Journal of Integrative Agriculture
Advanced Online Publication: 2013 Doi:

Overview of impacts of climate change and adaptation in China's agriculture[1]

WANG Jin-xia[1]*, HUANG Ji-kun[1]*, YANG Jun[1]

[1]*Center for Chinese Agricultural Policy, Institute of Geographical Sciences and Natural Resources Research, Chinese Academy of Sciences, Jia, No.11, Datun Rd, Anwai, Beijing, 100101, China*

Abstract

The purpose of this paper is to document the likely impacts of climate change on China's agriculture and the current adaptation efforts made by government and farmers. The review of literature shows that climate change will have a significant impact on agriculture, primarily through its effect on crop yields. The extent of predicted impacts highly depends on the crop, the CO2 fertilization effect assumption and adaptation abilities. Market response to the production shocks resulting from climate change will lessen the impacts on agricultural production predicted by natural scientists. On adaptation, the government's major efforts have been in the developing new technologies, reforming extension system and enhancing institutional capacity. Farmers do adapt to climate change, but their adaptation measures cannot fully offset the negative impacts of climate change. The paper concludes and makes implications for future studies.

Key words: climate change, agriculture, adaptation, China.

INTRODUCTION

While climate influences virtually all aspects of life, the impact on agricultural production is likely to be particularly important. Despite the fact that the relative importance of these impacts is still under debate, there is general consensus that China's agriculture sector will be affected significantly (Edition Committee of China's National Assessment Report on Climate Change, 2012). Moreover, since China is a large, important producing and trading nation, the impact of climate change on China will likely also affect the rest of the world via international trade. For example, the IPCC concluded that the expected effects of temperature increases and precipitation decreases—under the worst case scenario—could lead to a drop in China's rain-fed yields of rice, wheat and maize of between 20 and 36 percent over the next 20 to 80 years (IPCC, 2007). In contrast, cotton yields in China might increase (IPCC, 2007). However, these figures may overestimate changes in yield, as they do not account for the adoption of new technologies or changes in policy in response to climate change.

Within China, the combination of climate change and rapid economic growth will force the nation to look for new ways to both deal with the unfolding changes in weather patterns and find effective adaptation policies/measures. In recent years, China's government has put climate change adaptation into the nation's top policy agenda (Wang et al., 2010a). China has begun to formulate a set of plans to deal with adaptation issues by aiming at improved public access to information, stronger enforcement of laws, and higher accountability for emitters. In 2008, the Chinese government released China National Plan for Coping with Climate Change (NDRC, 2007). "China's Policies and Actions for Addressing Climate Change" was also issued in 2011 (PRC, 2011).

---

[1] WANG Jinxia, Tel: 86-10-64889841, Fax: 86-10- 64856533, E-mail: jxwang.ccap@igsnrr.ac.cn; Correspondence HUANG Ji-kun, Tel: 86-10-64889440, Fax: 86-10-64856533, E-mail: jkhuang.ccap@igsnrr.ac.cn

However, in order to improve its adaptive capabilities, China must first examine the likely impacts of climate change. How is climate change expected to affect agricultural production, price and trade in China? What are some of the ways the sector can adapt and what efforts are already underway? The overall goal of this paper is to review and document the impacts of climate change on China’s agriculture and the current adaptation efforts made by the government and farmers. In order to realize this goal, we have the following specific objectives. First, we review the likely impacts of climate change on crop yield, cropping system and production based on the studies that applied statistical analysis and crop modeling by the natural scientists. Second, we document the impacts of climate change on price and trade of major agricultural commodities as well as farmers’ income in China based on the studies that applied economic models by economists. Third, the current adaptive responses to climate change by both government and farmers are reviewed. Finally, based on the literature review, we provide discussions, synthesize the findings and conclude the paper with potential research issues for future studies. .

IMPACTS OF CLIMATE CHANGE ON CROP YIELD, CROPPING SYSTEM AND PRODUCTION

In this section, we firstly summarize the major findings on the impacts of climate change on crop yields. Then, the impacts on cropping system and production are examined. All findings reviewed in this section are from the studies conducted by natural scientists. The results from the impact assessments conducted by economists on production, price and trade of major agricultural commodities as well as farmers’ income are presented in the next section.

Impacts on crop yield based on historical evidence

The impacts of climate change on crop yield are often evaluated by either statistical analysis based on historical data or crop modeling that simulates the likely impacts in the future. On the statistical analysis based on historical data, major summaries of impacts of climate change on wheat, maize and rice yield in China are presented in Tables 1-3.

As Tables 1-3 shown, although the results are not fully consistency among different studies using similar statistical analyses, in general, the existing studies show that the long-term (e.g., more than 20 years) warming trend in the history was harmful for both wheat and maize yields (Tables 1 and 2) but beneficial to rice yield in China (Table 3). For example, Tao et al. (2008a) revealed that from 1979 to 2002, due to change of climate (mainly represented by warming in growing season), wheat yield in China declined (Table 1), which resulted in a reduction of total wheat production by 1.2×10^5 ton every ten years. At the regional scale, except for Jiangsu, Henan and Tianjin Provinces, the impacts of warming trend on wheat yield in all other provinces were negative (Table 1). On maize, except for Heilongjiang province, maize yield was negatively correlated with increasing temperature during the crop growing season either at the national level or regional level (e.g., Tao et al., 2008a; Zhang and Huang, 2012; also see Table 2). While for rice, it was found that its yield was positively correlated with warming trend of climate in China (Table 3). But at the regional scale, the relationship between rice yield and temperature is very complicated and hard to generate a general conclusion (Table 3). One interesting finding is that if one looks at the impact of climate change on a crop yield in the relative shorter term (e.g., 10 years), the result is often opposite with that for the same crop in the relative longer term (e.g., more than 20 years) presented above. For example, Xu et al. (1999) found that from 1990 to 1999, both wheat and maize yields were beneficial from and rice yield was hurt by change of climate in China, while the impacts of climate change were negative for wheat and maize yields (Tables 1 and 2) and positive for rice yield in the longer term in China in the past (Table 3)

In addition to warming trend, some studies also analyzed the impacts of precipitation change on crop yield. In general, wheat in the relative water richer regions (e.g., Zhejiang, Fujian and Guangdong provinces), its yield presented a negative relationship with precipitation (Table 1). That is, in these water richer regions, more precipitation could result in reduction of wheat yield. While in the relative water shortage regions (e.g., Xinjiang province and Guangzhong Plain), more precipitation has increased wheat yield (Table 1). Zhang and Huang (2012) found that overall, maize yield in China increased with the rise of precipitation (Table 2). For rice, its yield in most regions (particularly in southern China) was negatively correlated with precipitation (Table 3). For example, Zhang et al. (2010) and Tao et al. (2008a) found that in18 provinces (15 in southern regions) in China rice yield was negatively influenced by more precipitation. Some provinces (most in northern China) have enjoyed the increase of precipitation in term of increase in rice yield.

Impacts on crop yield in the future based on crop model simulation

In order to evaluate the impacts of climate change on crop yield in the future, crop model has become a major tool in analysis. However, one of the major shortcomings of the crop model is about its assumption on CO2 fertilization effect. The CO2 fertilization effect is a probable feedback effect of the terrestrial biosphere-atmospheric carbon system where elevated levels of CO2 increase the productivity of natural ecosystems. The review of literature indicates that without considering CO2 fertilization effect, crop yield will be negatively affected by climate change. However, with considering CO2 effect in the crop model simulation, the impacts of climate change on crop yield will become positive (Tables 4-8). The key issue here is that in the future, can crop production really enjoy the benefit of CO2 fertilization effect? In the literature, there is much uncertainty on this. In order to resolve this problem, many scientists have begun to conduct FACE experiments. Hopefully, in the future, the results of FACE experiments and other relevant studies can resolve the present puzzling issue on the CO2 fertilization effect. In addition to CO2 fertilization effect, the simulation results on the impacts of climate change on crop yield also depend on the climate change scenarios (A2 or B2) and assumptions on the adaptation measures and socio-economic development.

Without considering CO2 fertilization effect, the impacts of climate change on three major grain crops in the future in China will be negative and the impact differs largely under different assumptions. First, the existing studies showed that the impacts of climate change are expected to be higher under A2 scenario than those under B2 scenario. For example, if without adopting any adaptation measures in Shandong province, Yuan and Xu (2008) showed that wheat yield could be reduced by 5.7% by 2080s under A2 scenario, while the reduction of wheat yield will be 1.6% only under B2 scenario in the same year (Yuan and Xu, 2008, also see Table 4). It is also not hard to find such evidence for both maize and rice (e.g., Lin et al., 2005 in Tables 7 and 8). Second, the impacts of climate change are expected to be lower on irrigated crop (Table 5) than those of rainfed crops (Table 6). For example, under A2 scenario by 2020s, the negative impacts of climate change on rainfed wheat could reach 18.5% (Lin et al. 2005, also see Table 6), which is much higher than that for irrigated wheat (5.6%, Table 5).

Tao and Zhang (2011b) demonstrated that if the temperature will increase by 1^{o}C, the impacts of climate change on irrigated maize will range from 1.4% to 10.9%, this range will become larger for rainfed maize (Table 7). From the literature review, we also find the similar story for rice (Table 8). Third, over time, in general, the impacts of climate change on crop yield will become more serious. For example, under B2 scenario, rice yield will decline from 0.9% in 2050s to 2.5% in 2080s (Lin et al., 2005, Table 8). Finally, we also find the importance of including adaptation assumptions into the simulation. For example, without any adaptive responses, Wu et al. (2008) found that wheat in North China will be adversely affected by climate change. However, with some adaptation measures (e.g., changing crop cultivars as assumed by Tao and Zhang, 2011a), wheat in North China will increase from 18.6% in 2020s to 34.4% in 2080s (Table 4).

When the CO2 fertilization effect is included in the crop model simulation, the negative impacts of climate change on crop yield will be offset. For example, Ye et al.(2012) showed that with assumption of the CO2 fertilization effect, either with or without considering adaptation on technology improvement, the impacts of climate change on the yields of wheat, maize and rice will be positive (Tables 4 , 7 and 8). In overall China, if considering CO2 fertilization effect, yield of wheat will increase from change of climate. Except for impacts of CO2 fertilization on crop yield, the impacts of other assumptions (such as A2 and B2 scenarios, irrigated and rainfed conditions or adaptation measures) on crop yield are consistent with above discussions under no CO2 fertilization effect. For example, compared with B2 scenario, wheat yield will be higher under A2 scenario (such as 20.3% in A2 versus 16.2% in B2 found by Yuan and Xu, 2008, Table 4). Since the negative impacts of climate change on rainfed crop yield is higher than that for irrigated crop under no CO effect assumption, when considering CO2 fertilization effect, rainfed crop yield will also rise more from climate change than that of irrigated crop (Tables 4 to 8). Ye et al. (2012) revealed that if the technology improvement could be realized, under A2 scenario, wheat yield will increase by 15% (versus 9% without technology improvement) by 2050s (Table 4).

Despite the CO2 fertilization effect generally result in the positive effect of climate change on crop yield, there are still some debates on overall impacts of climate change on crop yield. For example, Tao and Zhang (2011b) demonstrated that even considering CO2 fertilization effect and assuming some adaptation responses (mainly changing cultivar), both irrigated maize and rainfed maize will reduce their yields when the temperature will increases (Table 7). In fact, Lin et al. (2005) also indicated the negative impacts of climate change on irrigated maize yield. For rice, we also find such evidence to show that if considering CO2 fertilization effect, the impacts of climate change are still possibly to be negative (Table 8).

Impacts on cropping systems

The scientific literature also predicts that China’s cropping systems will experience moderate changes as a result of climate change. In this paper, we highlight two interesting sets of changes. First, the existing studies estimated that both planting and harvesting dates of crops will change with climate change. For example, warmer temperatures will allow earlier planting dates for crops in north of the Yangze River Basin (particularly in the middle latitudes and high plateau regions). In addition, the harvesting dates can be pushed later in the year and the entire growing season will be extended (Lin et al., 2006). As a result, producers in some regions may be able to shift from a single to a multi-cropping system.

Second, there is evidence that the cultivated area under both single and triple-cropping (e.g., rice-rice-rice in Hainan of South China) systems could be increased. Based on the results of predictions using several alternative global climate models, temperatures in 2050 would increase 1.4^{o} C while precipitation would decrease 4.2 percent (Deng et al., 2006). Under this set of assumptions, scientists estimate that the planting areas of single cropping system will be able to expand 23.1 percent. At the same time, models project that the sown areas of three-cropping system will also increase in southern China. The potential for cropland expansion is primarily due to the warmer temperatures, which will allow production in regions that were formerly too cold. It is interesting to note that the share of cultivated area that will be double-cropped is predicted to change only slightly: from 24.2 percent to 24.9 percent. This, however, does not mean that the double-cropped area is static. According to the estimates by Li et al. (2002), double cropping regimes will be migrating towards the middle regions of the country (where originally only single cropping was an option).

Impacts on crop production

Because the predicted impacts of climate change on crop yield differ largely under different assumptions on CO2 fertilization effect, climate scenarios, and time period studies, the estimated impacts of climate change on agricultural production by natural scientists also differ largely among different studies. Discussions about the impacts of climate change on agricultural production are meaningless if one does not closely look at the major assumptions embodied in the modeling of each study. Here, we use the results from two studies by Lin et al. (2006) and Xiong et al. (2009a) to illustrate why the projected impacts of climate change on crop production differ significantly among studies. For example, Lin et al. (2006) showed that if the emission of CO2 doubled and there was no adaptation taken, the total crop production would decrease by 5%-10% in 2030. Xiong et al. (2009a) depicted that the cereal production in China would drop by 9% in medium-low CO_2 emission (B2) and by 18% in medium-high (A2) in 2040s when the overall effects of climate change, water availability and agricultural land conversion takes into account.

It is worth to note that the assessments of climate change on agricultural production made by natural scientists often do not consider any market response. Indeed, in real world, there will be market response from producers and consumers when agricultural prices change as the results of crop yield and crop area (or cropping system) changes. As the next section is going to show, the studies without considering market response likely tend to overestimate the impacts of climate change on agricultural production.

IMPACTS OF CLIMATE CHANGE ON AGRICULTURAL PORDUCTION, PRICES, AND TRADE AND FARMER’S INCOME

In this section, we review the studies by economists who have analyzed the impacts of climate change on China’s agriculture. The studies by economists normally separate the impacts of climate change into two components, one is direct impacts of climate change on crop yield or production based on the studies by natural scientists, the other is indirect impacts of climate change through market responses. On the other word, the economists take the direct impacts of climate change on agriculture from one research (or a set of studies) conducted by natural scientists, and then use these indirect impacts as the shocks to economic model (e.g., partial equilibrium or general equilibrium models) to generate further impacts on agriculture due to market responses.

While the impacts of climate change on agriculture in China evaluated by economists are rare up to now, the existing few studies do provide some interesting results. These include the impacts of climate change on national agricultural production, price, trade and farmers' income.

Impacts on national agricultural production

In general, the impact assessments of climate change on agricultural production show that overall impacts will be less than those found by natural scientists and reported in the previous section. Because food demand is inelastic, the reduction of agricultural production from the direct impact of climate change can induce more increase in agricultural price and raise farmer's incentive of production, which attract more inputs of labor and capital into agricultural production and therefore partially mitigate either negative or positive effects of climate change (Zhai et al.,2009; Li et al., 2011; Wang et al., 2009a). For example, by using the global general equilibrium model of AGLINK, Zhai et al. (2009) showed that climate change would cause China's total crop production decreasing only slightly (0.2%-0.5%) in 2080. By linking the China's national partial equilibrium model (CAPSiM) and global general equilibrium model (GTAP), Wang et al. (2009a) found that the production of rice, wheat and maize in 2030 would decrease by 5.6%, 5.0% and 5.1% respectively under scenario without considering CO_2 fertilization. These would be about 3% to 5% lower than the direct impacts predicted by the natural scientists and used by Wang et al. (2009a) as the production shocks in their economic modeling. Moreover, the negative impacts of climate change on China's agricultural production would be further mitigated by about 1% if the effects of climate change on other countries would take into consideration. This is because the economic analysis accounts for changes in agricultural trade flows and prices resulted from climate change in China and the rest of world.

Impacts on agricultural prices and trade

The projected changes in agricultural prices due to climate change will be more significant than changes in agricultural production in the future (Wang et al., 2009a). For example, Wang et al., (2009a) showed that if effects of climate change were considered in China only, the prices of rice, wheat and maize would rise by 14.4%, 12.5% and 6.9% in 2030 under A2 scenario and without considering CO2 fertilization effects. When the impacts of climate change were considered globally, under the same scenario (A2), the price of the three crops in China would increase higher by 17.6%, 15.9% and 10.9% (Wang et al., 2009a). On the contrary, the grain price would drop significantly if an analysis would consider the positive effect of CO_2 fertilization on grain production.

China's agricultural trade flows will change with change of climate because of the shift in comparative advantage of crop production caused by climate change in China and the rest of world. For example, Zhai et al. (2009) found that China's overall agricultural export would rise because of the relative less negative impacts of climate change in China than those in the rest of world. On grain sector, however, Wang et al. (2009a) found that the results are mixture. Under the scenarios that do not account for CO2 fertilization, because domestic production in China is projected to decrease and commodity prices are forecasted to increase. Following on these results, the analysis indicates that Chinese exports will decrease while imports increase in order to stabilize the domestic market (Wang et al., 2009a). Once again, the changes are less dramatic when climate change effects in the rest of the world are considered, which is consistent with Zhai et al. (2009). In contrast, China's trade balance will improve under the scenarios that consider a CO2 fertilization effect (Wang et al., 2009a). These results are in line with the increase in domestic production and decrease in prices because of the positive production effects of CO2 fertilization discussed in the previous section.

Impacts on farmer income

Researchers have long pointed out that rural people are particularly vulnerable to climate change, especially in the case of extreme weather events such as droughts and hailstorms (Tol, 1995; IPCC, 2007). In the dry regions of western China such as Ningxia province, a reduction in rainfall and an increase in the incidence of drought in recent years have been shown to affect local farming activities and farmer income (Ju et al., 2008). However, economist's analyses often show that fall in production due to external shocks such as climate change would not necessary lead to fall in farmers' income because increase in agricultural prices could be much larger than decreases in agricultural production. For example, Wang et al. (2009a) projected that if not considering the CO2 fertilization effect, the overall effect of climate change on farmer income in the Huang-Huai-Hai (3H) region would be positive because the increase in price would be about twice as large as the decrease in production. In contrast, the increase in production due to CO2 fertilization does not lead to corresponding increases in farmer income. Although grain production would rise with the positive contribution of CO2 to grain yields, the decrease in market price would be more significant.

The impacts of climate change on farmers' income have also been analyzed by economists through its impacts on crop net revenue using the Ricardian model based on household data. This model uses econometric analysis to directly estimate the impact of changes in temperature and precipitation on crop net revenue, but it can't separate this impact into crop yield, production and price. For example, applying a Ricardian model based on cross-sectional data comprised of 8405 households in 28 provinces, Wang et al. (2009b) empirically analyzed the impacts of climate change (temperature and precipitation) on crop net revenue. Results reveal that temperature has a fundamentally different effect on irrigated farming compared to rain-fed farming. The average impact of higher temperatures on farmers' crop net revenue is negative, while increased precipitation lead to increased net revenue on average. When the analysis separates irrigated and rain-fed farmers, they found that warming actually helps irrigated farmers while the incomes of rain-fed farmers are quite vulnerable to temperature increases. Higher precipitation, however, has almost identical effects on irrigated and rain-fed farms. When the analysis separates the effects of increasing temperatures and precipitation by season, they found that warmer temperatures in fall and spring are harmful to irrigated farms whereas warmer summers and winters are beneficial. Rain-fed farms only stand to benefit from warmer winters and will see declining net revenue due to warming in spring, summer and fall. Wetter winters will benefit both rain-fed and irrigated farmers, and more precipitation in the spring and fall will hurt both types of farmers. Increased rainfall in the summer leads to higher net revenue for irrigated farmers but decreased net revenue for rain-fed farmers. When the analyses were conducted by region, the study by Wang et al. (2009b) showed that for irrigated farms, warmer temperatures are more beneficial in the southeast and southwest regions, perhaps because these areas have abundant water resources. In the central region, irrigated farmers enjoy mild benefits from warming. Warming will likely help rain-fed farmers in very cold places but harm them elsewhere in China, especially in the far south, where the hotter temperatures will be coupled with inadequate and unreliable water supplies.

ADAPTIVE RESPONSES TO CLIMATE CHANGE

As discussed in the previous sections, the predicted impacts of climate change on China's agriculture in the future have been substantially influenced by the assumptions on the CO2 fertilization effect and adaptation capacity. In fact, how to realize the assumed CO2 fertilization effect or enjoy the benefit of CO2 fertilization is an issue highly relevant with adaptation capacity. In the future, if not adopting adaptation measures such as adjusting crop varieties or improving farm management, it is impossible to transfer the potential CO2 fertilization effect into the actual effect. In order to improve adaptation capacities in the agricultural sector, it is not only necessary for government to undertake actions such as improving irrigation infrastructure and adoption of improved technology or farm management as assumed by Xiong et al. (2005) and Ye et al. (2012), but also necessary for farmers to make appropriate responses (e.g., changing sowing date, cultivars or cropping patterns re as assumed by Yuan and Xu, 2008). If these actors are able to adapt adequately, it is possible that China's agricultural sector can actually take advantage of changes in temperature and rainfall. Future agricultural production will depend on the ability of these actors to make effective responses. In the rest of this section, we summarize the adaptive responses from the government and farmers.

Adaptive responses from government

While China has been working toward reducing its contribution to global climate change, it has only recently begun to address climate change adaptation. According to *China's National Climate Change Program*, established in 2007, the government is considering a number of strategies and activities in its efforts to help the agricultural sector adapt to climate change; a few examples are highlighted below.

Improve agricultural infrastructure. A number of opportunities exist for the government to invest in infrastructure that could facilitate adaptation. First, the government is considering accelerating the construction of supporting facilities in large-scale, water-saving irrigation projects. There are also efforts to build new smaller-scale irrigation and drainage projects in areas that are currently not irrigated. Officials have suggested that they also intend to control the spread of middle- and low-productivity agricultural zones and strengthen the restoration of degraded farmland. For example, in areas that are currently affected by salinization or alkalinization, investments in soil improvement can make them more productive as temperatures rise and rainfall changes. Finally, there are plans to accelerate the construction of water storage projects and projects that enhance water utilization—especially in mountainous and desert areas.

Strengthen research and development for new technologies. One of the main roles of government has been investment in the research and development of agricultural technology, especially in systems that are dominated by smallholders and lack investment by large private agricultural seed and/or research companies. Specifically, the government should both continue and expand breeding programs to encourage research on seed varieties with traits that promote resistance to drought, water-logging, high temperature, diseases and pests. In addition to these programs, the government has pushed for research to better understand the magnitude, source and mechanisms of climate change and its consequences. For technologies that have already been developed, the government needs to establish the means for transferring and promoting them to all farmers. In recent years, the extension system has deteriorated, and efforts should be made to restore its effectiveness.

Although many adaptation strategies are still in the planning stages, China has nonetheless made some tangible progress on implementation. Specific examples are discussed below, and there are undoubtedly many more, including China's efforts to mainstream climate change adaptation strategy into agricultural development program. Future research should provide more comprehensive documentation of these projects and analyses of their strengths, weaknesses and other lessons.

One example that is worth to note is government's effort to increase the political profile of and public investment in climate change research. Special funding arrangements have also been established for climate change adaptation. The first such project in China was announced in 2007 (Zhang, et al., 2008). As part of this program, several provinces have already begun to invest in technologies that will promote more reliable rainfall, such as cloud seeding—dispersing substances such as dry ice or silver iodide into clouds to induce rain—in Sichuan and Tibet and rainfall harvesting in Xinjiang. In Ningxia province, the provincial Science and Technology Department also plans to invest in improved climate forecasting. The provincial Academy of Agricultural Sciences has launched studies on agricultural adaptation, including improved crop varieties and ecological migration. As these projects were only recently initiated, their effectiveness has not been assessed and documented.

The other example is crop and livestock insurance, which has been taking off since the mid-2000s. Agricultural insurance is an active means to get agricultural risks under control and help farmers in managing the risks from natural disasters resulted from climate change. While there was almost no growth in crop and livestock insurance between 1985 and 2006, the policy-oriented and highly subsidized agricultural insurance has expanded rapidly since the mid-2000s. According to data from China Insurance Regulatory Commission (CIRC, 2012), the revenues earned by the insurances industry have soared after 2006. Between 2007 and 2011, annual growth was more than 80 percent per year. In 2011, revenues were 17.4 billion RMB.

Adaptive responses from farmers

In addition to government officials, farmers have an incentive to implement adaptation strategies. Here we review a few of the options farmers have in responding to climate change.

Crop choice. Based on empirical analysis of 8,405 farmers in 28 provinces in China, Wang et al. (2009b) showed that across China, farmers in warmer places are more likely to produce cotton, wheat, oil crops and maize and less likely to grow rice, soybeans, vegetables, potatoes and sugar. These results indicate that they are already beginning to make planting shifts according to local climatic conditions. In wetter locations, farmers are more likely to plant rice soybeans, oil crops, sugar, vegetables, and cotton and less likely to grow maize, potatoes, and wheat. Field studies in single provinces also find similar behavior among farmers. Ju et al. (2008) indicates that in Ningxia Province, farmers faced with drought are inclined to choose a crop that is more adaptive, multi-functional and high yielding, with better economic returns under such conditions. Primary examples include maize, potatoes and sunflowers.

Irrigation. Wang et al. (2010b) documented that farmers in locations with more rainfall are less likely to irrigate. In part, this is because they are able to get sufficient moisture without the expense of irrigation. However, the analysis also suggests that the marginal effects of climate change on irrigation choice depend on the distribution of seasonal rainfall and temperature. As a result, irrigation choice will vary from place to place.

Increased investment in irrigation infrastructure. Farmers, like the government, can invest in irrigation facilities. This is especially easy to see in areas of northern China that already face diminished access to surface water for a variety of reasons—not necessarily related to climate change. In these areas, farmers have turned to use of groundwater to maintain or improve productivity (Wang et al., 2009c). The share of land in north China irrigated by groundwater increased from less than 30 percent in the early 1970s to nearly 70 percent in 2004 (Wang et al., 2007). Over the past three decades, individual farmers have become the major investors in tubewells—water wells made of a tube or pipe bored into an underground reservoir with an electric pump at the top to pull water for irrigation. The share of individual tubewells increased from less than 10 percent in the early 1980s to more than 80 percent twenty years later. Researchers also found that in dry land areas, farmers will invest in rainwater harvesting facilities, such as water storage tanks (Ju et al., 2008).

Adoption of water saving technologies. Based on a field survey in six provinces in northern China, Blanke et al. (2007) found that when faced with increasing water shortages (which would be the case in some areas after climate change), farmers will adopt water saving technologies. According to survey data, by 2004 at least 42 percent of villages (compared to less than 10 percent of villages in the early 1980s) were using a number of different types of household-based water saving technologies such as plastic sheeting, drought resistant varieties, retaining stubble/employing low-till methods, and surface level plastic irrigation pipe.

Adopting new crop varieties to reduce weather-related risk. Faced with climate change and the prospect of increasing water scarcity, farmers have already shown a willingness to plant crop varieties with better resilience to adverse weather. The 2007 GEF /SCCF project report of Hebei, observed that farmers in Cang County in Hebei province selected drought-resistance crop varieties (including new varieties for wheat, cotton and maize) in response to decreased water availability. In addition, farmers planted productive and disease-resistant varieties (mainly for wheat) in some parts of Jiangsu Province. In Henan Province, certain winter wheat varieties were selected following a higher frequency of warm winters. Current development of heat tolerant and pest-resistant wheat varieties is at least in part a response to the early effects of climate change.

DISCUSSION

Discussions on impacts of climate change

Despite growing literatures on the impacts of climate change on China's agricultural production, there are still several research gaps that need to be addressed by the scholars in the future. First, almost all the studies analyzing the impacts of climate change on agricultural production focus on three major grain crops: wheat, maize and rice. Only a few studies analyze the impacts of climate change on soybean (Tao et al., 2008a). Second, most studies only assess the direct impacts of climate change on crop yields, the impacts on crop yields due to change of production conditions (e.g., change of water balance conditions), the indirect impacts on other aspects of agriculture (e.g., irrigated and crop sown areas, total production output, market price, trade, food security, farmer income and poverty issues) are rarely studied in the literature. The major reason behind of these is that almost all studies are conducted by natural scientists; the economic analysis on impacts of climate change has appeared only in recent years in China. Finally, most studies mainly assess the impacts of long term change of climate, only a few studies analyze the short term change of climate (mainly on the maximum and minimum temperature), the analysis on the vulnerabilities and risks of agricultural sector under climate change is even harder to be found.

Statistical analysis and crop modeling are two major approaches to analyze the impacts of climate change on agricultural production. Generally, statistical approach is used to understand the historical relationship between change of climate components (such as temperature and precipitation) and agricultural production, while crop models (mainly CERES model) are used to simulate the impacts of climate change in the future. However, with a few exceptions (e.g., Chen et al., 2012; Wang et al., 2009b; You et al., 2009), most statistical analysis have not controlled for the influence of socio-economic variables that are highly correlated with agricultural production (e.g., Tao et al., 2008a; Chen et al., 2006; Xu et al., 1999). For crop models, since they assume the same crops to be grown in the same places as climate changes, they cannot reflect the farmers' responses well. In recent years, some economists have begun to use partial or general equilibrium models to simulate the impacts of climate change on agriculture (Zhai et al., 2009; Wang et al., 2009a), however, this kind of studies is still very limited.

More importantly, there exist significant uncertainties on the existing impact studies. One of the major uncertainties comes from the various climate scenarios. Under different climate scenarios, their forecasting results on the change of climate such as temperature and precipitation always differ remarkably, which directly influence the simulation results on the climate change impacts. In recent years, in order to reduce the uncertainty from climate scenarios, some scientists have begun to apply a set of probability prediction on climate change (Tao and Zhang, 2011b). Another important uncertainty is due to the consideration of CO2 fertilization effect when applying the crop models to simulate the future impacts of climate change on agriculture. Almost all the publications indicate that climate change impacts on agriculture are negative when no CO2 fertilization effect is considered, however, the impacts become positive when the CO2 fertilization effect is considered (e.g., Lin et al., 2005; Xiong et al., 2009b). In fact, the CO2 fertilization effect also reflects the shortcoming of present crop models on analyzing the climate change impacts. The recent development of FACE experiments aim to overcome this problem.

Discussions on adaptation

Despite the importance of improving adaptation capacity to mitigate the impacts of climate change on agriculture sector, the current level of knowledge on climate change and its impacts is not sufficient to support the implementation of China's national plan on adaptations. As pointed out by IPCC report (2007), the implementation of adaptation plan are constrained by the institutional, socio-economic, attitudinal and behavior barriers and the availability of resources and building adaptive capacity are particularly important for developing countries. How to identify these constraints or barriers is one of the key steps to facilitate the adoption or implementation of suitable adaptation options in China. However, there are few empirical studies conducted in China to analyze this important issue. In addition, understanding the effectiveness and cost-benefit of adaptation options are also particularly important for policy makers to design suitable adaptation strategies. Presently, although some scientists have applied the top-down approach (mainly crop model) to examine the effectiveness of some adaptation options (Xiong et al., 2005;Xiong et al., 2009b; Tao and Zhang, 2011a), the bottom-up approach to evaluate the effectiveness and cost-benefit of adaptation practice are still in their infancy. Until now, only a few studies (e.g., Wang et al., 2010b) quantitatively analyze the farmers' adaptive responses to climate change (such as adjusting cropping patterns or changing irrigation choice). While Ju et al. (2008) analyzed farmers' responses to drought and proposed actions of changing crops or varieties in Ningxia, China, most existing studies are based on macro-level and qualitative analysis (e.g., Pan and Zheng, 2010; Wang et al., 2008; Xia et al., 2008). As Mirza and Burton (2005) pointed out, adaptation measures and implementations face challenges due to a lack of micro- and empirical social and economic analysis.

CONCLUSIONS

This paper has reviewed and documented the likely impacts of climate change on China's agriculture. It also has sought to provide insights into the adaptation responses from government and farmers. The existing studies show that climate change will have a significant impact on agriculture, primarily through affecting crop yields. The extent of the changes in yields highly depends on the crop being considered, assumptions related to the CO2 fertilization effect, alternative climate scenarios, and adaptation abilities. Economic studies show that climate change will affect not only agricultural production, but also agricultural prices, trade and farmer income. Results show that market response to the production shocks resulting from climate change will lessen the impacts on agricultural production predicted by natural scientists.

Both China's government and farmers have taken efforts in response to climate change but ore efforts are needed in the future. Currently, the government adaptation strategy has been focused on investment in agricultural infrastructure, the development of new technologies, and expanding agricultural insurance to deal with climate change. In the future, with rising knowledge on the impacts of climate change on agriculture in China, more efforts should be paid to investment in water conservation infrastructure, investment in agricultural science and technology, investment in government, community and farmers' capacity to adapt to climate change, and investment in risk management. Working with farmers by setting an enabling policy environment is also essential because many adaptation measures have to be adopted by farmers.

In the future, in order to provide more robust scientific evidences to support the adaptation plan and decision making on mitigating the climate change impacts on China's agricultural sector, the following research areas should be prioritized for further study. First, more efforts should be focused on major uncertainties of the predicted impacts of climate change. Recent efforts aimed at better understanding of the CO2 fertilization effect should be further enhanced. Second, the assessments of climate change impact in the agricultural sector are necessary to be extended from three major grain crops (wheat, maize and rice) to other grain and cash crops. Third, based on multidisciplinary cooperation, the comprehensive evaluation of climate change on agriculture are critical for formulation of China's adaptation strategy and policy measures. These include both direct impacts of climate change through its (influences on crop growth or yield and cropping system), indirect impacts on crop production through the change of production conditions and market response. These indirect impacts could reveal not only the overall impacts of climate change on agricultural production, but also its impacts on food market price, agricultural trade, food security, farmer income and poverty. Finally, for the adaptation studies, based on both top-down and bottom-up approaches, how to identify the effective adaptation options for various actors (central and local governments, community and households), the constraints for adopting or implementing these adaptation options, and the effectiveness or cost-benefit of potential adaptation measures options are also major areas needed more attention.

Acknowledgements

The authors acknowledge the financial support of Ministry of Science and Technology (2012CB955700, 2010CB428406), National Natural Sciences Foundation in China (70925001, 71161140351), International Development Research Center (107093-001), World Bank, and the CAS Strategic Priority Research Program (XDA01020304). We also thank useful comments from two anonymous reviewers and the assistances provided by Lijuan Zhang, Yumin Li, Kaixing Huang, Huang Chen and Yu Yang.

References

1. Blanke A, Rozelle S, Lohmar B, Wang J X and Huang J K. 2007. Water saving technology and saving water in China. *Agricultural Water Management*, **87**, 139-150.
2. Chen H, Zhang X, Zhao G, Liu W and Yu W. 2006. Spring climate change and its impact on wheat yield components in Henan Province. *Henan Meteorology,* **1**, 47-52.
3. Chen Y, Wu Z, Zhu T, Yang L, Ma G and Hsiao-ping C. 2012. Agricultural policy, climate factors and grain output: evidence from household survey data in rural China. *Journal of Integrative Agriculture*, **12** (1), 169-183.
4. CIRC [China Insurance Regulatory Commission]. 2012. *Reports on the progress of agricultural insurance*.
5. Deng K, Ju H, Xiong W and Yang X. 2006. Research progress on the impacts of climate change on China's agriculture. *Chinese Agricultural Science Bulletin*, **22**(5), 439-441.
6. Edition Committee of China's National Assessment Report on Climate Change. 2012. *China's National Assessment Report on Climate Change*. Science Publication House, Beijing.
7. Hao L, Wu Y, and Wang R. 2007. Impact of spring climate change on wheat yield in lower Haihe Plain. *Meteorology and Disaster Reduction Research,* **30**(4), 20-24.
8. IPCC. 2007. *A report of working group one of the intergovernmental panel on climate change-summary for policy makers*. Intergovernmental Panel on Climate Change.
9. Ju H, Conway D, Li Y, Harvey A, Lin E and Calsamiglia-Mendlewicz S. 2008. *The Impacts of Climate Change on Chinese Agriculture – Phase II, Adaptation Framework and Strategy Part 2: Application of the Adaptation Framework: A Case Study of Ningxia, Northwest China*. Report to DEFRA (now DECC) and DFID, ED02264, Issue 2.
10. Ju, H., Xiong, W., Xu, Y. and Lin, E., 2005, Impacts of Climate Change on Wheat Yield in China. *Acta Agronomica Sinica,* **31**(10), 1340-1343.
11. Li, X., Takahashi, T., Suzuki, N., Kaiser. M.H. 2011. The impact of climate change on maize yield in the United States and China. *Agricultural Systems*, **104**, 348-353.
12. Lin E D, Xiong W, Ju H, Xu Y, Li Y, Bai L and Xie L. 2005. Climate Change Impacts on Crop Yield and Quality with CO2 Fertilization in China. *Philosophical Transations of the Royal Society B*, **360**, 2149-2154.
13. Lin E. et al. 2006. National assessment report of climate change (II): climate change impacts and adaptation. *Advances in Climate Change Research,* **2**(2), 51-56. (in Chinese)
14. Mirza M, Burton I. 2005. Using Adaptation Policy Framework to Assess Climate Risks and Response Measures in South Asia: The Case of Floods and Droughts in Bangladesh and India. Balkema Publishers, London.
15. NDRC (National Development and Reform Commission). 2007. China's national climate change program, national development and reform commission. *People's Republic of China, Beijing.*
16. Pan J and Zheng Y. 2010. Analysis framework of climate change adaptation and policy implications. *Population, Resources and Environment in China,* **20** (10), 1-5. (in Chinese)
17. PRC (People's Republic of China). 2011. *China's Policies and Actions for Addressing Climate Change*. Information Office of State Council Information Office of the People's Republic of China, Beijing.
18. Shi Y, Wang Y, Chi J and Wei R. 2008. Impact of climate change on winter wheat production in the Hebei Plain. *Chinese Journal of Eco-Agriculture,* **16**(6), 1444-1447.
19. Sun F, Yang X, Lin E., Ju H and Xiong W. 2005. Study on the sensitivity and vulnerability of wheat to climate change in China. *Scientia Agricultura Sinica,* **38**(4), 692-696.
20. Tao F L, Yokozawa M, Xu Y, Hayashi Y and Zhang Z. 2006. Climate changes and trends in phenology and yields of field crops in China, 1981–2000. *Agricultural and Forest Meteorology,* **138**, 82-92.
21. Tao F L, Yokozawa M, Liu J and Zhang Z. 2008a. Climate–crop yield relationships at provincial scales in China and the impacts of recent climate trends. *Climate Research,* **38**, 83-94.

22. Tao F L, Hayashi Y, Zhang Z, Sakamoto T and Yokozawa M. 2008b. Global warming, rice production and water Use in China- Developing a Probabilistic Assessment. *Agricultural and Forest Mateorology*, **148**, 94-110.

23. Tao F L, Zhang Z. 2011a. Climate change, wheat productivity and water use in the North China Plain: a new super-ensemble-based probabilistic projection. *Agricultural and Forest Meteorology*, doi:10.1016/j.agrformet.2011.10.003.

24. Tao F L, Zhang Z. 2011b. Impacts of climate change as a function of global mean temperature: maize productivity and water use in China. *Climatic Change*, **105**, 409-432.

25. Tao F L, Zhang Z, Liu J, Yokozawa M. 2009. Modeling the impacts of weather and climate variability on crop productivity over a large area: a new super-ensemble-based probabilistic projection. *Agricultural and Forest Meteorology*, **149**, 1266-1278.

26. Tian Z, Xu X, Shi J. 2006a. Assessing the impact of climate change on wheat production in DingXi (Gansu province) and HeFei (Anhui provicve). *Progress in Geography*, **25**(4), 88-95.

27. Tian Z, Liu J, Cao M. 2006b. Simulation of the impact of climate change on chinese wheat production in Huang-Huai-Hai Plain. *Journal of Natural Resources*, **21**(4), 598-607.

28. Tol R S J, 1995. The damage costs of climate change: towards more comprehensive estimates. *Environmental and Resource Economics*, **5**, 353-374.

29. Wang J, Li H, Xia J, Ren G. 2008. Water scarcity in the Hai River Basin when climate changes and analysis of adaptation policies. *Advances in Climate Change Research*, **4** (6), 336-341

30. Wang J, Huang J, Yang J. 2009a. Water Security and Agricultural Development in 3H Region. *Climate Change*, Report Submitted to the World Bank.

31. Wang J, Mendelsohn R, Dinar A, Huang J, Rozelle S, Zhang L. 2009b. The Impact of Climate Change on China’s Agriculture. *Agricultural Economics*, **40**(3), 323-337.

32. Wang J, Huang J, Rozelle S, Huang Q, Zhang L. 2009c. Understanding the Water Crisis in Northern China: What Government and Farmers are Doing?. *International Journal of Water Resources Development*, **25**(1), 141-158.

33. Wang J, Huang J, Rozelle S. 2010a. Climate change and China’s agricultural sector: an overview of impacts, adaptations and mitigation. *Issue Brief No. 5*, ICTSD-IPC Platform on Climate Change, Agriculture and Trade.

34. Wang J, Mendelsohn R, Dinar A, Huang J. 2010b. How chinese farmers change crop choice to adapt to climate change?. *Climate Change Economics*, **1**(3), 167-185.

35. Wang J, Huang J, Rozelle S, Huang Q, Blanke A. 2007. Agriculture and Groundwater Development in Northern China: Trends, Institutional Responses, and Policy Options. *Water Policy*, **9**(S1), 61-74.

36. Wu Z, Liu C, Xu S. 2008. The assessment of the effects of the climate change on the weak winter wheat in Huang-Huaihai Plain. *Progress in Modern Biomedicine*, **8**(5), 933-936.

37. Xia J, Tanner T, Ren G, Cheng X, Wang J, Wang Z, Yan M, Liu X, Holman I. 2008. The potential impacts of climate change: screening for adaptation and management. *Advances in Climate Change Research*, **4** (7), 215-219.

38. Xiong W, Xu Y, Lin E. 2005. The simulation of yield variability of winter wheat and its corresponding adaptation options under climate change. *Chinese Agricultural Science Bulletin*, **21**(5), 380-385.

39. Xiong W, Lin E, Ju H, Xu Y. 2007a. Climate change and critical thresholds in China’s food security. *Climatic Change*, **81**, 205–221.

40. Xiong W, Matthews R, Holman I, Lin E, Xu Y. 2007b. Modelling China’s potential maize production at regional scale under climate change. *Climatic Change*, **85**, 433-451.

41. Xiong W, Conway D, Lin E, Xu Y, Ju H, Jiang J, Holman I, Li Y. 2009a. Future cereal production in China: the interaction of climate change, water availability and socio-economic scenarios. *Global Environmental Change*, **19**, 34-44.

42. Xiong W, Conway D, Lin E, Holman I. 2009b. Potential impacts of climate change and climate variability on China's rice yield and production. *Climate Research*, **40**, 23-35.

43. Xu B, Xin X, Tang H, Zhou Q, Chen Y. 1999. The influence and strategy of global climate change to agricultural geographical distribution. *Progress in Geography,* **18**(4), 316-321.

44. Yao F, Xu Y, Lin E, Yokozawa M, Zhang J. 2007. Assessing the impacts of climate change on rice yields in the main rice areas of China. *Climatic Change,* **80**, 395-409.

45. Ye L, Xiong W, Li Z, Yang P, Wu W, Yang G, Fu Y, Zou J, Chen Z, Ranst E V, Tang H. 2012. Climate change impact on china food security in 2050. *Agron. Sustain. Dev,* doi: 10.1007/s13593-012-0102-0.

46. You L, Rosegrant M W, Wood S, Sun D. 2009. Impact of growing season temperature on wheat productivity in China. *Agricultural and Forest Meteorology,* **149**(6-7),1009-1014.

47. Yuan J, Xu Y. 2008. Study on Adaptation Measures of Wheat Production in Linyi of Shandong Province Based on CEREs Crop Model. *Chinese Journal of Agrometerology,* **29**(3), 251-255.

48. Zhai F, Lin D, Byambadorj E. 2009. Impacts of climate change on China's agriculture: a analysis by CGE model. *ADB Report.* http://wenku.baidu.com/view/f96d2a5177232f60ddcca100.html.

49. Zhang T, Huang Y. 2012. Impacts of Climate Change and Inter-annual Variability on Cereal Crops in China from 1980 to 2008. *Journal of the Science of Food and Agriculture* **92**(8), 1643-1652.

50. Zhang J, Yan J, 2003. Evaluation model of wheat yield in regional response to climate change. *Journal of Arid Land Resources and Environment,* **17**(1), 85-90.

51. Zhang Y, Wang S, Wang F. 2000. Research on the possible effects of climate change on growth and yield of wheat in China. *Quarterly Journal of Applied Meteorology,* **11**(3), 264-270.

52. Zhang L, Luo R, Yi H, Tyler S. 2008. Climate adaptation in Asia: knowledge gaps and research issues in China. *Final Report to IDRC and DFID,* Digiscan Pre-press, Kathmandu, Nepal.

53. Zhang T, Zhu J, Wassmann R. 2010. Responses of rice yields to recent climate change in China: an empirical assessment based on long-term observations at different spatial scales (1981–2005). *Agricultural and Forest Meteorology,* **150**, 1128-1137.

54. Zheng Y, Wan C, Xu W. 1997. Estimation of production potential of wheat in Nanjing as influenced by future climatic changes. *Chinese Journal of Agrometerology,* **18**(3), 14-18.

55. Zheng Y, Zong X, Xu Y, Chen W. 1998. Possible effects of climate change on wheat production in Jiangsu. *Journal of Nanjing Institute of Meteorology,* **21**(2), 230-237.

Table 1. Summary on the impacts of climate change on wheat yield in China (results from statistical analysis)

Study region	Period	Impacts on yield	Authors
Positive impacts			
China	1990-1999	Climate change →Yield　(↑)	Xu et al.（1999）
Jiangsu	1951-1980	Under doubled CO2: Tem. (↑)→ Yield (↑)	Zheng et al.（1998）
Henan	1971-2004	Tem.(↑) →Yield (↑)	Chen et al.（2006）
Xinjiang	1979-2002	Pre. (↑) → Yield (↑)	Tao et al.（2008a）
Tianjin	1979-2002	T_n ↑ (1℃) → Yield ↑（4.2-12.0%）	Tao et al.（2008a）
Negative impacts			
China Jiangsu	1979-2002	China: climate change→ yield (↓) Jiangsu: Pre. (↑) → Yield (↓)	Tao et al. (2008a)
Gansu, Henan	1981-2000	Tem. (↑)→Yield（↓）	Tao et al.（2006）
Guanzhong Plain, Jiangsu,Shandong	1949-1999 1951-1980	Tem.(↑) → Yield (↓) Pre.(↓) → Yield (↓)	Zhang and Yan（2003） Zheng et al.（1998, 1997）
Zhejiang, Fujian, Guangdong	1981-2000	Pre. (↑) → Yield (↓)	Tao et al.（2008a）
Lower Haihe Plain and Hebei	1985-2004 1975-2006	T_m ↑(>1.2℃) → Yield (↓)	Hao et al.（2007） Shi et al.（2008）
Liaoning, Hubei and Hunan	1979-2002	T_m ↑(>1℃) → Yield ↓	Tao et al.（2008a）

Note: $T_{m:}$ Maximum temperature; T_n: Minimum temperature

Table 2. Summary on the impacts of climate change on maize yield in China (results from statistical analysis)

Study region	Period	Impacts on yield	Authors
Positive impacts			
China	1980-2008	Pre.(↑) → Yield (↑)	Zhang and Huang（2012）
China	1990-1999	Climate change → Yield (↑)	Xu et al.（1999）
Heilongjiang	1981-2000	Tem. (↑)→ Yield（↑）(271.1kg/ha/yr）	Tao et al.（2006）
Negative impacts			
China	1979–2002	Tem. (↑)→ Yield（↓）	Tao et al.（2008a）
China	1980-2008	Tem. (↑)→ Yield（↓） in 50% of provinces	Zhang and Huang（2012）
Henan	1981-2000	Tem. (↑)→ Yield（↓）（168.8kg/ha/yr）	Tao et al.（2006）
China	1980-2008	T_m (↑) → Yield (↓); T_n (↑) → Yield (↓);	Zhang and Huang（2012）
9 provinces (Liaoning, Tianjing, Shanxi, Gansu, Shaanxi, Anhui, Jiangsu, Guizhou, Xinjiang)	1979-2002	T_m（↑）→ Yield （↓）	Tao et al.（2008a）

Note: $T_{m:}$ Maximum temperature; T_n: Minimum temperature

Table 3. Summary on the impacts of climate change on rice yield in China (results from statistics analysis)

Study region	Period	Impacts on yield	Authors
Positive impacts			
China	1951–2002	Climate change → Yield (↑)	Tao et al. (2008a)
12 provinces (Ningxia, Heilongjiang, Liaoning, Anhui, Jiangsu, Henan, Zhejiang, Fujian, Yunnan, Guangxi, Guangdong, Hubei)	1981–2005	Tem. (↑)→ Yield （↑）	Zhang et al. (2010)
Heilongjiang, Yunnan, and Guangxi Provinces,	1980-2008	Tn (↑) → Yield (↑)	Zhang et al. (2010)
Guangxi and Ningxia	1980-2008	Tm (↑) → Yield (↑)	Zhang and Huang (2012)
Ningxia, Jilin, Shanghai, Heilongjiang, Liaoning	1950-2002	T_m↑(1℃) → Yield ↑（3.1-9.0%） T_n (↑) → Yield (↑)	Tao et al.（2008a）
7 provinces (Tianjin, Shandong, Hebei, Henan, Shanxi, Shaanxi and Hunan)	1981–2005	Pre. (↑)→ Yield （↑）	Zhang et al.（2010）
Negative impacts			
China	1990-1999	Climate change → Yield (↓)	Xu et al.（1999）
9 provinces (Anhui, Tianjin, Shandong, Henan, Shanxi, Shaanxi, Sichuan, Jiangxi and Guizhou)	1981-2000	Tem. (↑)→ Yield （↓）	Zhang et al.（2010） Tao et al.（2006）
18 provinces (Ningxia, Heilongjiang, Liaoning, Anhui, Hubei, Hunan, Jilin, Jiangsu, Zhejiang, Fujian, Yunnan, Guangxi, Guangdong, Shanghai, Hubei,Sichuan, Jiangxi and Guizhou)	1981-2005 1981-2000	Pre. (↑)→ Yield （↓）	Zhang et al.（2010） Tao et al.（2008a）
Guizhou	1950-2002	T_m ↑(1℃) → Yield ↓(1.3-5.8%) T_n (↑) → Yield (↓)	Tao et al.（2008a）
Shaanxi	1980-2008	In Shaanxi Province, Tn (↑) → Yield (↓)	Zhang and Huang（2012）
Hebei, Jiangxi, Sichuang and Shaanxi,	1980-2008	Tm (↑) → Yield (↓)	Zhang and Huang（2012）

Note: $T_{m:}$ Maximum temperature; T_n: Minimum temperature

Table 4. Summary on the impacts of climate change on wheat yield in China (results from crop model)

Assumptions		Study region	Impacts on yield (relative to 1961-1990 level if no explain)	Authors
CO2 effect	Adaptation (A) and socio-eco scenarios (S)			
Positive impacts				
With CO2 effect	A^a+S	China	Relative to 2009 level（Baseline): W/O A: A2- Yield（↑）from 0% in 2020s to 13% in 2050s B2- Yield（↑）from 0% in 2020s to 9% in 2050s With A: A2- Yield（↑）from 4% in 2020s to 15% in 2050s B2- Yield（↑）from 9% in 2020s to 15% in 2050s	Ye et al., (2012)
	A^b	Shandong	W/O A: A2-Yield （↑）20.3% in 2080s B2-Yield （↑）16.2% in 2080s	Yuan and Xu (2008)
	A^c	North China	Under A2 and B2: With A: Decrease the yield variability, stabilize the yield. W/O A: Yield （↑）about 10% in 2080s	Xiong et al. (2005)
	A^d	North China	With A : Yields（↑）from 37.7% in 2020s to 87.2% in 2080s	Tao and Zhang (2011a)
	No	China	No adverse impacts on yield if tem. ranges from 0.9-3.9oC	Xiong et al. (2007a)
Without CO2 effect	A^d	North China	With A: Yields（↑）from 18.6% in 2020s to 34.4% in 2080s	Tao and Zhang (2011a)
Negative impacts				
Without CO2 effect	No	China	Yield (↓) 20% by 2070s	Ju et al. (2005)
	No	China	Under doubled CO2: (based on data from 1970s to 1990s and get the results):Tem.(↑) and Prec.(↑) in most areas → yield (↓)	Zhang et al. (2000)
	A^b	Shandong	With A: Reduce the adverse impacts of climate change on wheat production in Linyi in 2080s. W/O A: A2-Yield （↓）5.7% in 2080s B2-Yield （↓）1.6% in 2080s	Yuan and Xu (2008)
	No	North China	Based on data from 1960s to 1990s and get the results: Climate conditions become worse → yield (↓)	Wu et al. (2008)
	No	China	Yield (↓) if tem. rises beyond 2.5^{o}C	Xiong et al. (2007a)

Note: 1) Definition of the adaptation (A): a.Technology development, b - Delaying sowing date, changing cultivars; c - Priority for agricultural water use, limiting land losses and technology improvement; d - Different cultivars. 2) Definition of socio-economic scenario (S): assumptions are consistent with SRES (A2 and B2) scenarios.

Table 5. Summary on the impacts of climate change on irrigated wheat yield in China (results from crop model)

Assumptions		Study regions	Impacts on yield (relative to 1961-1990 level if no explain)	Authors
CO2 effect	Adaptation (A) and Socio-eco scenarios (S)			
Positive impacts				
Without CO2 effect	No	Gansu Anhui	By 2080s: Gansu: yield (↑) by 3.38% and 4.09% under A2 and B2 Anhui: yield (↑) by 15.2% and 8.5% under A2 and B2	Tian et al. (2006a)
With CO effect	No	China	A2: yield (↑) by 13.3% in 2020s to 40.3% in 2080s B2: yield (↑) by 11.0% in 2020s to 25.5% in 2080s	Lin et al. (2005)
	No	North China	Under A2 and B2: Yield (↑) by 2100s	Tian et al. (2006b)
	No	China	Yield (↑) by 4.0% and 3.5% under A2 and B2 by 2070s	Ju et al. (2005)
	No	Gansu; Anhui	By 2080s Gansu: yield (↑) by 36.3% and 36.7% under A2 and B2 Anhui: yield (↑) by 34.7% and 30.5% under A2 and B2	Tian et al. (2006a)
Negative impacts				
Without CO2 effect	No	China	A2: yield (↓) by 5.6% in 2020s to 8.9% in 2080s B2: yield (↓) by 0.5% in 2020s to 8.4% in 2080s	Lin et al. (2005)
	No	North China	Keeps the current level	Tian et al. (2006b)
	A[a]	China	Relative to 2000 level（Baseline), by 2070s: Without A: yield (↓) in northeastern China, the middle and lower reaches of the Yangtze River basin and part of Loess Plateau regions. With A: yield (↓) in about 2/3 of irrigated sown area	Sun et al. (2005)
	No	China	Yield (↓) by 20.2% and 19.4% under A2 and B2 by 2070s	Ju et al. (2005)
	No	China	Under doubled CO2 (1970s to 1990s): winter wheat yield (↓) by 7.0% in areas with suitable water spring wheat yield (↓) by 17.7% in areas with suitable water	Zhang et al. (2000)

Note: 1) Definition of the adaptation (A): a - adjusting crop variety, structure and technology improvement. 2) Definition of socio-economic scenario (S) assumptions: considered and assumed by the authors.

Table 6. Summary on the impacts of climate change on rainfed wheat yield in China (results from crop model)

Assumptions		Study region	Impacts on yield (relative to 1961-1990 level if no explain)	Authors
CO2 effect	Adaptation (A) and Socio-eco scenario (S)			
Positive impacts				
Without CO2 effect	No	Gansu Anhui	By 2080s: Gansu: yield (↑) by 1.91% and 0.18% under A2 and B2 Anhui: yield (↑) by 11.5% and 5.43% under A2 and B2	Tian et al. (2006a)
With CO2 effect	No	China	A2: yield (↑) from 15.4% in 2020s to 23.6% in 2080s B2: yield (↑) from 4.5% in 2020s to 12.7% in 2080s	Lin et al. (2005)
	No	North China	Climate change → yield (↑)	Tian et al. (2006b)
	No	Gansu; Anhui	By 2080s: Gansu: yield (↑) by 43.8% and 37.7% under A2 and B2 Anhui: yield (↑) by 52% and 52.9% under A2 and B2	Tian et al. (2006a)
Negative impacts				
Without CO2 effect	No	China	A2： yield (↓) by 18.5% in 2020s to 20.4% in 2050s	Lin et al. (2005)
	No	North China	wheat yield (↓)	Tian et al. (2006b)
	A^a+S	China	W/O adaptation: yield (↓) in northeastern China, the middle and lower reaches of the Yangtze River basin and part of Loess Plateau regions by 2070s. With adaptation: yield (↑) in most area in China by 2070s	Sun et al. (2005)
	No	China	Under doubled CO2 (1970s to 1990s): winter wheat yield (↓) by 7.7% in rainfed areas spring wheat yield (↓) by 31.4% in rainfed areas	Zhang et al. (2000)

Note: 1) Definition of the adaptation (A): a - adjusting crop variety, structure and technology improvement. 2) Definition of socio-economic scenario (S) assumptions: considered and assumed by the authors.

Table 7. Summary on the impacts of climate change on maize yield in China (results from crop model)

Assumptions		Study region	Impacts on yield (relative to 1961-1990 level if no additional notice)	Authors
CO2 effect	Adaptation (A) and socio-eco scenarios (S)			
Positive impacts				
With CO2 effect	A^{a}+S	China	Relative to 2009 level（Baseline) and W/O A: A2: yield（↑）from 2% in 2020s to 9% in 2050s B2: yield（↑）by 4%, 6% and 4% in 2020s, 2040s, and 2050s. With A: A2: yield（↑）from 6% in 2020s to 13% in 2050s B2: yield（↑）from 11% in 2020s to 9% in 2050s	Ye et al., (2012)
	No	China	A2: rainfed yield (↑) from 9.8% in 2020 to 20.3% in 2080 B2: rainfed yield (↑) from 1.1% in 2020 to 10.4% in 2080	Lin et al. (2005)
Without CO2 effect	No	China	B2: irrigated yield (↑) by 0.2% by 2020	Lin et al. (2005)
Negative impacts				
With CO2 effect	A^{b}	China	With A and under irrigation condition: 1◦C → yield (↓) from 1.6% to 7.8%; 2◦C → yield (↓) from 10.2% to 16.4% With A and under rainfed condition: 1◦C → rainfed yield changes from −10.8% to 0.7% 2◦C → rainfed maize yield (↓) from 5.6% to 18.1%	Tao and Zhang (2011b)
	No	China	A2：irrigated yield (↓) from 0.6% in 2020 to 2.8% in 2080 B2：irrigated yield (↓) from 0.1% in 2020 to 2.2% in 2080	Lin et al. (2005)
	No	China	Under irrigation condition: Yield (↓): 6.6% in A2 and 4.8% in B2 by 2080s Under rainfed condition: Yield (↓): 0.1% in A2 and 0.7% in B2 by 2080s	Xiong et al. (2007b)
Without CO2 effect	A^{c}	Shandong Henan	With A: 1) Shandong: maize yield (↓) from 9.1% in 2020s to 25.5% in 2080s; 2)Henan: maize yield (↓) from 9.7% in 2020s to 24.7% in 2080s	Tao et al. (2009)
	A^{b}	China	With A and under irrigation condition: 1◦C → yield (↓) from 1.4% to 10.9% 2◦C → yield (↓) from 9.8% to 21.7% With A and under rainfed condition: 1◦C → yields (↓) from 1.0% to 22.2% 2◦C → yields (↓) from 7.9% to 27.6%	Tao and Zhang (2011b)
	No	China	Under irrigation condition: A2: yield (↓) from 5.3% in 2020s to 14.4% in 2080s B2: yield (↓) from 0.4% in 2050s to 3.8% in 2080s Under rainfed condition: A2: yield (↓) from 10.3% in 2020s to 36.4% in 2080s B2: yield (↓) from 11..3% in 2020s to 26.9% in 2080s	Lin et al. (2005)
	No	China	Under irrigation condition: A2: yield (↓) from 6.6% in 2020s to 10.1% in 2080s B2: yield (↓) from 4.6% in 2020s to 7.6% in 2080s Under rainfed condition: A2: yield (↓) from 11.4% in 2020s to 15.8% in 2080s B2: yield (↓) from 9.5% in 2020s to 11.4% in 2080s	Xiong et al. (2007b)

Note: 1) Definition of the adaptation (A): a - Technology development; b - Different cultivars; c - Shifting planting window. 2) Definition of socio-economic scenario (S): assumptions are consistent with SRES (A2 and B2) scenarios.

Table 8. Summary on the impacts of climate change on Rice yield in China (results from crop model)

Assumptions		Study region	Impacts on yield (relative to 1961-1990 level if no explain)	Authors
CO2 effect	Adaptation (A) and socio-eco scenarios (S)			
Positive impacts				
With CO2 effect	A^{a}+S	China	Relative to 2009 level（Baseline): W/O A: A2- rice yield（↑）from 6% in 2020s to 18% in 2050s B2- rice yield（↑）from 9% in 2020s to 8% in 2050s With A: A2- rice yield（↑）from 11% in 2020s to 21% in 2050s B2- rice yield（↑）from 17% in 2020s to 12% in 2050s	Ye et al., (2012)
	A^{b}	China	With A : 1◦C→ rice yield changes from -10.1% to 3.3% 2◦C→ rice yield changes from -16.1% to 2.5%	Tao et al. (2008b)
	No	China	B2：irrigated rice yield （↓）	Yao et al. (2007)
	No	China	Under irrigation condition: A2: yield (↑) by 3.8% in 2020 to 7.8% in 2080 A2: yield (↑) from 2.1% in 2020s to 4.3% in 2080s Under rainfed condition: B2: yield (↑) by 0.2% in 2020s	Lin et al. (2005)
Negative impacts				
Without CO2 effect	A^{b}	China	With A : 1◦C→yield （↓）from 6.1% to 18.6% 2◦C→yield （↓）from 13.5% to 31.9%	Tao et al. (2008b)
	A^{c}+S	China	With A: A2: rice yield（↓）from 8.6% in 2050s to 26.2% in 2080s B2: rice yield（↓）from 4.9% in 2020s to 18.4% in 2080s	Xiong et al.(2009b)
	No	China	Under irrigation condition: A2: yield (↓) by 8.9% in 2020 to 16.8% in 2080 B2: yield (↓) by 1.1% in 2020 to 12.4% in 2080 Under rainfed condition: A2: yield (↓) from 12.9% in 2020s to 28.6% in 2080s B2: yield (↓) from 5..3% in 2020s to 15.7% in 2080s	Lin et al. (2005)
	No	China	B2：irrigated rice yield （↑）	Yao et al. (2007)
With CO2 effect	A^{b}	China	With A: 1◦C→ yield changes from -10.1% to 3.3% 2◦C→ yield changes from -16.1% to 2.5%	Tao et al. (2008b)
	No	China	B2: irrigated rice yield (↓) by 0.4% in 2020 to 4.9% in 2080	Lin et al. (2005)
	No	China	B2: yield (↓) from 0.9% in 2050s to 2.5% in 2080s	Lin et al. (2005)

Note: 1) Definitions of the adaptation (A): a - Technology development; b - Shifting planting dates, application of irrigation and fertilization automatically; c - Priority for agricultural water use, limiting land losses and technology improvement. 2) Definition of socio-economic scenario (S): assumptions are consistent with SRES (A2 and B2) scenarios.