize and wheat yields in China have increased by 90%, 150% and 240%

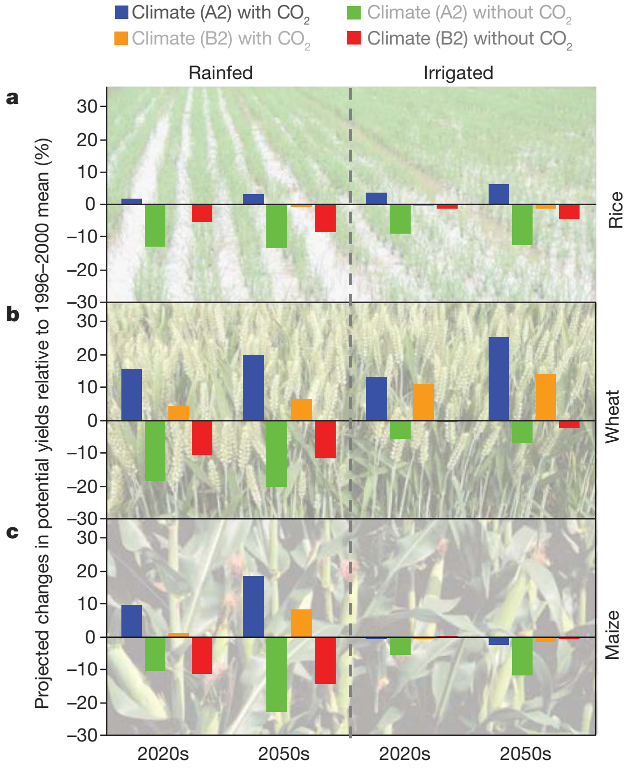


Figure 5 | The potential climate change impact on crop yield in China. Projected future percentage changes in the yields of rice (a), wheat (b) and maize (c) cultivated in China. The yield is defined as harvested grain biomass per unit cultivated area. Changes are expressed as the relative differences of 2020s and 2050s yields in comparison to the yield of 1996–2000. The left-hand panels show rainfed yield changes and the right-hand panels show irrigated yield changes. These results are obtained from ref. 79. In that study, the effects of CO_2 fertilization and climate change are accounted for, but not the effects of future developments in agro-technology, which is assumed to remain today. The separate effects of climate and CO_2 changes on yield are shown for IPCC climate scenarios A2 and B2 (ref. 7).

over the last four decades (Fig. 4c). We now investigate whether this situation will prevail in the future.

Future changes in crop production. Given the diversity of climate projections over China, spatially explicit crop models must be applied to address future changes. We reviewed the results of several such crop modelling assessment studies[77–80]. Some crop models predict that cereal yields will benefit globally from the synergy of climate change and the fertilizing effect of elevated CO_2 (refs 77–79). However, the range of model results is large, implying large uncertainties. In the comprehensive study of Xiong *et al.*[78], the cereal production in 2050 is projected to increase from 13% to 22% (IPCC scenarios B2 to A2; ref. 7) relative to the 1961–1990 mean. The most significant cereal production increases are projected in the northeast, northwest and southeast coastal provinces[78]. In eastern China, increased crop productivity is projected, ranging from 7% for rice to 25% for winter wheat[77]. In contrast, irrigated maize could experience a slight decrease by 2050 (Fig. 5).

Without incorporating the synergy of CO_2 fertilization in the crop model of ref. 78, climate change may induce a net yield reduction of 13% by 2050. More precisely, the projections for climate-induced yield reductions are 4–14% for rice, 2–20% for wheat, and 0–23% for maize by the mid-twenty-first century[79] (Fig. 5). Another study[80] projected that a one degree rise in temperature may decrease rice yield with a probability of 90%.

Hope for the best, but adapt for the worst. First, the magnitude of the CO_2 fertilization effect on crop yields is still debated and is therefore a source of uncertainty[81–86]. Without this mechanism, crop models that have been used so far to assess future production changes in China suggest a yield drop of up to 20% in response to climate change scenarios from a single climate model (Fig. 5). However, the very uncertain projections of rainfall by different climate models (see above) further increase the uncertainty of future crop yield changes[87].

Second, not all the effects of climate are included in the current generation of crop models used in this review. Neither pest and diseases effects, nor the possible decrease of glacial water supply are accounted for. Trends in increasing surface ozone concentration, causing crop plant damage in case of high exposure, could also negate the beneficial effect of CO_2 fertilization[88,89]. Relative grain loss due to increased levels of O_3 pollution in 2020 was projected to be 7–10% for rice, 2–7% for wheat and 16% for maize, assuming no change in agricultural production practices and again using 7-h and 12-h mean ozone exposure indices[90]. In addition, competing water use by industry and households could limit the water available for agricultural production[68,91]. Non-agricultural withdrawals could attenuate the projected cereal yield increase over China by 3–7% (ref. 78).

Third, an important source of uncertainty lies in the adaptation potentials themselves. Provided the flexibility of agro-technology and sufficient resources for farmers, the adverse effects of climate change might be overcome by increased use of fertilizers[73], expanded irrigation[74], and by the introduction of new crop varieties[75,76]. Any assessment of the impact of climate change on crop production in China will thus remain very rough unless it incorporates scenarios of adaptation potentials from agro-technology.

On the basis of these three sources of uncertainties, we can see that in the ‘best case’, crop production in China will not diminish in response to climate change, thanks to species and practice adaptation and to CO_2 fertilization. But a worse scenario, in which we speculatively posit no or negligible CO_2 fertilization benefits, lessening of glacial water supply in the future, the adverse effects of extreme events, pests and diseases, the damaging effects of O_3, and which lacks a large practice and varieties adaptation portfolio, can also be envisaged. If we apply the estimation of future crop production change considering climate change only[79] (see above) and relative grain loss due to increased levels of O_3 pollution in 1990 and 2020 (ref. 90), then we might see decreasing crop productivity by 3–22% for wheat, 8–18% for rice, and 9–30% for maize over the next decades. Such a scenario would have quite adverse implications for food security.

Conclusion and outlook

Our review suggests that—on a countrywide basis—the consequences of recent climate change on water resources and agriculture (Fig. 6) have been limited both because climate trends remained moderate compared to natural variability, and because of the overriding benefits delivered by technological progress, in particular improved agricultural practice. But is there worse to come? It has been projected that glaciers will retreat and continue to melt during this century[2,61,62]. The resultant increase in glacier runoff is temporary and may stop if the glaciers reach a new equilibrium. In western China, this major rearrangement in the

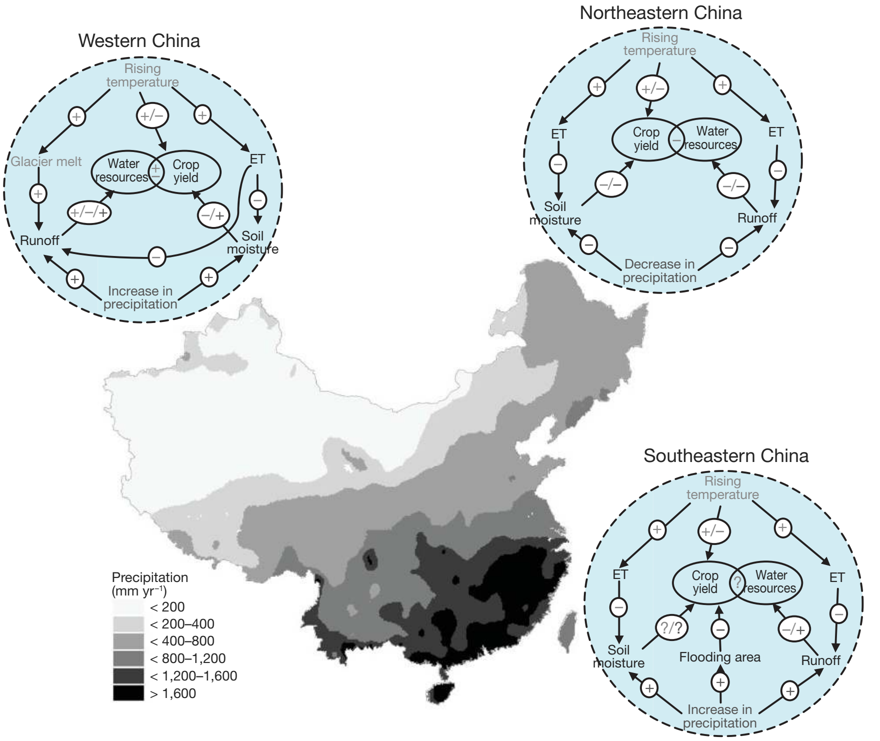


Figure 6 - Schematic diagram of climate change and its potential impacts on water resources and agriculture in China over the past five decades. Impact cycle diagrams for southeastern, western and northeastern China are superimposed on the annual precipitation map of China. Over the last few decades, China has experienced a pronounced warming. Precipitation has increased in the south and northwest of the country; in contrast, the northeastern part has suffered from drought. These changes have already produced significant impacts on agriculture as well as water resources. In western China, reducing glacier mass driven by rising temperature and increased precipitation caused an increase in runoff that benefited agriculture in western China. In northeastern China, warmer conditions and decreased rainfall have been accompanied by increased drought, which produced a negative impact on agriculture. The wetter southeastern China has had more rainfall with an increase in high rainfall events. These increased extreme rainfall events are likely to cause decreased crop yields, particularly through increased flooding. It is not clear whether the decrease in soil moisture and runoff due to the increase in evapotranspiraion (ET), driven by rising temperature, is beneficial for crop yield in southeastern China, because this region has high precipitation.

water supply could have adverse consequences on agricultural production. In northern China, by contrast, the uncertainty of future river runoff is dominated by the uncertainty of global climate models in projecting rainfall. Regarding crop production, when they incorporate a significant CO_2 fertilization effect, crop models simulate an increased crop production over China. Given the uncertainty of this process, as well as the effects of climate trends, climate extremes, ozone exposure, and farmers' adaptability in the future, one cannot rule out the possibility of strong negative climate change impacts on food production, even though the most optimistic scenario provides a net increase.

There is an urgent need to discover whether or not dangerous climate thresholds exist, above which China's sustainable economic development could be negatively affected. Our ability to pin down such regional thresholds is hindered today by the uncertainty of global climate in response to rising greenhouse gas concentrations, and of regional climates in response to aerosols and ozone forcing. Clearly, regional climate simulations must be improved—in particular for precipitation. In addition, most climate models lack key regional feedback processes involving land-use. In this context, forest plantations, urbanization and irrigation feedbacks[4] are critically important throughout China. Further, identifying the interactions through which climate change and human management will affect water availability and food production remains a challenge. In particular, there is a need for integrated studies over specific climate regions of China, combining dense regional observations with data from agricultural experiments, and long-term records of river runoff, local irrigation and glacier mass balance records.

Over the past decade, China has been active in mitigating and adapting the impacts of climate change on water resources and agriculture. China has issued a series of laws to enhance the sustainable use of water resources, particularly for agricultural development. Agriculture and water resources were two of the four key areas for adaptation to climate change, set out in China's national climate change programme[92]. China has long emphasized the importance of enlarging regional water storage and strengthening the water resource and management infrastructure. Hydraulic projects such as the South-to-North Water Diversion Project are planned to help optimize the allocation of water resources, to control floods on major rivers, and to alleviate drought in the north[93,94]. China is developing stress-resistant cultivars through the Seed Project, responding to the increasing extreme climate events[95]. Meanwhile, the largest plant biotechnology capacity outside North America is being built in China[96]. Making use of existing sectoral planning, for example, the "green wall policy" (or Three-North Shelterbelt Reforestation programme) and the "grain for green programme" (or Conversion of Cropland to Forest Programme) was also stressed in China's national climate change programme to protect existing forest carbon stock and enhance carbon sequestration[92]. Even if the emission of greenhouse gases were to stop[97], recent studies indicate that the climate system will continue to change for the remainder of this century, arguing—even in the absence of unambiguous historical climate change impacts on agriculture—for the continued development of adaptation strategies to protect vulnerable ecosystems and to ensure agricultural security.

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