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Chinese Food Security and Climate Change: Agriculture Futures

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Abstract

Climate change is now affecting agriculture and food production in every country of the world. Here the authors present the IMPACT model results on yield, production, and net trade of major crops in China, and on daily calorie availability as an overall indicator of food security under climate change scenarios and socio-economic pathways in 2050. The obtained results show a relatively optimistic outlook on yield, production and trade toward 2050. The outcomes of calorie availability suggest that China will be able to maintain a level of at least 3,000 kilocalories per day through 2010 to 2050. Overall, Chinese agriculture is relatively resilient to climate change. It is unlikely that Chinese food security by 2050 will be compromised in the context of climate change. The major challenge to food security, however, will rise from increasing demand coupled with regional disparities in adaptive capacity to climate change.

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Keywords Climate change; food security; scenario; adaptation; mitigation; policy

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1 Introduction

The world faces multiple challenges to food security ranging from continuous population growth and rapid diet transition to decreasing cropland area and insufficient production practices (Beddington et al., 2012). The world's population, for example, has increased from 1.65 billion in 1900 to over 6 billion in 2000 and further to 7 billion in 2011 (Smith, 2011). Overall, food production per capita has remained stable during the twentieth century, largely due to technological advances. Breakthroughs in wheat and rice production, which have been known as the Green Revolution (Evenson and Gollin, 2003), have greatly contributed to the ease of the population burden in various parts of the world. However, some 800 million to 1 billion people still experience chronic and transitory hunger at present, partly due to the rapid rise in food price (Sanchez and Swaminathen, 2005; Borlaug, 2007). Global food prices have risen dramatically in the past few years and are forecast to rise further and become more volatile, disrupting assumptions that stable and declining food prices and assured supplies can be taken for granted (Beddington et al., 2012). The food system faces additional pressure as the dominant diet pattern is shifting towards higher consumption of calories, fats and animal products. Moreover, as the dominant source of the human food supply, the per capita availability of world cropland has been decreasing at a rate of 0.8% per year during the twentieth century (Ramankutty et al., 2008) and will continue to decrease at the foreseeable future. The demand for cereals will probably grow by 50% until 2030 and even higher production will have to be achieved through agricultural intensification for a world of 9 billion people in 2050 (Tilman et al., 2002; Schmidhuber and Tubiello, 2007).

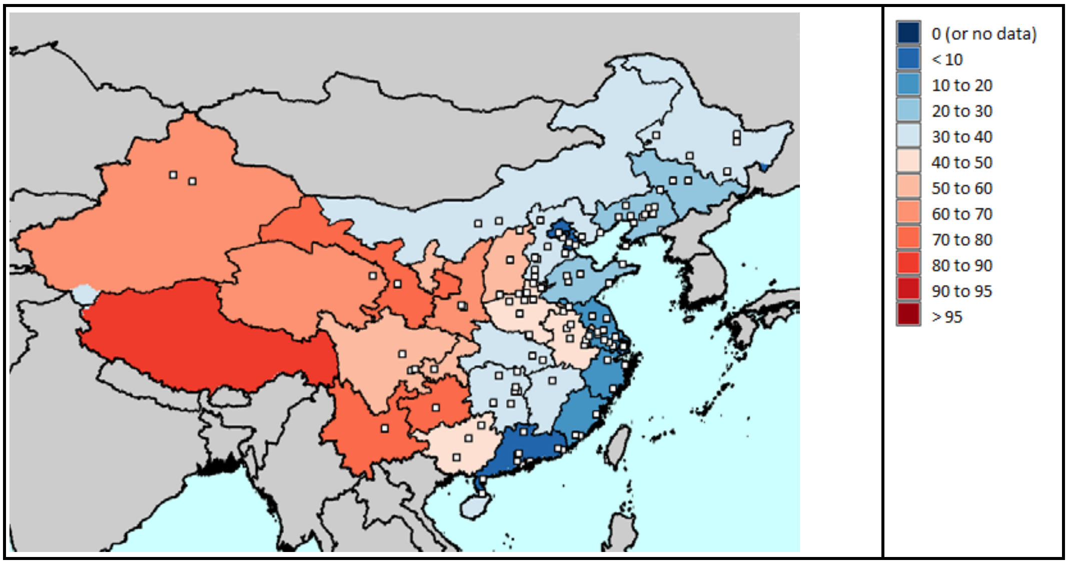
Climate change will further exacerbate the already-fragile global food production system and the natural resource base. Global surface temperature has increased 0.8°C during the twentieth century; four thirds of this increase occurred in the last three decades (Hansen et al., 2006; Ye et al., 2013a). The acceleration in global warming and its associated changes in precipitation have already affected global agriculture and the food production system in many ways (Godfray et al. 2011). Crop production is affected by climatic variables such as rising temperatures, changing precipitation regimes and increased atmospheric CO_2 levels (Long, 2012); it is also affected by biological variables such as the lengths of the crop growth periods and the crop cycle (Ye et al., 2013b). Experimental findings on wheat and rice under managed environments, for instance, indicated decreased crop duration (and hence yield) of wheat as a consequence of warming and reductions in yield of rice of ~5% °C^{-1} rise above 32°C (Gregory et al., 2005). These effects of temperature were considered sufficiently detrimental that they would largely offset any increase in yield as a consequence of increased atmospheric CO_2 concentration. It is clear that climate change has the potential to interrupt the progress toward a world without hunger (Wheeler and von Braun, 2013). This is particularly true for China as the world's most populous country and the largest grain producer (Zhang et al., 2010; FAO, 2013).

China embarked on economic reform more than three decades ago when the government introduced the household responsibility system (HRS) in agriculture. Price distortions were reduced, and key land rights were reallocated from collective farms to individual households across the country in late 1970s. Bold policies and institutional reforms motivated higher grain production and dramatically improved food security, which resulted in what was considered as "the greatest increase in economic well-being within a 15-year period in all of human history" (Sachs et al., 1994; Zeng, 2010). During the past few decades, agricultural productivity rose steadily, and per capita grain output reached a level similar to that in developed countries. With sustained growth in agriculture, rural incomes rose significantly, permanently lifting millions of people out of poverty (Ye and Van Ranst, 2009). The Chinese population has increased over 30% since 1980, reaching 1.34 billion in 2010. The production of staple grains has generally come up with the population growth, enabling China to feed approximately 20% of the world's population on less than 9% of the world's cropland. Despite these notable improvements, food insecurity remains a fundamental issue for many poor and remote households (Huang and Rozelle, 2009). At present, more than 100 million farmers and their families still live in poverty (Khan et al., 2009) and are vulnerable to many different kinds of stresses because they lack the financial resources to respond. The rural poor are particularly vulnerable to an uncertain climate. Moreover, although the average figures mentioned above show substantial improvements in economic performance and human well-being, substantial regional differences remain.

As shown in Figure 1, the poverty rates of the densely populated provinces on the eastern seaboard, shaded in blue colors, are mostly lower than 20 percent of the population, while in the western provinces, shaded in red colors on map, the poverty rate is much higher; 60 to 90 percent of the population there earn less than the equivalent of US$2 per day.

Therefore, the objectives of this paper are to (1) assess the effects of climate change on the yields of major crops in China in a spatial explicit manner using the CERES model; (2) predict the future trends of agricultural development in China in mid-21st century under climate change in terms of a range of food security indicators such as food trade, daily kilocalorie availability, number of malnourished children, etc.; and (3) formulate policy recommendations to ensure food security under climate change.

Figure 1. Poverty as measured by population share (%) living on US$2 per day or less



Source: Wood et al. (2010) available at labs.harvestchoice.org/2010/08/poverty-maps.

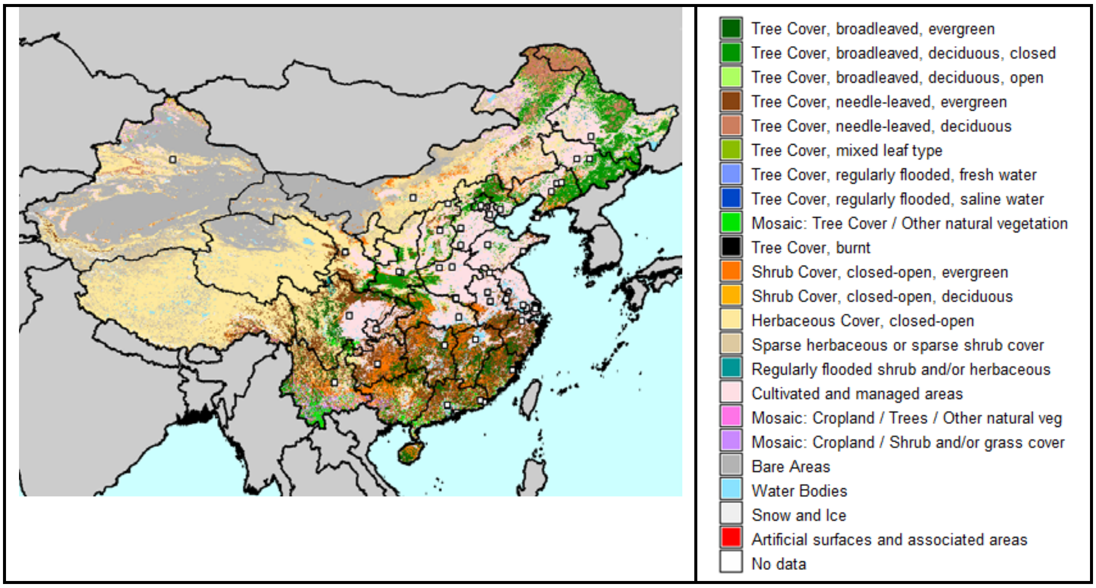
2 Material and Methods

2.1 Land use and agriculture overview

Satellite-based land cover inventory in year 2000, as mapped in Figure 2, shows that crop production is largely limited to the Three River Plain in the northeast, the North China Plain, the Loess Plateau, the lower Yangtze River Basin, and the Sichuan Basin as indicated by the "cultivated and managed areas" land cover type (Ye et al., 2008). Croplands in southeast, south, and southwest China are much fragmented, as indicated by the two "mosaic" land cover types, and are thus of secondary importance to agriculture. Aggregate, cropland is accounted for only 14% of the total land mass, which is equivalent to 0.1 hectares per capita.

Key agricultural commodities in terms of area harvested and value for the period of 2006–2008 are given in Table 1 and Table 2, respectively. Rice,

Figure 2. Land cover inventory as in year 2000



Source: GLC2000 (JRC, 2000).

maize and wheat are traditionally the most important crops in China. They take nearly half of the total area of major agricultural harvests. In monetary terms, these big three plus cotton account for 47% of the total value of key agricultural commodities listed in Table 2. Rice and maize are still in the top two positions, while cotton is in the third position with wheat ranking the fourth.

The irrigated and rainfed production of major food crops were evaluated and mapped in terms of estimated yield and harvest area based on the SPAM dataset (You et al., 2009), as shown in Figure 3 and Figure 4 for wheat as an example. The estimated yield and harvest area maps for the other two major food crops in China, maize and rice, are shown in Figure S1 through Figure S4 as Additional Materials to this paper.

Table 1. Harvest area of leading agricultural commodities, 2006–2008 average

Rank	Crop	% of total	Area harvested (000 hectares)
1	Paddy rice	17.7%	29,291
2	Maize	17.7%	29,288
3	Wheat	14.3%	23,650
4	Soybeans	5.5%	9,062
5	Fresh vegetables	5.2%	8,532
6	Rapeseed	3.7%	6,073
7	Seed cotton	3.5%	5,834
8	Potatoes	2.6%	4,367
9	Groundnuts with shell	2.5%	4,190
10	Sweet potatoes	2.2%	3,673
	Total	100.0%	165,072

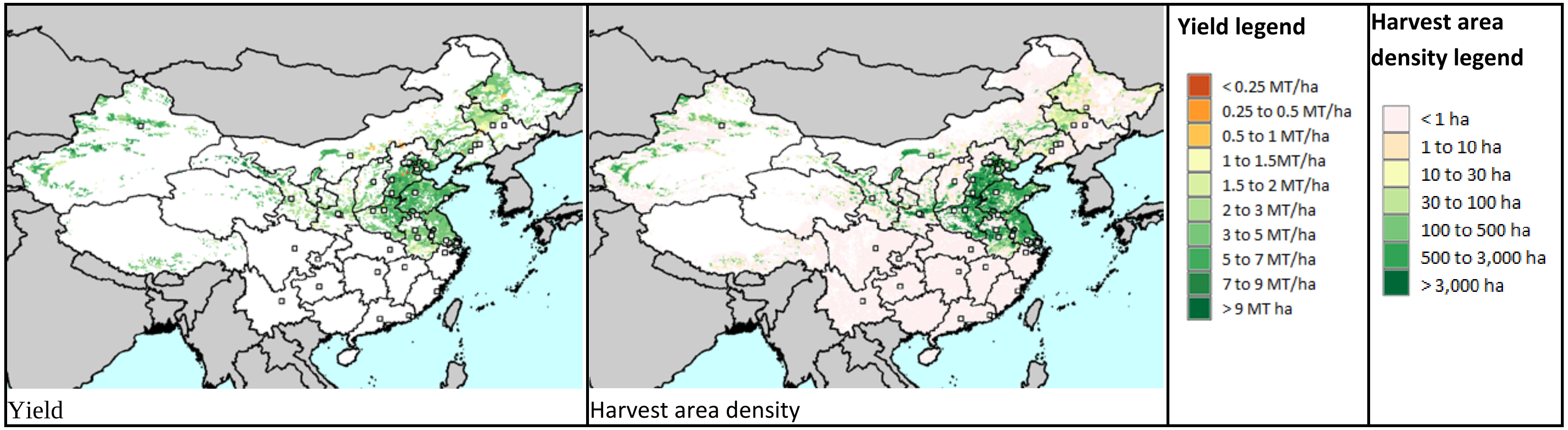
Source: FAOSTAT (FAO, 2010)

Table 2. Value of production for leading agricultural commodities, 2006–2008 average

Rank	Crop	% of total	Value of Production (million US$)
1	Paddy rice	20.7%	65,377
2	Maize	11.6%	36,573
3	Seed cotton	7.3%	22,988
4	Wheat	7.2%	22,713
5	Fresh vegetables	6.4%	20,049
6	Apples	4.9%	15,306
7	Asparagus	3.1%	9,747
8	Groundnuts with shell	2.3%	7,222
9	Lettuce and chicory	2.2%	7,065
10	Soybeans	2.0%	6,367
	Total	100.0%	315,479

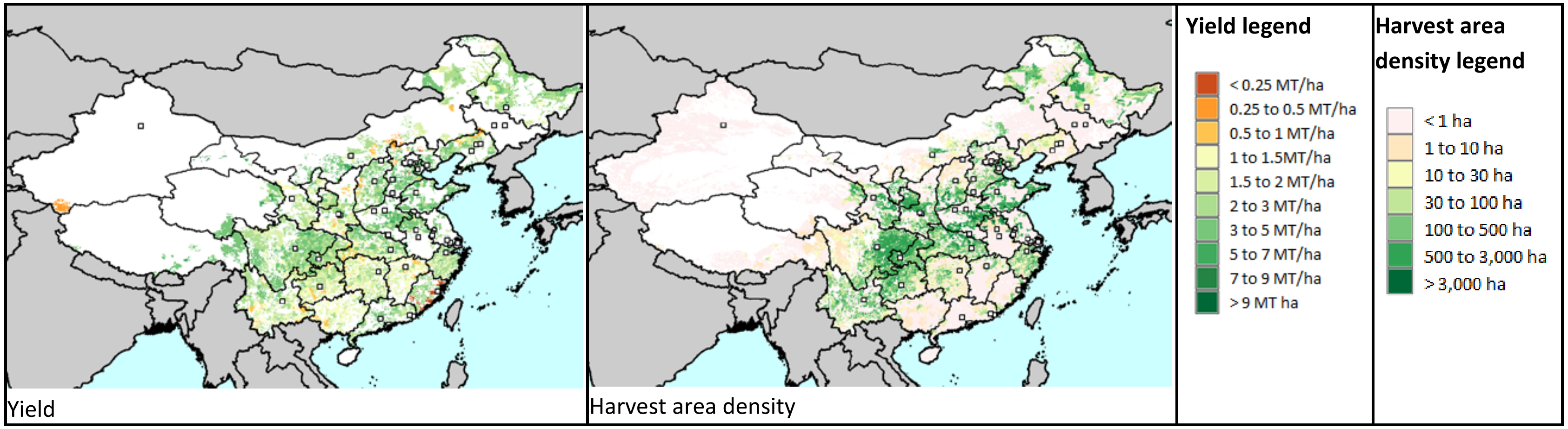
Source: FAOSTAT (FAO, 2010)

Figure 3. Yield and harvest area density of irrigated wheat in year 2000



Source: SPAM Dataset (You et al., 2009).

Figure 4. Yield and harvest area density of rainfed wheat in year 2000



Source: SPAM Dataset (You et al., 2009).

2.2 Climate scenarios

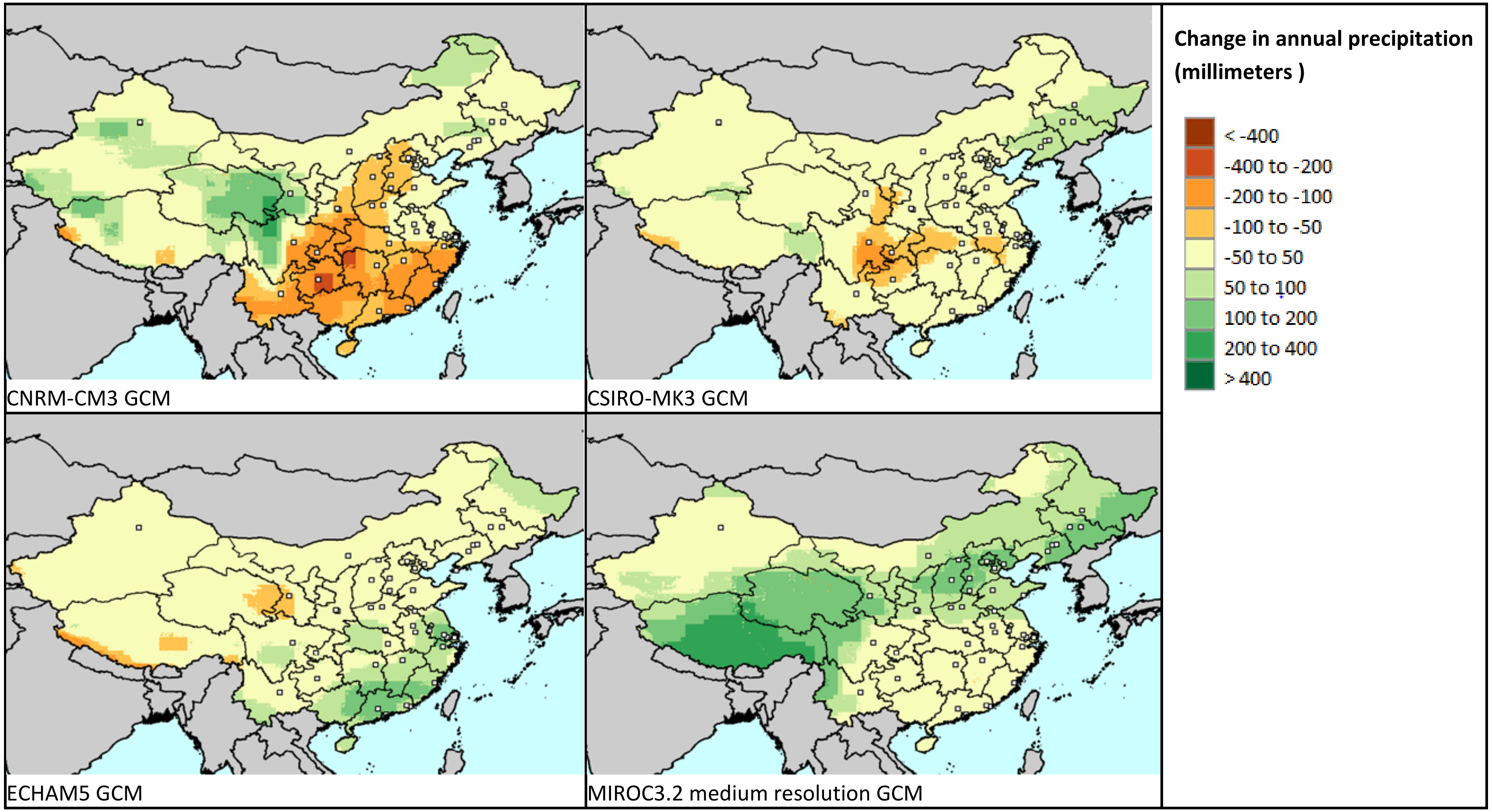
Four climate scenarios, downscaled from 4 GCMs – CNRM, CSIRO, ECHAM, and MIROC – driven by SRES emission scenario A1B or B1, were used to accommodate the likely ranges of future temperature and precipitation changes. The CSIRO scenario, for example, represents a dry and relatively cool future, while the MIROC scenario represents a wet and warmer future. The scenario-based temperature and precipitation were then utilized for crop modeling analysis.

Figure 5 shows precipitation changes between 2010 and 2050 for China from 4 downscaled GCMs driven by the A1B emission scenario; Figure 6 shows changes in maximum temperature for the month with the highest mean daily maximum temperature between 2010 and 2050 for China from the same GCMs.

In one of the major agricultural regions in China, the North China Plain, for example, climate is expected to be drier according to the CNRM scenario; the annual precipitation can decrease by 100 mm (Figure 5). To the contrary, the MIROC GCM depicts a much wetter future in the same region – annual precipitation can be 100 mm higher in 2050 than in 2010. The same amount of precipitation can be expected in the North China Plain by 2050 under the other two GCMs – CSIRO and ECHAM. The disparity among GCM results explains why the multi-model ensemble approach is used to deal simulated crop yields under climate change scenarios.

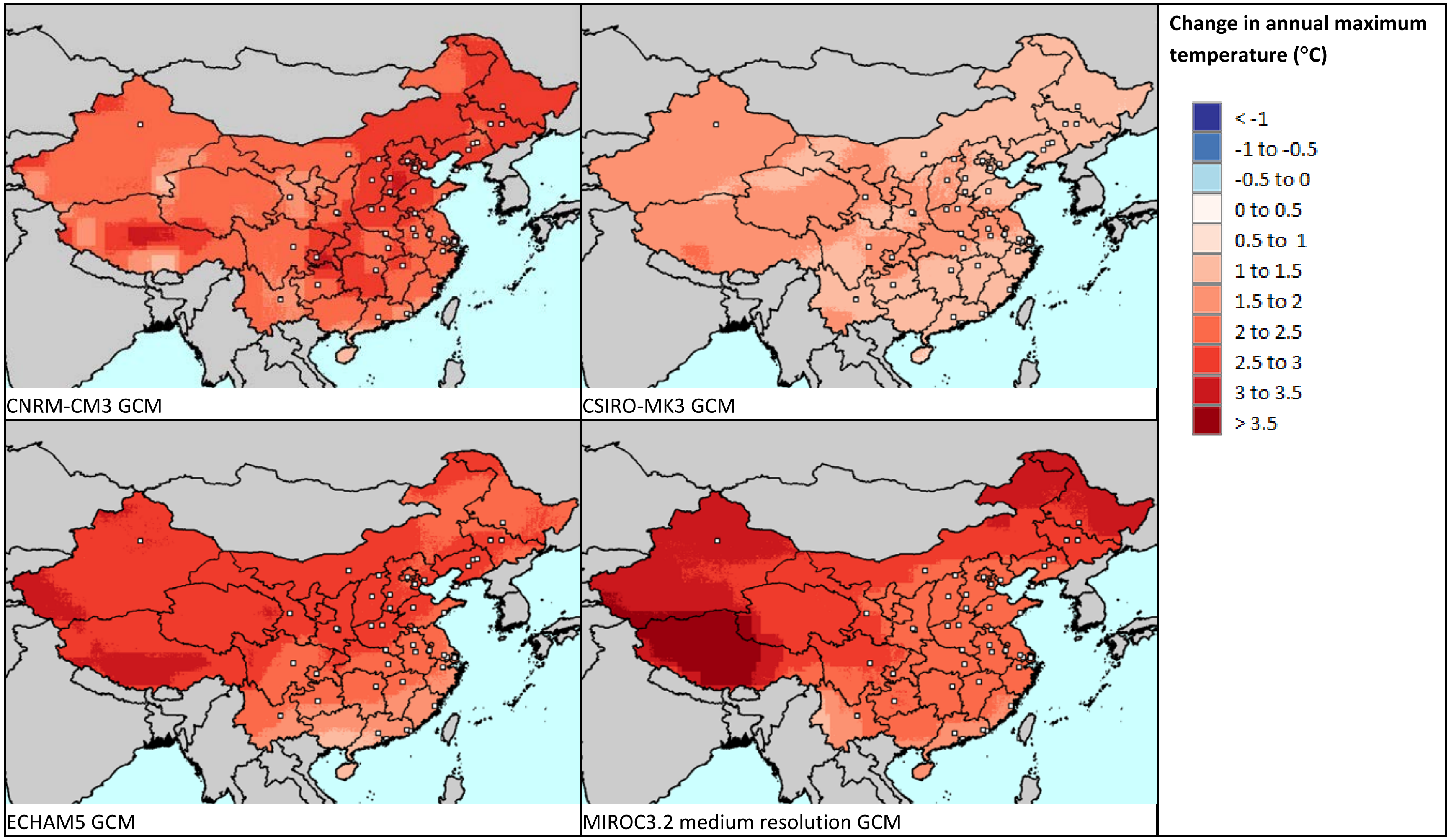
The GCM results are more unanimous on temperature change. They all depict a warmer future (Figure 6). The disagreement on temperature is much smaller than on precipitation. In North China Plain, temperature will increase 1–2°C under CNRM, ECHAM, and MIROC, while the CSIRO GCM predicts a less warm future of <1°C. The general picture is that the higher latitudinal (e.g., Northeast) and higher altitudinal regions (e.g., Tibetan Plateau) are expected to receive higher warming, compared to the lower latitudinal/altitudinal regions.

Figure 5. Changes in mean annual precipitation for China between 2000 and 2050 using the A1B scenario (millimeters)



Source: IFPRI calculations based on downscaled climate data available at http://ccafs-climate.org/.

Figure 6. Changes in normal annual maximum temperature for China between 2000 and 2050 using the A1B scenario (°C)



Source: IFPRI calculations based on downscaled climate data available at http://ccafs-climate.org/.

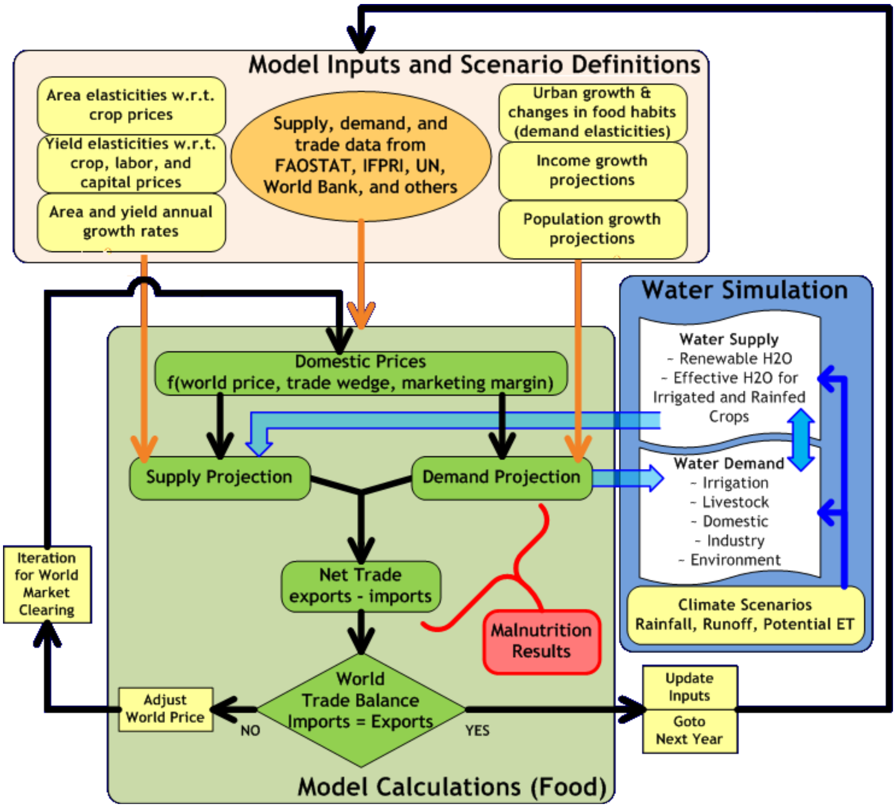
2.3 The modeling framework

Three models were used in this paper to analyze the biophysical and socioeconomic consequences of climate change (Figure 7): IFPRI's IMPACT model (Cline and Zhu, 2008), a partial equilibrium agriculture model that emphasizes policy simulations; a hydrology model and an associated water-supply demand model incorporated into IMPACT; and the DSSAT crop modeling suite (Jones et al., 2003) that estimates yields of selected crops under varying management systems and climate change scenarios. The modeling methodology reconciles the limited spatial resolution of macro-level economic models that operate through equilibrium-driven relationships at a national level with detailed models of biophysical processes at high spatial resolution. The DSSAT system is used to simulate responses of five important crops (rice, wheat, maize, soybeans, and groundnuts) to climate, soil, and nutrient availability, at current locations based on the SPAM dataset of crop location and management techniques. This analysis is done at a spatial resolution of 15 arc minutes, or about 30 km at the equator. These results are aggregated up to the IMPACT model's 281 spatial units, called food production units (FPUs, Figure 8). The FPUs are defined by political boundaries at the river basin scale.

2.4 Income and demographic scenario settings

Three pathway scenarios were designed using combinations of economic and demographic drivers to facilitate model simulations. These include a baseline scenario that is "middle of the road", a pessimistic scenario that chooses driver combinations that, while plausible, are likely to result in more negative outcomes for human well-being, and an optimistic scenario that is likely to result in improved outcomes relative to the baseline. These three overall scenarios are further qualified by four climate scenarios (e.g., Figure 5). The drivers used for simulations with the IMPACT model include: population, GDP, rainfed and irrigated exogenous productivity and crop-specific area growth rates, irrigation efficiency, and future climate. In all cases except climate, the country-specific (or more disaggregated) values can be adjusted

Figure 7. The IMPACT modeling framework

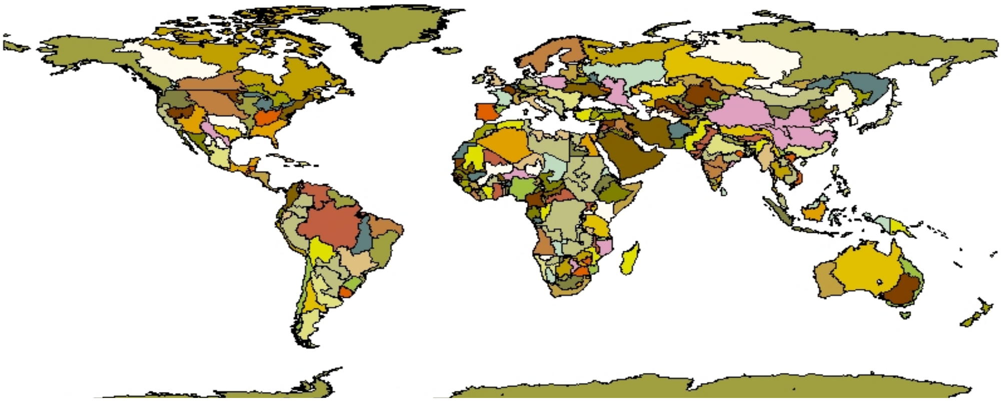


Source: Nelson et al. (2010).

individually. Differences in GDP and population growth define the overall scenarios analyzed here, with all other driver values remaining the same across all the three socio-economic pathway scenarios.

Table 3 documents the GDP and population growth choices for these three overall scenarios adopted in this paper. Table 4 shows the annual growth rates for different regional groupings as well as for China. Figure 9 illustrates the three GDP per capita scenario pathways, derived from the three GDP projections and the three population projections obtained from the United Nations Population office. The “optimistic scenario” combines high GDP with

Figure 8. The 281 food production units or FPUs adopted by the IMPACT model



Source: Nelson et al. (2010).

Table 3. GDP and population choices for the three overall socio-economic pathway scenarios

Parameter	Pessimistic	Baseline	Optimistic
GDP, constant 2000 US$	Lowest of the four GDP growth rate scenarios from the Millennium Ecosystem Assessment GDP scenarios (Millennium Ecosystem Assessment, 2005) *and* the rate used in the baseline (next column)	Based on rates from World Bank EACC study (World Bank, 2010), updated for Sub-Saharan Africa and South Asian countries	Highest of the four GDP growth rates from the Millennium Ecosystem Assessment GDP scenarios *and* the rate used in the baseline (previous column)
Population	UN High variant, 2008 revision	UN medium variant, 2008 revision	UN low variant, 2008 revision

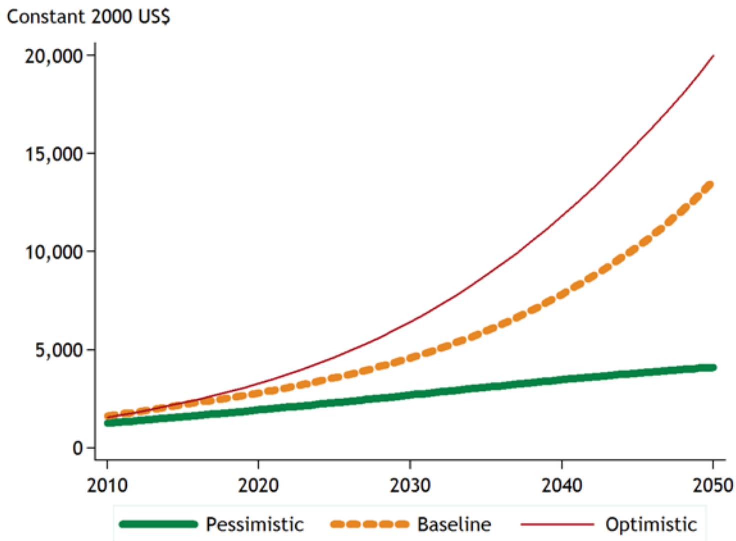
Source: Based on analysis conducted for Nelson et al. (2010).

Table 4. Average scenario per capita GDP growth rates (percent per year)

Category	1990–2000	2010–2050		
		Pessimistic	Baseline	Optimistic
China	8.09	3.65	5.18	6.24
Developed	2.7	0.74	2.17	2.56
Developing	3.9	2.09	3.86	5
Low-income developing	4.7	2.6	3.6	4.94
Middle-income developing	3.8	2.21	4.01	5.11
World	2.9	0.86	2.49	3.22

Source: World Development Indicators for 1990–2000 and authors' calculations for 2010–2050.

Figure 9. GDP per capita scenarios



Source: Based on IMPACT results of July 2011, computed from World Bank and United Nations population estimates (2008 revision).

low population. The "baseline scenario" combines the medium GDP projection with the medium population projection. Finally, the "pessimistic scenario" combines the low GDP projection with the high population projection. In all scenarios, China's income growth exceeds those of the developed group of countries and most developing countries, although it is expected to slow from the current rapid pace.

Note that the scenarios used apply to all countries; that is, in the optimistic scenario, every country in the world is assumed to experience high GDP growth and low population growth.

The GDP per capita scenario results for China and the U.S. are summarized in Table 5. In the pessimistic scenario, U.S. per capita income increases less than 2 times while in the optimistic scenario, it almost triples between 2010 and 2050. The Chinese per capita income triples in the pessimistic scenario and increases almost 12 times in the optimistic scenario. However, despite China's much more rapid growth than in the U.S. its per capita income in 2050 is still only one-fifth of that in the U.S.

Table 5. China and U.S. per capita income scenario outcomes for 2010, 2030, and 2050 (2000US$ per person)

	2010	2030	2050
Pessimistic			
China	1,264	2,699	5,640
U.S.	37,504	51,132	58,291
Baseline			
China	1,627	4,590	13,584
U.S.	37,723	56,517	88,841
Optimistic			
China	1,551	6,433	20,000
U.S.	39,218	67,531	101,853

3 Results and Discussion

3.1 Climate change impact on crop yield

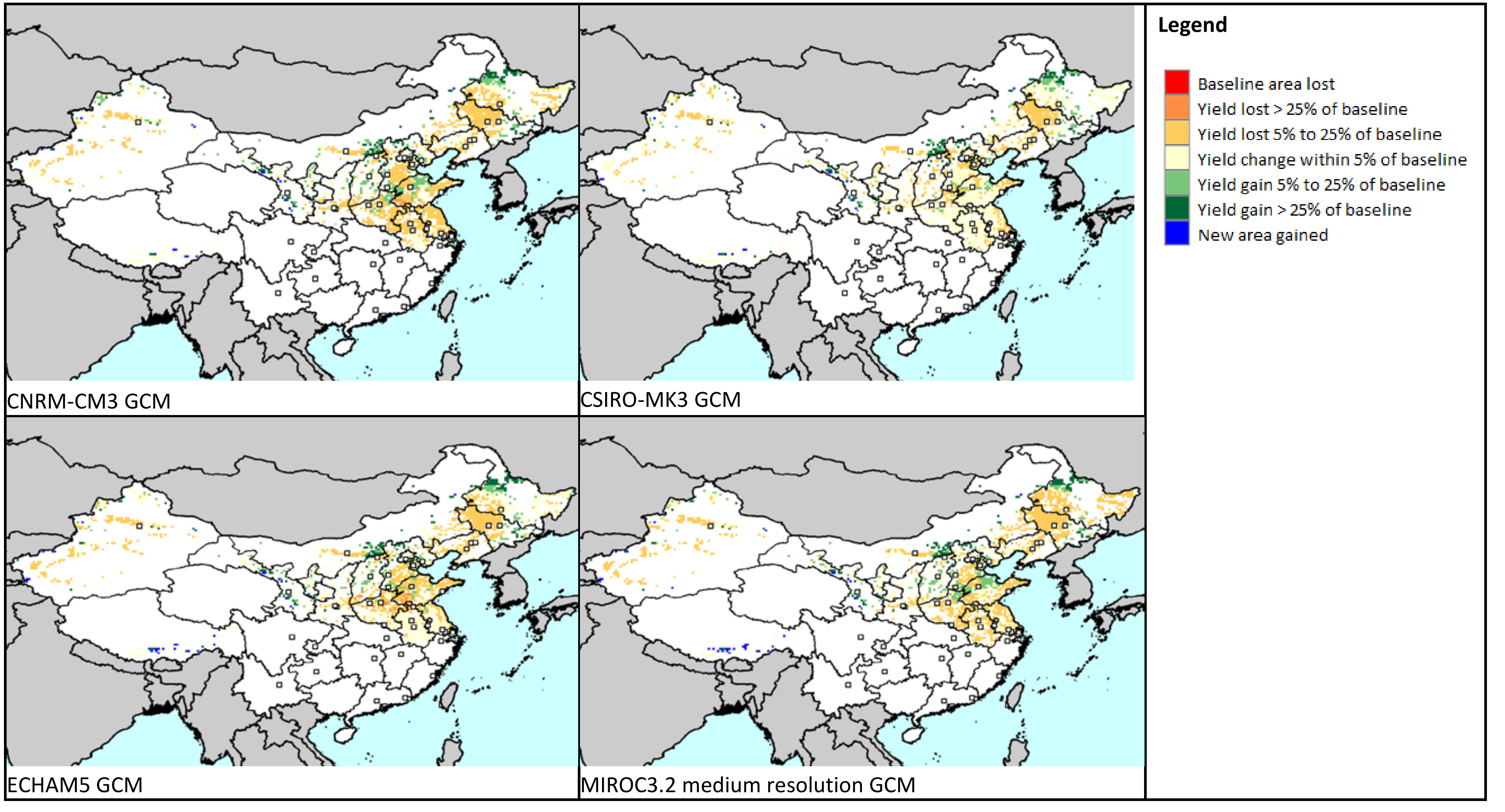
The yields of major crops (rice, wheat, maize, soybeans, and groundnuts) under each of the four climate scenarios through 2050 were simulated using the crop-specific CERES models of the DSSAT crop modeling system and subsequently compared to the current or baseline yields – which were also simulated using DSSAT – to drive the yield differences. For a specific locality, crop variety, soil and management practices were held constant across the entire simulation period. The obtained results for wheat, maize, and rice – under both irrigated and rainfed farming – were mapped for qualitative evaluation of climate change impact on crop yield in 2050 relative to yield under current climate in 2000 (Figure 10 and Figure 11 for maize; Figure S5 through Figure S8 for wheat and rice). The legends of these figures were intentionally kept identical. Yield loss was mapped in yellowish/brownish colors and yield gain was mapped in greenish/bluish colors.

The changes of the yields of maize, rice, and wheat under two typical GCMs – CSIRO and MIROC – cross-driven by the A1B and B1 emission scenarios, respectively, in 2050 over 2000 were summarized in Table 6. Chinese crops respond mildly to climate change. Irrigated yields tend to decrease, as in the case of maize in particular (Figure 10). This decrease would probably be caused by the decreasing availability of irrigation water due to more intense competition of water use from urban sprawl and due to groundwater depletion in major maize regions such as the North China Plain. Rainfed yields tend to increase because the expected warmer and wetter climates under both CSIRO and MIROC scenarios are favorable to these rainfed varieties (Figure 11). Overall, the yields of maize and rice will increase slightly, but the yield of wheat will decrease only marginally, by 2050 under the climate change scenarios considered.

Table 6. Yield change under climate change scenarios in 2050 over 2000, %

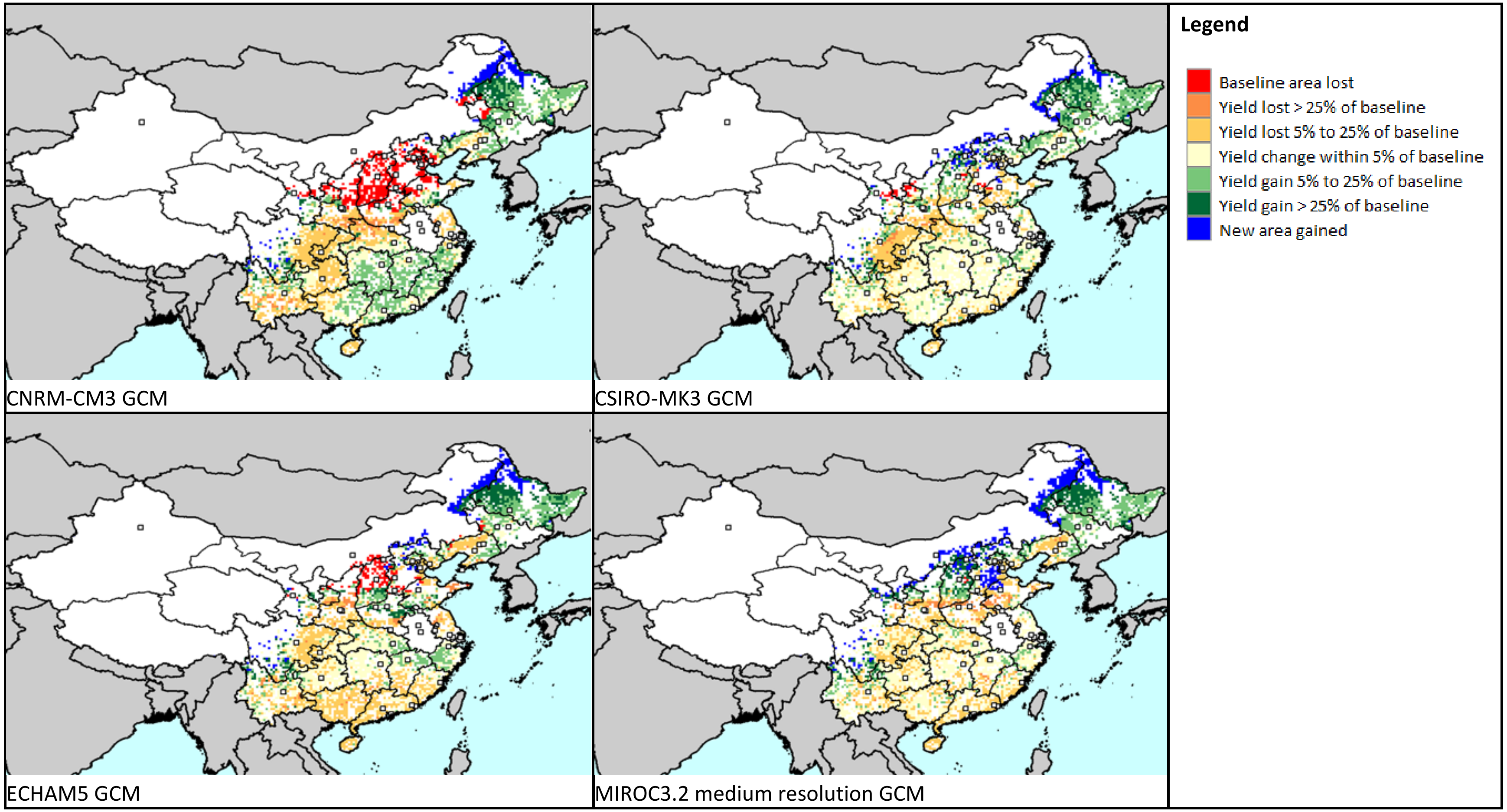
Scenario	Maize	Rice	Wheat
Irrigated			
CSIRO A1B	–3.49	0.44	2.96
CSIRO B1	–4.08	0.02	1.39
MIROC A1B	–4.18	- –5.09	–9.81
MIROC B1	–3.96	–1.92	–4.53
Rainfed			
CSIRO A1B	3.75	12.38	2.01
CSIRO B1	3.7	3.46	–2.11
MIROC A1B	2.51	14.32	2.89
MIROC B1	1.93	12.08	2.97
Average			
CSIRO A1B	0.85	2.83	2.37
CSIRO B1	0.59	0.71	–0.78
MIROC A1B	–0.17	–1.21	–1.94
MIROC B1	–0.43	0.88	0.12
All scenarios	0.21	0.80	–0.06

Figure 10. Yield change between 2000 and 2050 under four climate change scenarios: irrigated maize



Source: IFPRI calculations based on downscaled climate data and DSSAT model runs.

Figure 11. Yield change between 2000 and 2050 under four climate change scenarios: rainfed maize



Source: IFPRI calculations based on downscaled climate data and DSSAT model runs.

3.2 Agricultural vulnerability outcomes

The simulation results on production, yield, area, net export, and world price per crop under the three pathway scenarios are shown in Figure 12 through Figure 14 for wheat, maize and rice, respectively. The box and whisker plots are used in these figures to present the effects of climate change modeled by the MIROC and CSIRO GCMs under the A1B and B1 emission scenarios in the context of each of the economic and demographic pathways (optimistic, baseline, and pessimistic). Each box has 3 lines. The top line represents the 75th percentile, the middle line represents the median, and the bottom line represents the 25th percentile.

Wheat yield in China will increase steadily from 2010 to 2050 by 17%, partly due to the increase in factor inputs stimulated by the significant increase of world wheat price by 60% (Figure 12). Accordingly, wheat production will increase from 100 million tons in 2010 to 123 million tons in 2050, although the wheat area remains constant at 24–25 million hectares during 2010–2050 under all scenarios.

World maize price is projected to increase more than other cereals in percentage terms. Maize price doubles from about US$100 in 2010 to US$200 in 2050 under all scenarios (Figure 13). As a result, the maize yield will jump by 45% from 5.1 tons per hectare in 2010 to 7.4 tons per hectare in 2050, despite the marginal effect of climate change on maize yield (Table 6). In line with the price increase, maize area will expand by 18% from 28 million hectares in 2010 to 33 million hectares in 2050. Consequently, maize production will increase significantly by 70%, from 140 million tons in 2010 to 240 million tons in 2050.

Although world prices of key commodities are all expected to rise under all scenarios, the pattern of rice price increase is more distinct. The rice price pathways diverge significantly depending on the overall scenario, with the pessimistic scenario leading to the highest prices (Figure 14) – a consequence of higher population and lower income in countries where rice is a staple for the poor. Even under the optimistic scenario, rice price will still rise by 40% during 2010–2050. Despite price increases, rice yield is expected to increase only slightly from 4.1 tons per hectare in 2010 to 4.7 tons per hectare in 2050. Rice production remains roughly constant until 2025 at 125 million tons, or a

3% increase over 2010, and then declines to 90% of current levels in 2050 as area devoted to rice declines from around 30 million hectares in 2010 to 23 million hectares in 2050.

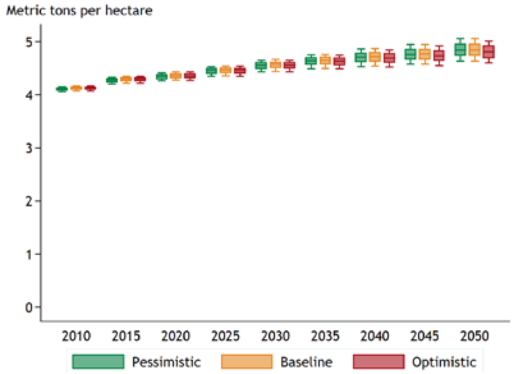
The discrepancy between price increase and area decrease reflects the fact that demand for rice tends to decrease as income increases due to the effect of higher income on rice consumption and diet pattern change (Chern et al., 2003; Kearney, 2010). It is interesting to observe that China will probably turn from a net importer of rice (slightly less than 5 million tons in 2010) to a net exporter by 2020 (Figure 14). Under the baseline and the optimistic overall scenarios in 2050, China is expected to have a surplus of 5–9 million tons of rice for export. Under the pessimistic scenario, China remains a net importer of rice by 2050 but with a much smaller volume of 1 million tons.

Perhaps the most promising scenario result is that China will remain a major importer of maize from the world food market at the scale of ~20 million tons per year, although the domestic production capacity is expected to grow constantly during 2010–2050, resulted from yield improvements and area expansions (Figure 13). Obviously, the imported maize will be overwhelmingly used as feed to meet the domestic demands of animal products (Chern et al., 2003; Ray et al., 2012).

China is expected to become a smaller and smaller importer of wheat (Figure 12). The wheat self-sufficiency level will approach 100% by 2050 under all scenarios.

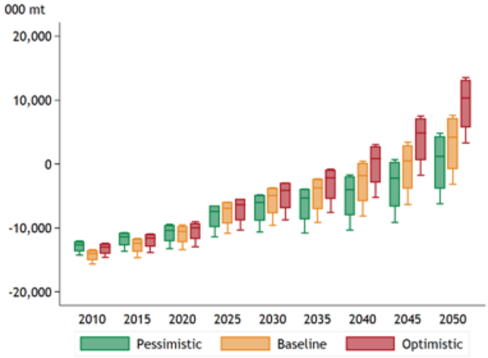
Figure 12. Scenario outcomes for wheat production, yield, area, net export, and price

Production

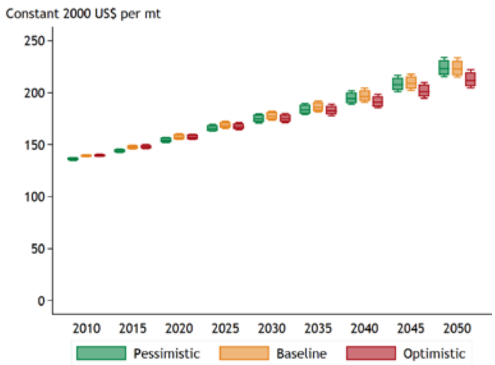


Yield

Area



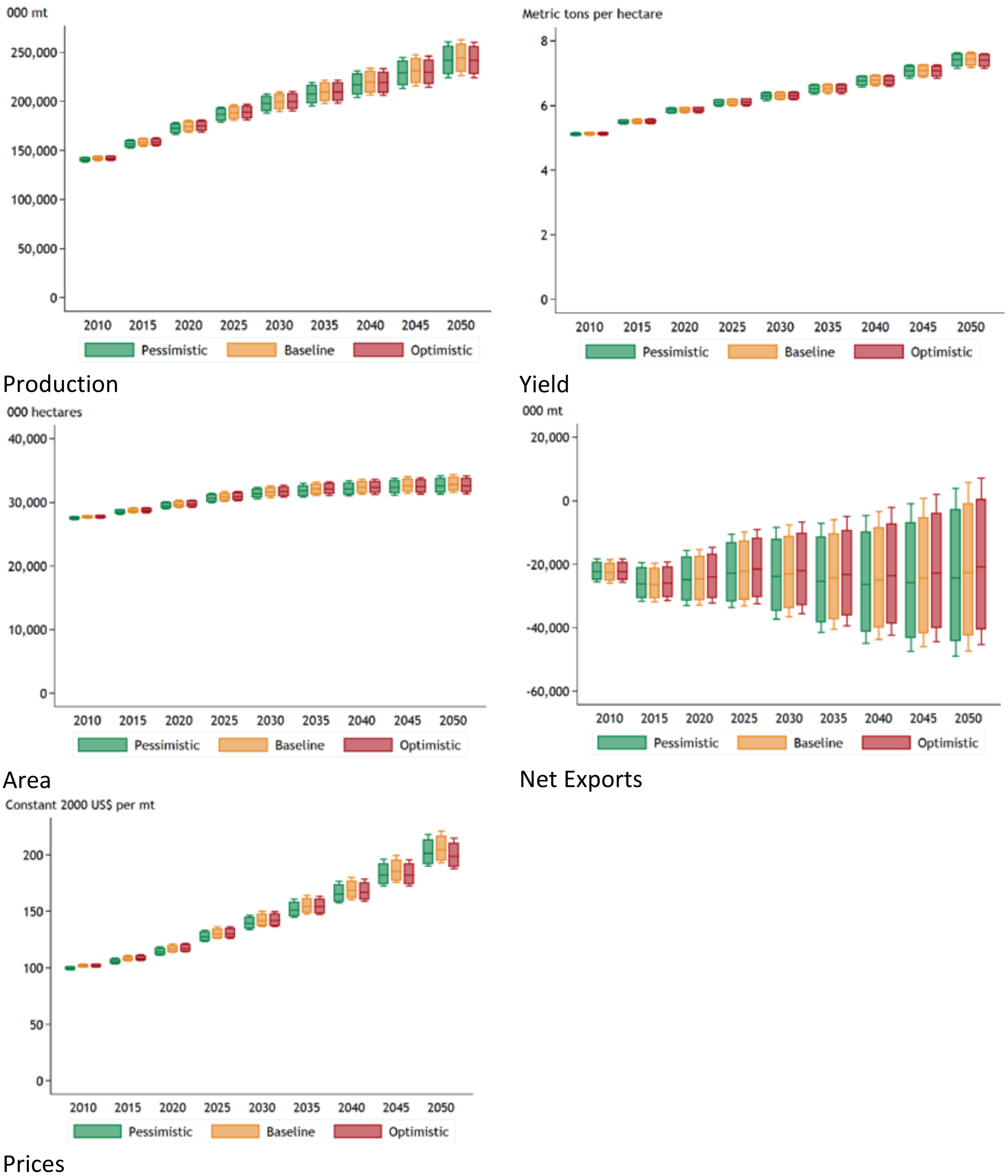
Net Exports



Prices

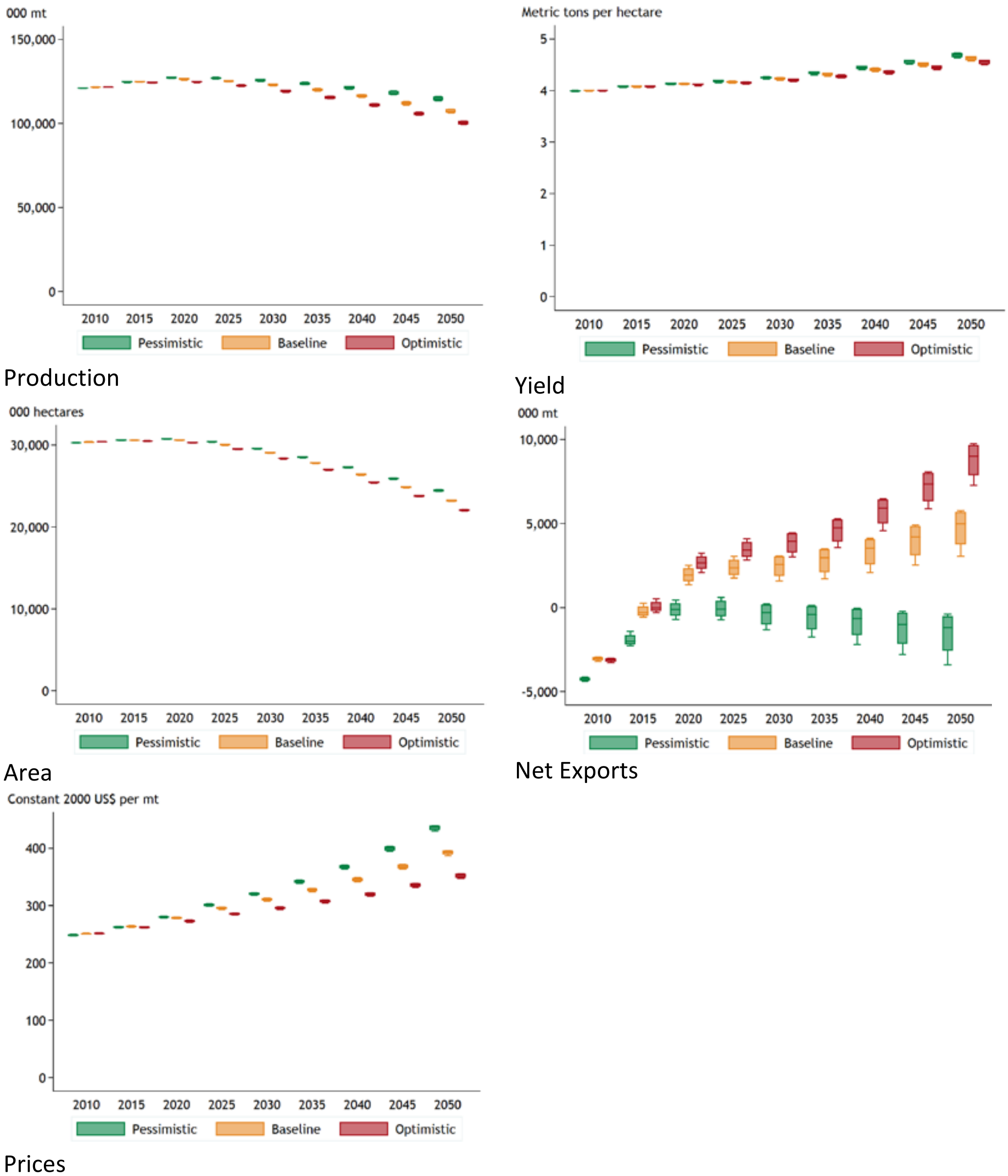
Source: Based on IMPACT results of July 2011.

Figure 13. Scenario outcomes for maize production, yield, area, net export, and price



Source: Based on IMPACT results of July 2011.

Figure 14. Scenario outcomes for rice production, yield, area, net export, and price



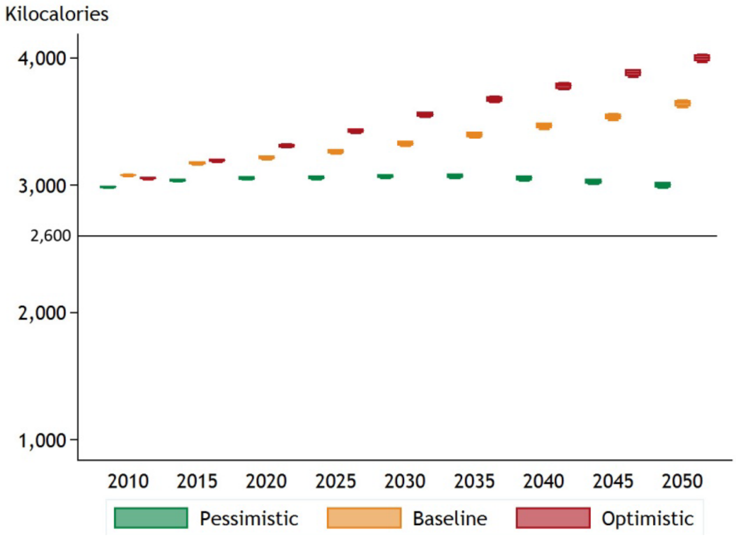
Source: Based on IMPACT results of July 2011.

3.3 Human vulnerability outcomes

Figure 15 shows scenario outcomes for the average daily kilocalories per capita, and Figure 16 shows the number of malnourished children under five. The story is much the same in both figures in qualitative terms. The baseline and optimistic scenarios show increases in calorie availability. The pessimistic scenario shows no increase but a stable level at about 3,000 kilocalories per day across the period 2010–2050. Climate change has relatively little effect within an overall scenario.

These scenario levels of calorie availability are well above the 2020 goal of 2,600 kilocalories per day stipulated by the Chinese Food and Nutrition Development Strategy (MOA, 2002; Xu, 2011). These levels allow sufficient development rooms to meet higher nutrition requirements in China by 2050. The Chinese food security in terms of per capita calorie availability will be unlikely compromised by 2050.

Figure 15. Average daily kilocalories availability under multiple income and climate scenarios (kilocalories per person per day)

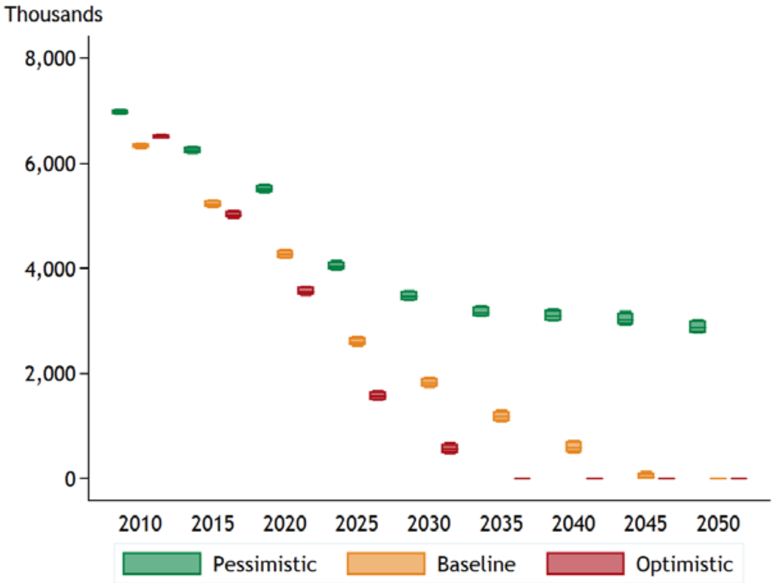


Source: Based on IMPACT results of July 2011.

As expected, the baseline and optimistic scenarios do best in reducing malnourished children. In the optimistic scenario the count drops close to zero, while with the baseline it falls from about 8 million children in 2010 to about 2 million in 2050. The pessimistic scenario is the least desirable from the perspective of reducing malnourished children. After a slow decline to just below 6 million by the mid-2020s, the decline stops and the number increases slightly.

As the box and whiskers plots indicate, within a particular overall scenario climate change has relatively little impact on the number of malnourished children. The range in 2050 from the different climate scenarios is typically less than 1 million children malnourished. The reason, as discussed above, is the function of trade to buffer the impact of climate change on domestic food production.

Figure 16. Number of malnourished children under 5 years of age under multiple income and climate scenarios



Source: Based on IMPACT results of July 2011.

4 Conclusions and Recommendations

China has been extraordinarily successful in transforming its highly planned economy into a free market-based system within a considerably short period of a few decades, especially in the agricultural sector which enables China to feed approximately 20% of the world's population on less than 9% of the world's cropland. The analysis of the IMPACT model results presented in this paper suggests that Chinese agriculture is relatively resilient to climate change compared to other parts of the world. In light of the slowing in population growth before ~2030 and of the outlook of a decreasing population size thereafter, the overall status of the Chinese food security by the middle of the twenty-first century will unlikely be substantially compromised in the context of climate change. The human vulnerability outcomes shows that the daily calorie availability will be well above the officially stipulated level of 2,600 kilocalories per day, and that the mortality count of children under five years due to malnutrition will be continuously decreasing from the current levels, even under the most pessimistic scenario by 2050. The major challenges, however, will rise from the increasing demand of a richer diet (Ray et al., 2012) – driven by the rapid growth in income levels which are expected to double against the current levels in 2020 – coupled with regional disparities in the adaptive capacity to climate change. There is a particularly high level of uncertainty as to how climate change will play out in specific locations. The immediate implication of this point is that the grain handling and transportation facilities need to be reexamined, and repositioned if necessary, to ensure a fair spatial distribution. Smooth and timely shipments of large quantities of grains across regions should be considered as one of the first steps in China's adaptive capacity building.

The scenario outcomes of grain production, derived from the IMPACT results and shown in Figure 12 to Figure 14, depict a relatively optimistic outlook on yield, production and trade toward 2050. The maize yield, for example, is predicted to jump by 45% during 2010–2050, contrasting with the simulated effect of climate change on maize yield using the DSSAT crop model (Table 6). DSSAT simulation shows that climate change can cause max. 4% change in maize yield, either increase or decrease, between 2010 and 2050. The multi-scenario ensemble effect of 0.2% (Table 6) suggests that overall effect of climate change can even be neutral over a large country like China in this particular case. The fundamental drivers behind these two differential rates of yield change, 45% versus 4%, are technology and trade. Technology development in terms of varietal performance and input use efficiency has been a major driver of yield improvements globally, as in the case of the Green Revolution (Evenson and Gollin, 2003). But over a shorter period of time, food price may play a more important role on raising crop yield by means of higher inputs. The jump of maize yield by 45%, as predicted by the IMPACT model, was associated with a sharp price increase by 100% during 2010–2050. These two important processes of yield change, either biophysical or socioeconomic, were both considered by the IMPACT model but not by DSSAT. This simple observation of yield change drivers has profound implications on future food security.

The first implication is on the importance of crop breeding for food security under climate change. Breeding and agronomic improvements have, on average, achieved a linear increase in global food production, at an average rate of 32 million tons per year (Tester and Langridge, 2010). This rate has been sustained for more than 40 years. An even higher rate is needed for a growing population with a richer diet. This requires substantial changes for methods in agronomic processes and management practices. In China, production growth can only be realized through higher yields, given the decreasing trend and outlook in crop areas. As a recent study (Ye et al., 2013b) suggested, maintaining yield growth rate on a yearly basis has great significance in ensuring food security in China. Therefore, continued investment in enhancing agricultural productivity should remain a key policy element in managing climate risks facing Chinese agriculture. Joint efforts on crop breeding are needed to produce innovative varieties that maintain yields but tolerate drought, salinity, pests and diseases, and other climate shocks (Trethowan et al., 2010). The second implication is on the role of international trade in climate change adaptation, which is notably missing in the current thinking of climate change in China. As the IMPACT results show, open international trade is key to buffer the impact of climate change on domestic production and thus to maintain a stable supply through price and market effects. This illustrates the importance of keeping international trade open for Chinese food security; it also indicates the importance of vulnerability alleviation for the rural poor in designing adaptation strategies to cope with climate change.

In a broader context, challenges of ensuring food security under climate change require urgent and substantial increase in the focus of research, innovation, transformation of knowledge, and education at all levels across all sectors related to agriculture (Smith and Olesen, 2010). This is only possible through capacity building actions toward a harmonized system of climate change adaptation and mitigation through agricultural intensification for food security. Such actions involve not only national and local governments but also international organizations and the international research community. It is important to note that investment in agricultural research is an efficient long-term mitigation strategy since investment in yield improvements compares favorably with other commonly proposed mitigation strategies (Burney et al., 2010). It is also important to note that reforms in the governing scheme of the intellectual property rights are much needed to facilitate effective transfer and assimilation of climate change- and food security-related knowledge.

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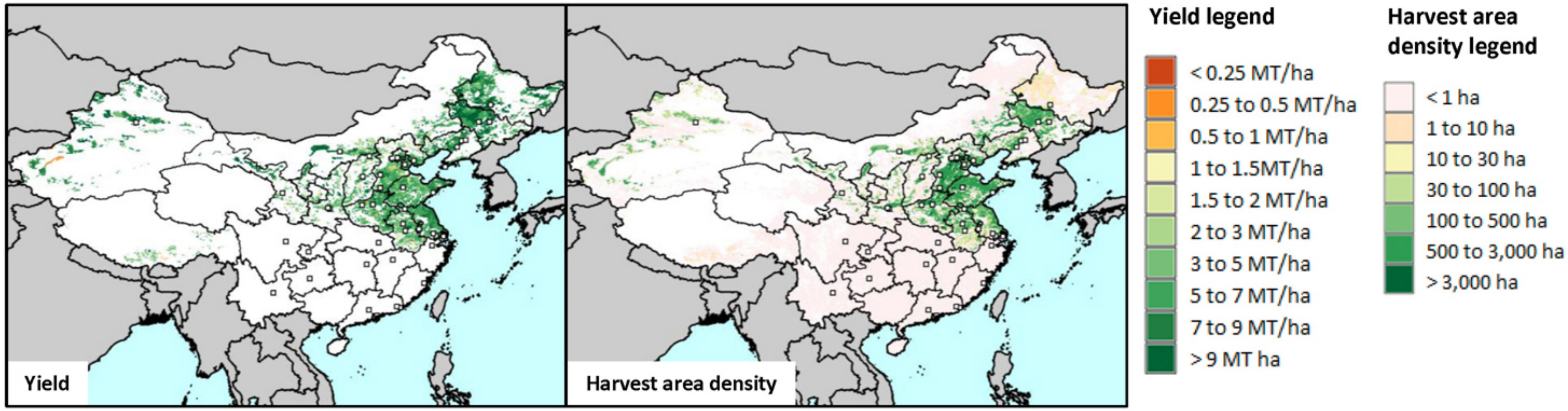
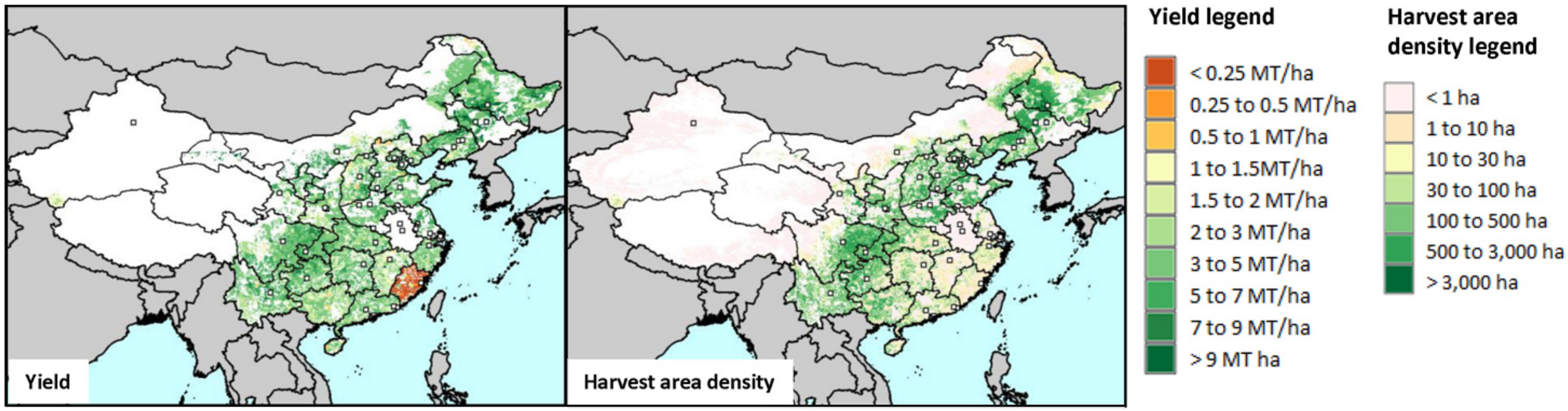
Additional Materials

Figure S1. Yield and harvest area density of irrigated maize in year 2000



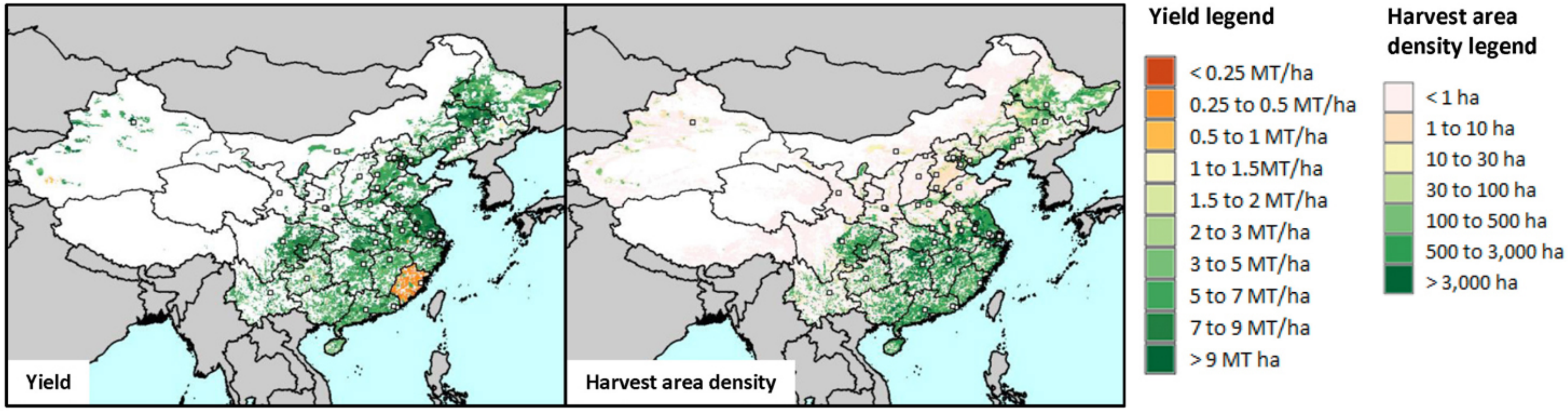
Source: SPAM Dataset.

Figure S2. Yield and harvest area density of rainfed maize in year 2000



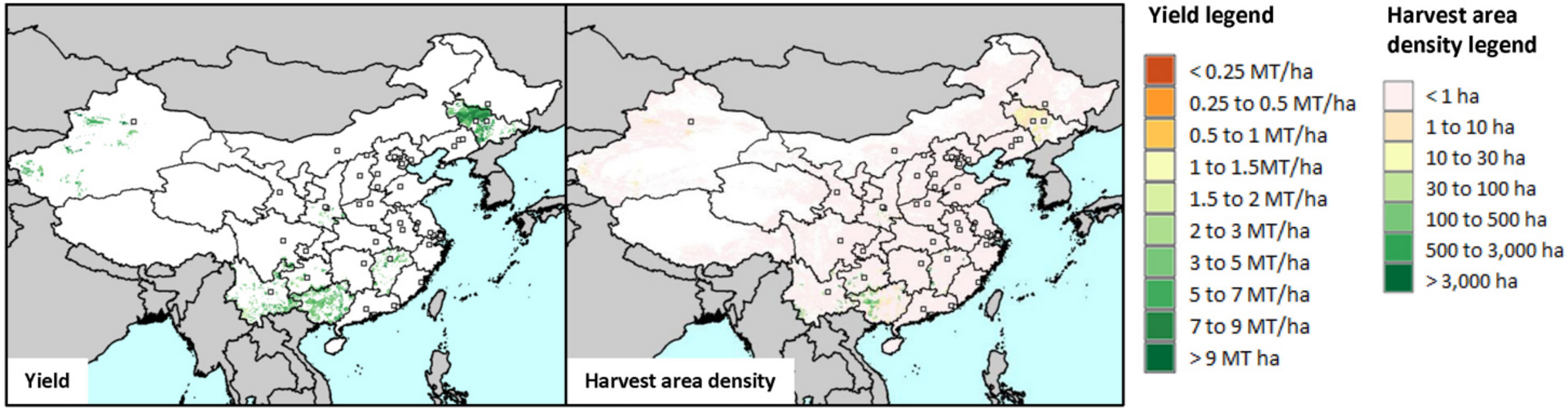
Source: SPAM Dataset.

Figure S3. Yield and harvest area density of irrigated rice in year 2000



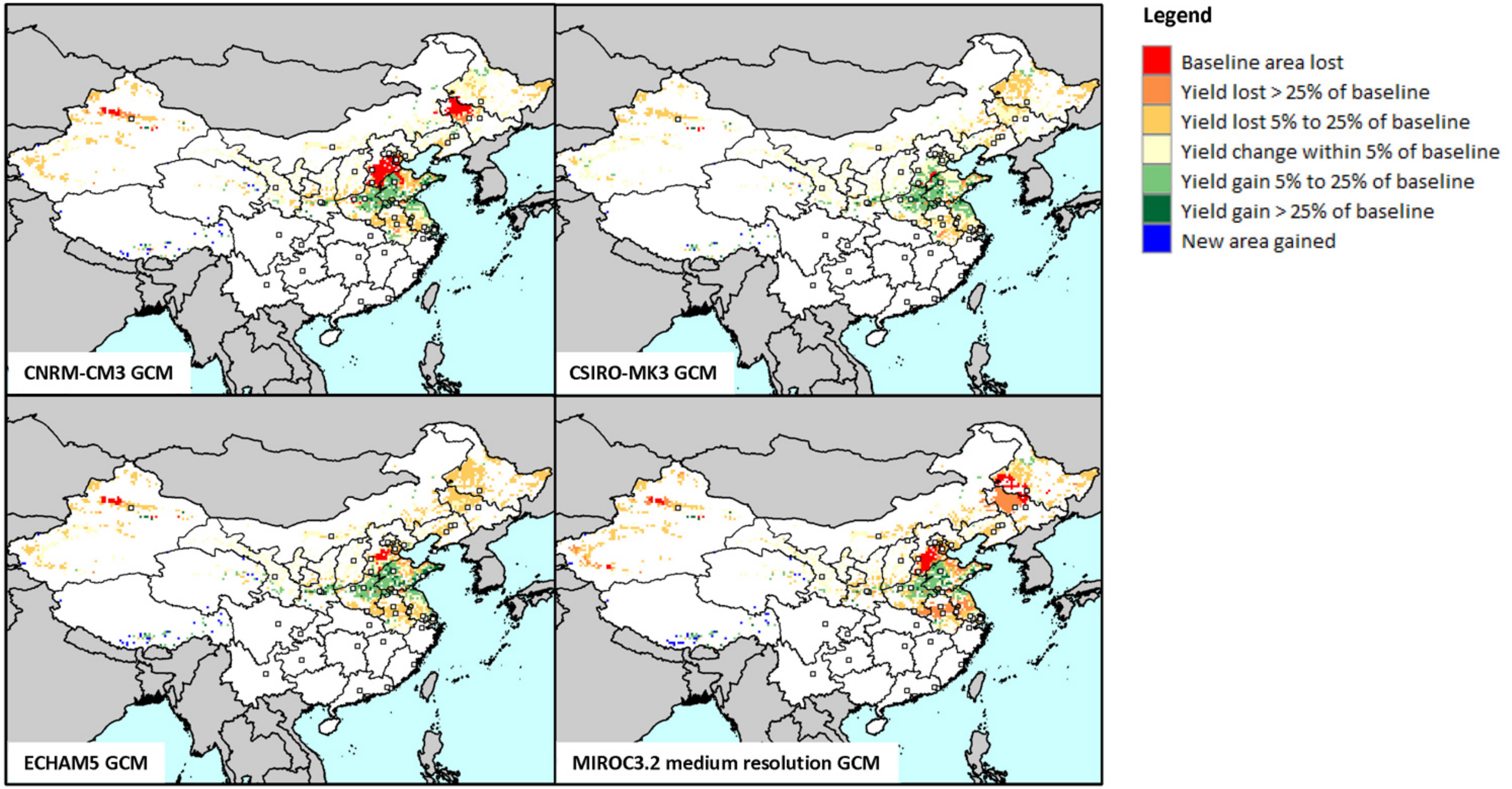
Source: SPAM Dataset.

Figure S4. Yield and harvest area density of rainfed rice in year 2000



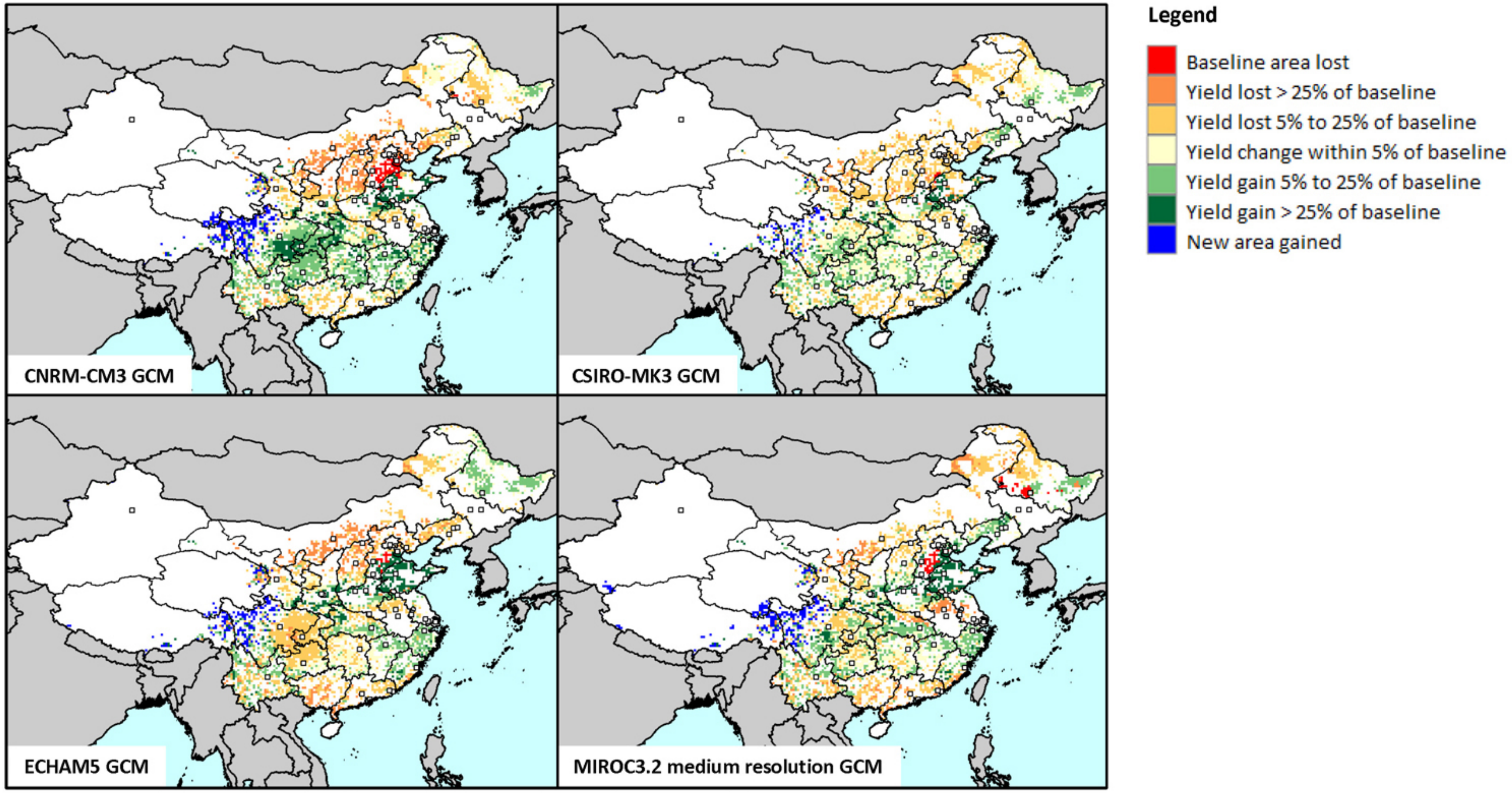
Source: SPAM Dataset.

Figure S5. Yield change between 2000 and 2050 under four climate change scenarios: irrigated wheat



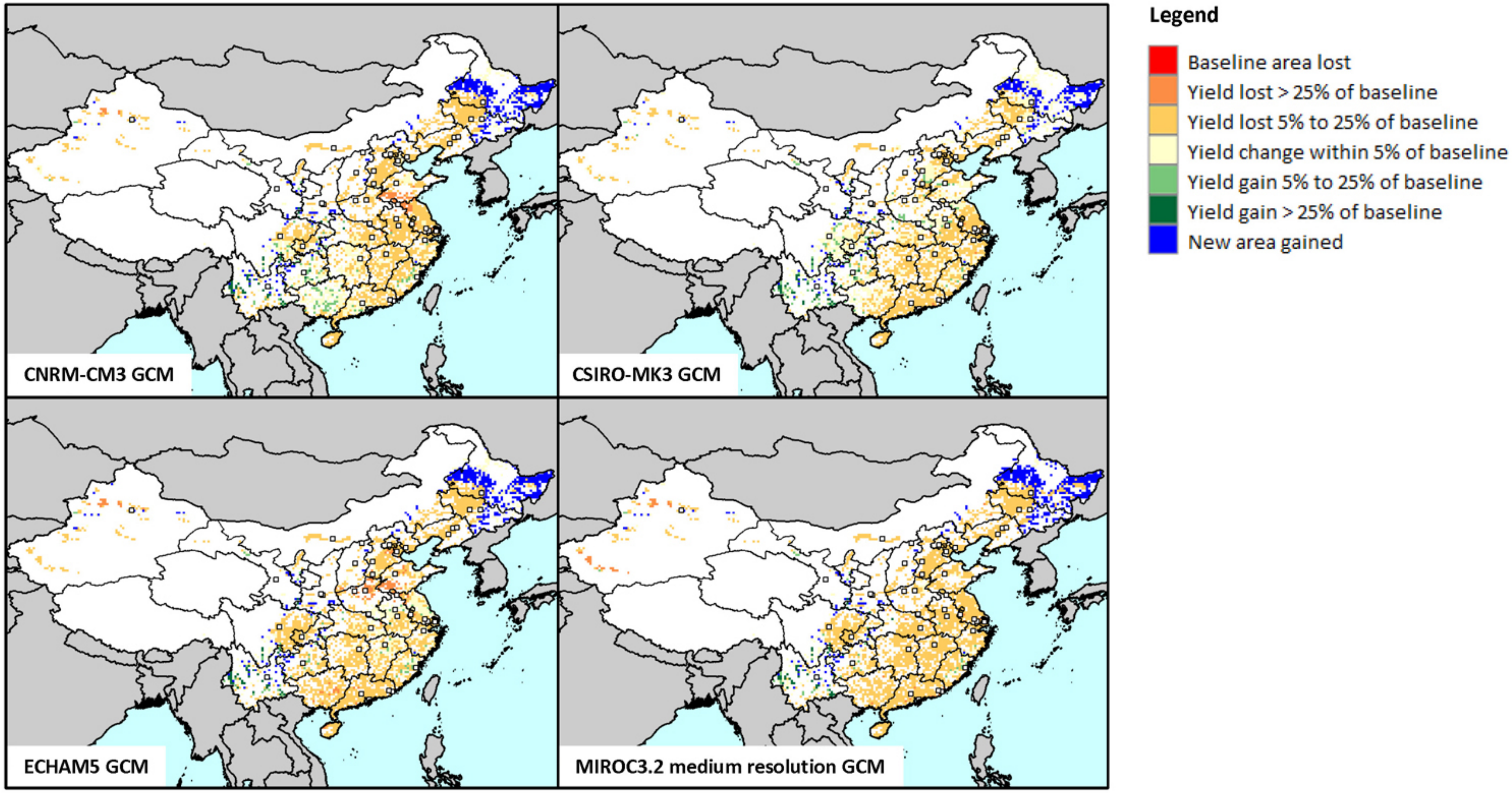
Source: IFPRI calculations based on downscaled climate data and DSSAT model runs.

Figure S6. Yield change between 2000 and 2050 under four climate change scenarios: rainfed wheat



Source: IFPRI calculations based on downscaled climate data and DSSAT model runs.

Figure S7. Yield change between 2000 and 2050 under four climate change scenarios: irrigated rice



Source: IFPRI calculations based on downscaled climate data and DSSAT model runs.