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The impacts of climate change on agricultural production systems in China

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Abstract Climate change can bring positive and negative effects on Chinese agriculture, but negative impacts tend to dominate. The annual mean surface temperature has risen about 0.5–0.8 °C. The precipitation trends have not been identified during the past 100 years in China, although the frequency and intensity of extreme weather/climate events have increased, especially of drought. Water scarcity, more frequent and serious outbreaks of insects and diseases, and soil degradation caused by climate change have impacted agro-environmental conditions. However, temperature rise prolonged the crop growth seasons and cold damages have reduced in Northeast China. The projection of climate change indicates that the surface temperature will continue to increase with about 3.9 to 6.0 °C and precipitation is expected to increase by 9 to 11 % at the end of 21st century in China. Climate warming will provide more heat and as a consequence, the boundary of the triple-cropping system (TCS) will extend northwards by as much as 200 to 300 km, from the Yangtze River Valley to the Yellow River Basin, and the current double-cropping system (DCS) will move to the central part of China, into the current single cropping system (SCS) area which will decrease in SCS surface area of 23.1 % by 2050. Climate warming will also affect the optimum location for the cultivation of China's main crop varieties. If no measures are taken to adapt to climate changes, compared with the potential yield in 1961–1990, yields of irrigated wheat, corn and rice are projected to decrease by 2.2–6.7 %, 0.4 %–11.9 % and 4.3–12.4 % respectively in the 2050s. Climate warming will enhance potential evaporation and reduce the availability of soil moisture, thus causing a greater need for agricultural irrigation, intensifying the conflict between water supply and demand, especially in arid and semi-arid areas of China. With adequate irrigation, the extent of the reduction in yield of

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China's corn and wheat can be improved by 5 % to 15 %, and rice by 5 % or so than the potential yield in 1961–1990. Adaptive measures can reduce the agricultural loss under climate change. If effective measures are taken in a timely way, then climate change in the next 30–50 years will not have a significant influence on China's food security.

1 Introduction

Global warming and climate change have become a primary concern of the global community. The Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC AR4) stated that global surface temperature increased by 0.74 °C over a 100 year period from 1906 to 2005. The linear warming trend over the last 50 years was 0.13 °C/decade, and 11 of the 12 warmest years since 1850 occurred during the recent years of 1995–2006. Warming of the global climate system thus seems unequivocal. The report also indicated that most of the observed warming of the climate system over the last 50 years was very likely due to human activities. Multi-mode and multi-emission scenarios estimated that the increase in greenhouse gases caused by human activities will cause the earth's average surface temperature to increase by 1.1 to 6.4 °C by the end of the 21st century compared with the 1990s, and the average sea level will rise by 18–59 cm (IPCC 2007). Although these predictions have a certain degree of uncertainty, the impact of climate change on human activities has been widely recognized. The IPCC AR4 has clearly pointed out that climate change will have a strong influence on agriculture, and developing countries will be more vulnerable to adverse impacts and may face an increased threat of food shortages.

China and China's economy are still very much dominated by agriculture with more than half of the population living in rural areas (~674 million people in 2010). Agricultural production directly affects China's social stability and people's standards of living, with farmers coping with a range of complex geographical areas and climatic differences (Ju et al. 2007; Piao et al. 2010). Although there is still much uncertainty about specific (local) changes due to climate change, there is an agreement that climate change will have an important, mainly negative impact on Chinese agriculture with implications for China's food supply and a potential threat to China's food security (Zhou 2010; Qin et al. 2007). It is therefore of great significance to identify the impacts of climate change on China's agricultural production and food security and to take actions to mitigate the risks of climate change on these issues.

2 Climate trends in China

2.1 Observed climate trends

The effects of climate change are predominantly demonstrated by rising temperatures. There was a temperature increase of 0.5 °C–0.8 °C in China between the years of 1906 and -2005, particularly noticeable during the most recent 50 years, mainly in the middle and late 1980s (Tang et al. 2010). From 1951 to 2009, the upward trend of China's annual temperature became more and more obvious, with an average rise of 1.38 °C and an annual warming rate of about 0.23 °C/decade (SNARCC 2011). The years 2007 and 2007 were the warmest years since 1951 in mainland China. The linear ascending trend of temperature is more obvious in winter and more noticeable in northern China (Yu et al. 2011).

The annual average precipitation did not show any trend changes in the past 100 years (1910–2010) in China, with fluctuations between decades occurring. Precipitation was lower in the 1920s, 1940s, 1960s, 1980s and 2000s, whereas more precipitation was recorded in the 1910s, 1930s, 1950s, 1970s and 1990s, roughly indicating a 20 year cycle (SNARCC 2011). The maximum mean annual total precipitation occurred in the 1950s and the minimum happened in the 2000s (Yu et al. 2011). Seasonally, there was a reduction of 27.3 mm in autumn and an increase of 20.6 mm in spring, while the changes in summer and winter were not significant during the past 100 years. Certain fluctuations of seasonal precipitation existed among years and decades (Yan et al. 2011). While during the last 50 years of 1951–2009, there was a slight decrease in precipitation within China, varying in different regions. Annual precipitation reduced significantly in the North China. Among the four seasons, precipitation in summer shows slightly increased (Yu et al. 2011).

2.2 Future climate change

Simulations by seven climate models under the SRES A2 greenhouse gas and aerosol scenario indicate that the surface temperature, the maximum temperature and the minimum temperature over China will rise by 0.3 °C–2.3 °C, 0.1 °C–2.0 °C, and 0.5 °C–2.7 °C, respectively during the 2020s (2001–2030, compared with 1961–1990). The magnitude is generally larger in higher latitudes (Jiang et al. 2004). The results from Gao et al. (Gao et al. 2010; Qin et al. 2007) demonstrated that the annual average temperature in China will increase by 1.3–2.1 °C, 2.3–3.3 °C and 3.9–6.0 °C by the 2020s, 2050s and 2100 s respectively. To be specific, the warming trend in northern China will be greater than in the south and greater in winter and spring than in summer and autumn (Hu et al. 2012). In the context of global warming, China's cold waves may continue to decrease, and hot days in summer may increase in southern areas. Warm winters and hotter summers may be seen more frequently in China (Pan et al. 2011; Gao et al. 2012a).

In the end of 21st century, precipitation will increase by about 9–11 % in China. However, northern China may experience a more marked increase, while the Bohai Sea coastal region and the Yangtze River estuary areas and southwestern may become drier (Gao et al. 2010). It is estimated that the country's average annual precipitation will increase by 2–3 % by 2020 and by 5–7 % in 2050. There will be more rainy days in northern China, but the spatial-temporal variation of precipitation change is quite large (NARCC 2007). There will be more days of heavy precipitation in south regions, and the frequency of sandstorms in northern China may be maintained at a relatively low level or even be reduced as a consequence of precipitation increases (Zhang et al. 2011; Chang et al. 2012).

3 Impacts of observed climate change on agriculture

Climate change affects agriculture mainly through changes in temperature, precipitation, CO_2 concentration and altered frequencies of extreme weather and climate events causing different impacts on agriculture in different regions.

3.1 Farming system adjustment

In northern China, observations confirm that temperature rise has improved conditions related to crop heat requirements, crop damages due to cold waves have been reduced and the planting period has been extended (Ji et al. 2012). The frequency of frost freezing (grade≥4) damage of apple trees has reduced from 80 % in the 1950s to 20 % in 2000 in Northeast China and the occurrence of cold waves have decreased significantly there, going down 1–2 times/decadal in the last 50 years (Li et al. 2001; Zhao 2010; Gao et al. 2012b). The maize growing season length has been extended by 7–10 days; farmers have applied late-maturing varieties to replace early-maturing cultivars (Jia and Guo 2009). In the Liaoning Province in Northeast China, the accumulated thermal degrees above the 10 °C threshold temperature in the growth season has greatly increased from 1956 to 2005, and the first starting date above 10 °C threshold temperature has been brought forward significantly by about 6 days in most areas. The growing season associated with the contour of 3350 °C of accumulated degrees has markedly shifted northward and eastward in the recent 10 years (Zhao et al. 2009).

China's long-term agricultural planting structure and patterns have been changed due to climate warming, making it possible to develop multi-cropping system in middle/high latitude regions. Compared with the planting systems of the 1950–1980's, the northern boundary of the double-cropping system (DCS) from 1981 to 2007 has significantly moved in North Chinese provinces such as Shanxi, Hebei and Beijing. The northern boundary of the triple-cropping system (TCS) resulted in a large spatial displacement in Central and East Chinese provinces such as Hubei, Jiangsu and Zhejiang. Without the consideration for potential changes in crop varieties and changing socio-economic conditions, grain yield per hectare could increase by about 54–106 % if the single cropping system (SCS) changed to DCS, while increases of about 27–58 % if the DCS changed to a TCS have been reported (Yang et al. 2010). During the ten-year period from 1986 to 1995, the multiple-cropping index of China's arable land has increased by 9.5 %, and the index in Northeast China has reached 102 % (Du and Guan 2007).

Although temperature rises provides more heat resources in the North, negative effects or unforeseen challenges exist as well. In the Southern China Areas, with increased heat and drought, lot crop lands were lost the advantage with high production capacity. Moreover, in a warming climate, some traditional agricultural technologies have lost their previous advantages, for example irrigating before a cold winter on winter wheat which originally moistened soil and prevented diseases and pests transfer has become inefficient due to increased evaptransportation rated and pest survival in a warmer winter. In some regions, the potential advantage of temperature increases can't be fully utilized due to the scarcity of water resources.

3.2 Agro-environmental degradation

Under climate change, there are serious conflicts between water supply and demand, with the number of rainless days significantly increasing with a mean rate of 4d/decade during between 1958 and 2007 with highest increases observed during autumn (Wu et al. 2011). Drying trends were particularly evident in the northern China (Li et al. 2010; Ma et al. 2005). For example, the productivity of typical grassland in Inner Mongolia showed a clear downward trend since 1993 and the grazing capacity had decreased significantly in 2001–2007 due to higher climatic aridity (Han et al. 2010; Ding and Liu 2011). Climatic warming has also intensified soil moisture evaporation and led the soil salinity moving upward, which results in salinity increases aggravating the harm of saline and alkaline soil, similar to irrigated regions along the Yellow River, with total soil salt contents of light, moderate and severe salty soil increasing by 0.08 g/kg, 0.13 g/kg and 0.19 g/kg respectively from 1973 to 2008 (Gao et al. 2009; Xiao et al. 2011). Over irrigation induced the secondary salinity in extensive areas, thus reduced the productivity and prompted an increasing trend of desertification (Liu et al. 2010a; Zhao et al. 2011).

China's agricultural losses caused by pests and diseases currently account for about 20–25 % of the total agricultural output value (SNARCC 2011). Climate warming increased epidemics of diseases and insects as well as the spread of weeds. Some diseases and insects, never or seldom being seen before, have emerged extensively, such as armyworm and corn borer in 2012 in Northeast China where there has been an increase in species quantity and distribution. Changing crops and increasing multiple cropping indexes also provides a more conducive environment for the spread of pests and pathogens. For example, large-scale outbreaks of rice plant hopper in south China in 2005–2007 was closely related to the warm winter and higher humidity with the affected area amounting to 26.7 million hectares (Xia 2008). These factors have hampered controlling negative consequences on the environment.

3.3 Extreme event intensified

Among the climatic and meteorological disasters, drought followed by flood and hails have the greatest impacts on agriculture in China. During 1991–2008, an average annual 25.1 million ha of farmlands suffered from drought in China, with grain production losses of about 28.3 million tons and economic losses of about 33 billion Yuan RMB. In 2009, there were about 29.3 million ha crop lands suffering from drought and 11 million livestock had difficulty accessing sufficient drinking water.[1] According to the 2010 drought statistics, cropland hit by drought amounted to 13.3 million hectares, of which 9.0 million hectares suffered was impacted disastrously. The annual loss of grain due to drought during 2010 was more than 16.8 million tons, accounting for about 3.08 % of the total grain output (Zhang 2010). Central China, with a major production base of winter wheat, suffered from serious droughts in 2009 with a usual occurrence of 1 in 30 or 1 in 50 years in certain regions. In 2010, Dongting Lake in the Hubei Province shrunk by two thirds with water level falling by about 5 m which hampered fish breeding and migration. Meanwhile, the continuous drought has turned Poyang Lake into a prairie. The lake showed the smallest extent in history, just one-tenth of that in a normal year.

Flood hit areas have increased in Southern China over the past 10 years, in particular the Yangtze Valley flood in 1998 and the Huaihe River Valley flood in 2003 (Ye et al. 2006). Indeed, there are a number of examples of the impacts of extreme weather over the last decade. In mountainous areas, the unique topography and heavy torrential have resulted in serious soil erosion and loss of lives (Cui et al. 2008). During a rare low-temperature freezing rain and snow disaster in south China in early 2008, the number of consecutive freeze days and snowfall had their maximum values since 1951 affecting several regions. The strength (or probability) of such disasters previously was once in a 100 year (Wang et al. 2008). These disasters cause much chaos for cropland ecosystems.

4 Future impacts of climate change on agriculture

4.1 Field management practice

Climate change will alter fertilization demands of crops and lead to higher volatilization of applied fertilizer. Between temperatures of 15 and 28 °C, rapid volatilization of available N

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[1] The State Flood Control and Drought Relief Headquarters, Chinese Ministry of Water Resource. Bulletin of Flood and Drought Disasters in China, 2010.

increases by about 4 % for every degree C increase, and the average emission period is shortened to 3.6 days. The application amount of N is projected to increase by about 8 % and 16 % for temperature increases of 2 °C and 4 °C respectively (Yan and Zhu 2000). Farmers are thus likely to apply more fertilizer to ensure crop nutrition and this may exacerbate pressures on the environment through increased leaching rates of nitrates. Future climate change is also projected to have a significant effect on the occurrence and development of pests and diseases. Under CO_2 doubling conditions, armyworm populations will double their generation in a year (Wang et al. 2002). In the aestivation regions of wheat yellow stripe rust (WYSR), like the Qinghai and Gansu provinces in Northwest China temperatures are projected to increase more in winter than in summer, which is conducive to the survival of WYSR during the winter as well as a southward spreading (Wang et al. 2008). The spread of pests and weeds will be more prevalent and consequently more pesticides and herbicides will be applied.

Climate warming could intensify the conflict between the supply and demand for water resources. China's agricultural and pastoral areas will loss 5 to 10 % of their surface area if the temperature rises by 1 °C. Although climate change may cause an increase in precipitation in some areas, soil moisture will eventually reduce by about 11 % in arid and semi-arid areas (SNARCC 2011). Climate warming will accelerate glacier melting in northwest glacier regions, which will induce more melting water for irrigated agriculture. However, if the glaciers continue to shrink, melting glacier water will be less and less over time and irrigated agriculture will ultimately suffer from production reduction (Zhao et al. 2008). This is bound to lead to increased overuse and exploitation of surface and underground water which may break the normal water cycle and result in the uneven distribution between different economic sectors in need of water and potential conflicts.

4.2 Cropping systems

China is a country with a large landmass and with a variety of cropping systems. Most of the agricultural areas employ various cropping systems (including intercropping and multiple cropping), with the exception of the northeast and northwest China which is dominated by the single cropping system (SCS). When the annual average temperature increases by 1 °C, the number of successive days with ≥10 °C accumulated thermal heat extend on average by 15 days or so (NARCC 2007). If only temperature is considered, without taking precipitation and soil condition in consideration, the regional cropping system in the lower reach of Yangtze River would shift from DCS to TCS and the TCS boundary would move northward by about 200 to 300 km in 2050, which would increase grain yield per unit area (Yang et al. 2011; Liu et al. 2010b). It seems that climate warming would play a positive role in opportunities for agricultural planting systems, such as SCS shifting to DCS, lower impacts from cold waves (countering increased winter survival of pests and diseases). In reality, the benefit of a temperature rise should be integrated with other agro-environment factors such as irrigation water availability and local cropland conditions. Climate change will increase crop water consumption and reduce soil quality etc, with severe challenges to implement multiple cropping systems. Structural adjustment of crop production systems will require detailed analysis including the suitability of crops varieties for new locations and matching the water availability for crops during the growing period (Yuan et al. 2011; Li et al. 2010).

4.3 Grain crop production

The main concern regarding the impacts of climate change on Chinese agriculture is the production of grain crops. Under three GCM models[2] (GFDL, MPI and UKMOH) running simulations, temperature increases about 1.3 to 1.8 °C and precipitation increase reached from 2.6 % to 5.9 % in 2050. Crop yield of winter wheat, rice and summer corn in irrigated areas are likely to change by −1.6 to −2.5 %, −3.7 to 10.5 % and −11.6 to 0.7 % respectively. Combined with output changes in other rain-fed regions, production of total major crops may be reduced by an average of 5–10 % in China (Wang 2003). Applying SRES A2 and B2 scenarios from PRECIS[3] and in combination with CERES crop models, research indicates that rain-fed wheat, corn and rice output will decrease on average by 11.4–20.4 %, 14.5–22.8 % and 8.5–13.6 % respectively, if the current level of technologies is still in use by 2050s (which is unlikely). If irrigation water is guaranteed, then the output of wheat, corn, and rice will have a lower reduction of 2.2–6.7 %, 0.4–11.9 % and 4.3–12.4 % respectively. In the 2080s, the reduction in the production of all the three crops will be more significant (Erda et al. 2005). Irrigation can increase the yields of the three major crops, lowering the loss of corn and wheat outputs by 5–15 % and rice by 5 % (Xiong et al. 2007). If atmospheric CO_2 concentration reaches 600 ppm, wheat and maize yields will increase by 38 % and 12 %, and water use efficiencies will improve by 40 % and 25 % respectively in North China, compared with those without CO_2 fertilization (Ruiping et al. 2010). The contribution of CO_2 fertilization is a crucial factor to determine the future grain production in China.

4.4 Food security

Climate change will bring additional pressures on China’s grain production. According to estimates of production potential, it is possible that food production could meet the 600 million ton demand for a maximum population of 1.5 billion, but climate change will make this more difficult. Through analysis of China’s economy, population and land use factors, the largest gap between food supply and demand is projected to equal about 68 million tons, accounting for about 10 % of total demand, which will possibly happen in 2040 or so (Yao 2007). Wang and Zheng (2001) estimated that the food gap should be below 8 % even if China becomes a moderately developed country. Other research indicates that China’s total grain harvest will be up to 714 million tons by 2030, together with other minor crops, which will be sufficient for grain demand of 659 million tons (Cai et al. 2008). Moreover, if the fertilizer effect of higher CO_2 concentration is considered, there will still be a potential increase of grain yield. Under this assumption, climate warming would therefore not pose a great threat to China’s food supply. If adaptive actions can be prompt and effective, climate change will not have a significant impact on China’s food security in the next 30–50 years (Xiong et al. 2007; Cai et al. 2008).

In short, climate change will result in increased fluctuations in China’s food production and the impact cannot be ignored. It is reported that the government has to invest an

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[2] Equilibrium mode: to increase the concentration of CO_2 to twice that of the pre-industrial level and to simulate characteristics of global and regional climate change. For example, the American Geophysical Fluid Dynamics Laboratory model (GFDL), the British Meteorological Bureau Model of High-resolution (UKMOH) and the German Model of Paiksbulank Institute (MPI).

[3] PRECIS (Providing Regional Climates for Impacts Studies): the regional climate model researched by the Hadley Centre of the UK Meteorological Office. A2 and B2 are different scenarios for greenhouse gas emissions.

additional 0.8–3.48 billion U.S. dollars each year to ensure food security for when the population is peaking while mitigating climate change impacts, otherwise agricultural loss will be 3.2–8.0 billion U.S. dollars each year (Qin et al. 2005). Therefore, the potential growth of China's future grain production capacity is facing a huge challenge.

5 Closing comments and discussions

5.1 Adaptation could compensate the adverse impacts of climate change on crops

In China, the annual mean surface temperature has increased by about 0.5 to 0.8 °C and precipitation trends have not been obvious during the past 100 years. Meanwhile, water scarcity, more frequent and serious outbreak of insects and diseases, and soil degradation caused by climate change can all deteriorate agro-environmental conditions. Advantages and disadvantages of climate change impacts are recognized, although it appears that in large regions the overall balance will be negative. However, grain production in China has showed a continuous increase from 2004 to 2012 even with warming and decreased precipitation, which implies that adaptations of improved technologies and policy stimuli may have played positive and crucial roles and could compensate grain loss by climate change to some extent. In the years of 1998–2002, China had encountered a tendency of cereal grain yield stagnation. Some of these trends have been influenced by warming temperature and weather disasters. Farmers have spontaneously adapted to climate by changing the time of cultivation and selecting other cultivars and crop species. Other adaptations included dissemination of water saving techniques, irrigation regime adjustment, application of information and communication technology etc., indicating that current technologies can be used to combat adverse effects of climate change at present and can likely be used in future. Current research usually predicts future crop yield at present technology levels, but societies commonly seek the adaptation measures to mitigate negative impacts and maintain or even increase crop yields under future climate change. These measures include selection of the most favorable crops, guidance for new cultivars breeding, and application of dynamic cropping systems, which benefit crop yield growth even with climate change.

5.2 Crop yield prediction with many assumptions and need more research to clarify

Climate change projections indicate that both the surface temperature and precipitation will increase at the end of 21st century in China. Changes in climatic suitability will lead to invasions of weed, pest and diseases, which can lower agricultural productivity. Current knowledge of the impact of climate change on crops yield mainly concentrate on effects due to rising temperatures and shifts in rainfall patterns without consideration of the impacts of pests and diseases, and land production capacity (Zhang et al. 2007; Brown et al. 2011). When all effects are considered, including fertilizer runoff and land degradation etc, the comprehensive effects of climate change are very likely negative (Müller et al. 2011). However, a current understanding of crop yield formation is still not comprehensive enough to evaluate the combined effects in several climate variables. Raising temperature will extend the growing season in temperate regions, but it also accelerates crop development and shortens the crop life expectation (Xingguo et al. 2009). The effects of extreme events on crop growth and water availability are likely to be underestimated. Meanwhile, climate warming drives extension of multiple-planting areas, which would lead to the increase of annual grain yield, but water availability is a vital barrier for multiple-planting development in reality (Xiong et al. 2009). It should be noted that significant limitations exist in the capacity to evaluate future agricultural productivity in China (Yao et al. 2011). This includes uncertainties of agro-environment changes in future periods.

5.3 Future crop yields will increase with CO_2 but decrease without in most studies

Crop yield growth development will respond differently with or without CO_2 fertilization. Erda et al. (2005) indicates that under climate change, irrigated output of wheat, corn, and rice will decrease by 2.2–6.7 %, 0.4–11.9 % and 4.3–12.4 % respectively, but if taking the fertilizer effect of CO_2 into account, output of the irrigated crops will increase on an average by 3–25 %. Crop modeling studies without CO_2 fertilization tend to show negative impacts on crop production, but higher CO_2 concentrations can offset the negative effects of higher temperatures, resulting in average increases in yield (Lobell and Gourdji 2012). However, Muhuddin et al. (2007) demonstrate that rain-fed wheat yield will decrease by about 29 % and the effect of elevated CO_2 is small, for example only 4 % in south-eastern Australia. It should be noted that most results attributing positive effects of CO_2 fertilization come from modeling studies without any limitation of water and fertilizer supply. In reality, crop growth will encounter altered environment conditions; water supply for instance could be insufficient for crop demand (Stöckle et al. 2010). The fertilizer effects of CO_2 are usually obtained under ideal water and fertilizer environments, and the effects considered in models are obtained via relative analysis based on theories (Martinez et al. 2005). Results from Free Air Carbon Enrichment (FACE) experiments show that the stimulation of grain yield by CO_2 enrichment is lower than expected, the effects of CO_2 enrichment in some crop models, including EPIC, may be overestimated (Long et al. 2005; Chavas et al. 2009). In actual production, the fertilizer effect of CO_2 and its long-term performance needs further research.

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