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**Integrated Model Development for the Assessment of
Food Security in China Related to Climate Change and Adaptation**

A thesis
submitted in fulfillment
of the requirements for the degree
of
Doctor of Philosophy
at
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by
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Abstract

This thesis developed a practical methodological framework, which integrated the bio-physical and socio-economic processes within the food system across different scales. The framework provides a useful tool for the assessment of food security and possible adaptation related to climate change. It was applied in China, a country with rapid economic growth and a large population, in order to evaluate multiple dimensions of food security related to climate change and socio-economic development in the future.

In the framework, an improved bio-physical crop model was coupled with an improved food economic model by scaling up from the farm level to the national level. The bio-physical crop model was developed from the site-based Decision Support System for Agrotechnology Transfer (DSSAT) model in order to investigate the impacts of climate change on physical production of a crop only related to environmental factors. The food economic model was developed from a partial equilibrium economic model, China's Agricultural Policy Simulation Model (CAPSiM). This was done in order to simulate the response of a socio-economic system to the negative consequences on a food economic system from the bio-physical change in crop production due to climate change.

Case studies of China and the Jilin province were investigated by applying the framework. The impacts of climate change on yield and phenology of maize under multiple greenhouse gas emission scenarios were studied at provincial and national levels in three time periods, 2020s, 2050s, 2070s, using the improved bio-physical crop model. In general, maize yield reduction due to climate change ranges from -3% in 2020 to -14% in 2070. The worst yield is -20.5% in 2070 produced under the

A1FI scenario. Food security for China until 2050 was projected under multiple climate change and socio-economic scenarios by using the food economic model, and analyzed with respect to food availability, food price and the system resilience to sudden disasters. Modelled climate change impacts on food availability in this study are minimal, producing only a 23 Mt (~8%) gap between supply and demand for maize by 2050. The socio-economic system will compensate for the impacts of climate change on the self-sufficiency of grains by about 8% of total production for the whole country. The impacts on single grain would cause the prices of other grains to rise in future. The effectiveness of potential adaptation measures was assessed quantitatively at both farm and national levels. Uncertainties among different scenarios are discussed for China and the Jilin province.

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R. I. P.

Abbreviations

CAPSiM	China's agricultural policy simulation model
CC	Climate change
CIF	Cost, insurance, and freight
CPI	Consumer price index
DSSAT	Decision support system for agrotechnology transfer
EU	European Union
FAO	Food and Agriculture Organization
FAPRI	Food and Agricultural Policy Research Institute
FOB	Free on board
GDP	Gross domestic product
GECAFS	Global environmental change and food systems
IMF	International Monetary Fund
mm	millimetre
Mt	Million metric tonnes
MOA	Ministry of Agriculture, China
NAFTA	North American Free Trade Agreement
NBS	National Bureau of Statistics of China
OECD	Organization for Economic Co-operation and Development
RMB	Ren Min Bi (Yuan, Chinese currency)
SRES	Special Report on Emissions Scenarios (by IPCC)
t, ton tonne	Metric tonne, 1000 kg
USD	U.S. dollar
USDA	U.S. Department of Agriculture
WTO	World Trade Organization

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Chapter 1 Introduction and Background

1.1 Introduction

This thesis concerns the impacts of climate change on food security and the corresponding optional adaptations. The aim of the thesis is to develop an integrated assessment framework to combine the effects of bio-physical and socio-economic factors involved in food security and climate change. A case study was carried out for China's food security assessment using maize as the key crop. On the bio-physical side, the impacts of climate change on maize production were analysed by using a spatial-explicit crop model at provincial and national scales. On the socio-economic side, the responses of the national grain market to those impacts were simulated by a partial equilibrium food policy-economic model on major food products. For comparison purposes, scenarios of vital features in relation to national food security, e.g. grain supply-demand balance and grain prices, were developed with and without consideration of climate change impacts. Adaptation options to climate change are also discussed at both farm and national levels.

In Chapter 1, the research associated with impacts of climate change on agriculture and food security is reviewed, as well as the methods in the integrated assessments of impacts of climate change and the models simulating the bio-physical process of crop production and the agricultural economic system. Based on the literature review, several questions are posed for the integrated assessment of food security under climate change in this thesis.

In Chapter 2, the historical path of food security in China and the challenges brought by climate change and economic growth are reviewed. The methodology for

integrating the bio-physical and socio-economic processes of food systems associated with climate change is then introduced.

In Chapter 3, the improved version of the DSSAT model for simulating the bio-physical process of crop production for spatial studies is introduced.

In Chapter 4, the impacts of climate change on maize were projected using the improved DSSAT for the case study of Jilin, China, and the effects of potential adaptation options are analysed at farm level. Uncertainty among different climate change scenarios is discussed.

In Chapter 5, the impacts of climate change on maize simulated by the improved DSSAT are discussed for the whole of China. The regional difference and uncertainty are then addressed by province.

In Chapter 6, the partial equilibrium model for simulating the food economy and policy is introduced in detail. Assumptions and constructing data for the model are described.

In Chapter 7, food security of China in the next few decades is analysed with respect to three dimensions. The risks brought by climate change to food security and potential adaptations at the national level are discussed. Uncertainties among climate change and socio-economic scenarios are also considered.

In Chapter 8, the main findings and projections are summarised and future research areas are suggested.

1.2 Background

Food security is one of the basic needs of human beings and is essential for a sustainable economic world. The relationship between climate change and food systems is manifold because of the complicated interactions among climatic, environmental, social and economic aspects. Against the background of accelerating global climate change, the study on food security assessment in China, which has the largest population in the world, has a special significance in terms of regional socio-economic development, as well as making contributions to the climate change scientific research field.

1.2.1 Food security: definition and measurement

There are several of meanings of the term “food security” in the literature. Commonly, food security is used to describe whether a country, community, or household has enough food to “satisfy” its members’ demand. However, the term food security has a much richer meaning than this when we further question on how easily and to what extent people are satisfied. Usually, it merely addresses the capacity of domestic food supply, which is the physical availability of food without taking into account its economic availability governed by market prices. At the household and individual scale, food nutrition and preference also need to be considered as the vital components of “security”, which the narrow definition of food security fails to cover.

A comprehensive definition of food security was given by the Food and Agriculture Organization (FAO) in the World Food summit in 1996. It stated that “*food security exists when all people, at all times, have physical and economic access to sufficient, safe and nutritious food to meet their dietary needs and food preferences for an active and healthy life*” (FAO, 1996). This definition requires the security not only for individual or household but also at national, regional and/or global levels, as well as the satisfaction in both food quantity and quality.

Based on the FAO’s definition, the international research programme of Global Environmental Change and Food Systems (GECAFS) suggested that food security could be measured by three dimensions (GECAFS, 2006):

- food availability, with the elements related to production, distribution and exchange
- food access, with the elements related to affordability, allocation and preference
- food utilization, with the elements related to nutritional value, social value and food safety

The stability of these three status variables is also an essential measurement in the assessment of food security. Food stability indicates that a population, household or individual should not risk losing access to food from sudden shocks, e.g. the economic or climatic crisis, or cyclical events, e.g. seasonal food insufficiency (FAO, 2007a).

In the 2010 special issue on food security in *Science*, Barrett (2010) suggested to divide the security in supply and demand side separately. In his article, several other indicators of food security besides the three aspects mentioned above were summarized and proposed, including inter- and intra-household food distribution, the food preference and values due to socio-cultural reasons, the employment status, coping capability to insufficiency, food diversity, the different demand among all age groups, and the spatial patterns and trends of food security. The food insecurity was

thought to be associated with disasters, which act locally and are therefore not captured in aggregated food availability .at the national level

In the review of Schidhuber and Tubiello (2007), the authors discussed and assessed opinions about the measurements of food security. They suggested that the three dimensions of food security based on the FAO concept have a number of advantages, especially in practice: the three dimensions have clear meaning and are easily calculated, and the data and parameters required are available, easily obtained, and consistent in history.

1.2.2 Food security and climate change: fact and opinion

Scientific research and observations have provided more and more evidence of global warming and climate change over the world: the average surface temperature is likely to increase by about 1.1 to 6.4 °C between 1990-2100, and the warming trend is projected to accelerate (IPCC, 2007a); even with a high uncertainty, climate variability is also predicted to increase, especially extreme weather events will become even more extreme and/or frequent (IPCC, 2001b; Knutson & Tuleya, 2004; Meehl et al., 2000). As a result, the global environment has been experiencing a broad range of impact from such changes, such as fresh water scarcity, land use and cover change, sea level rise, ecological degradation.

As one of the important driving forces, the changes in climatic and environmental systems have various influences on food security:

The physical production process of crop and livestock will be affected by the changes in temperature, water availability, CO₂ concentration, and climate variability.

Increases in temperature affects the plant bio-physical process (Lin, 1996; Scherm & Van Bruggen, 1994), changes growth seasons at different latitudes (Chmielewski, et al., 2004; Chmielewski & Rötzer, 2002; Tucker et al., 2001), and alters the distribution of agro-ecological zone shifts towards poles (Rosenzweig & Hillel, 2005). The direct impact of temperature on crop productivity varies in agro-ecological zones depending on the differences between the initial environmental temperature and the optimal temperature for crop growth (Kurukulasuriya & Rosenthal, 2003). The direct impact on productivity in the livestock sector will be more frequent incidences of heat stress (Nienaber et al., 1999; West, 2003) and the increased risk of animal diseases due to warmer temperature.

The results from observation and modelling research indicate that the warming trend would also lead to increasing surface evaporation which changes soil moisture conditions and accelerate both seasonal and inter-annual hydrological cycles (Frei et al., 1998; Huntington, 2006; Kattenberg et al., 1996), and the transpiration from crops is increasing as well. That leads to a change in the pattern of precipitation, and thus water availability for agriculture may decline. Estimations indicate that the annual global evaporation from food production regions would double in the coming 25 to 50 years (Postel, 1998; Rockström, 2003). In the semi-arid regions like the western areas of Jilin province in China, field experiments show that the periodic water deficits for crops could be more than 200mm, resulting in low yield in rain-fed dryland (Qu et al., 2005). In the northeast and north China the effect of water stress on rain-fed crops could increase to about 65% in coming decades because of the expected increase in soil-moisture deficit and the decrease in precipitation (Tao, et al., 2003b). Even the relatively water-rich areas would face the decline of reliability of obtaining water because of the potential large changes in water demand from climate change impact on agriculture (Rosenzweig et al., 2004). Hence the irrigation requirement for food production, which is the dominant withdrawal from rivers and aquifers (Gleick, 1993), will face with the major challenge for future grains supply and agricultural freshwater management (Postel, 2003; Rockström et al., 1999).

On the other hand, the rising CO₂ concentration will increase photosynthesis rate and improve water use efficiency of crops by reducing evapotranspiration. However, the net result may be moderated by an increase in weeds at the same time. Numerous studies have been conducted to estimate such agronomic effects on crops and grass productivity (Amthor, 2001; Fuhrer, 2003). Although observations of an increase in rapid production throughout the world might be explained by the carbon fertilization effects, the impacts of rising CO₂ concentration on crop yields are still uncertain (Kurukulasuriya & Rosenthal, 2003).

Climate variability and extremes are often associated with an intensified hydrological cycle. Water resources for irrigation are likely to be more variable or even sharply reduced. This would exacerbate the already existing water crisis, especially in arid and semi-arid regions (Rosenzweig et al., 2004; Burton, 2001), such as the farming-grazing transition zones in northeast China. The climatic deviations are likely to induce more frequent incidence of pests and diseases, which would damage crop (Rosenzweig et al., 2001) and livestock production (Darwin et al., 1995; Sirohi & Michaelowa, 2007). In addition, increases in rainfall intensity can lead to higher rates of soil erosion (Molnar, 2001) and leaching of fertilizer chemicals, resulting in soil degradation.

Climate and environment changes would also influence the economic dimension of food production, which is tightly associated with production and adaptation practices.

Extra inputs and investments might be required to maintain current normal cropping in the food system. More fertilizer and pesticides will be used due to increasing decomposition rate and pest disease risk under higher temperature (Rosenzweig & Hillel, 2000, Reilly, 2003). Increasing investment for construction and operation of agricultural infrastructure is also required to offset the more frequent and intensive disasters (FAO, 2007b). For a better response to future

climate conditions, investment in breeding, variety selection and improvement of facilities are also expected to increase. The availability of natural resources crucial for food production are threatened by the climate-change-induced environmental change, such as losses in arable land (Barton et al., 2004), and thus demands more effort for effective natural resource management.

In general, the crop production in tropical and subtropical areas is more likely to suffer from unfavourable conditions due to droughts, while poleward regions where agriculture is currently limited by the short growing period might benefit (IPCC, 2001a, 2007b). Global assessments of the climate change impacts on agriculture have reported that the whole loss ranges from -2.5% to -0.7% in terms of food supply and from -0.047% to 0.010% in terms of agricultural welfare in the case of a doubling of CO₂ concentration, employing either simplified or complex adaptation processes at national or global scales (Fischer et al., 1994; Harasawa, 2003; Kane et al., 1992; Reilly & Schimmelpfennig, 1999; Schimmelpfennig, 1996). Regionally, the results derived from diverse climate scenarios demonstrate a range from severe negative effects to potential increase in yield, and the welfare changes between -5.48% and 2.73% (Bosello & Zhang, 2005; Matthews, 1997; Parry et al., 1999; Parry et al., 2004). The impacts at sites also vary widely within a region, particularly for countries with vast territories, such as the United States (Adams et al., 1999; Adams et al., 1995) and China.

With regard to China, simulations (see Table 1-1) from both global and regional studies indicated that impacts on China's food production could be significant. Studies from the crop responses to different levels of CO₂ concentration, heat stress and water use in specific sites or regions, based on crop model simulation and field and chamber experiments, indicated that crop yield depends more heavily on water constraints than on other agro-meteorological factors (Bai & Lin, 2003). Significant differences in projected yield derived from different crop models were found between irrigated and rain-fed regions, especially in the north and northeast plains

(Sun et al., 2005; Xiong et al., 2005), and the limitation in water availability would be of utmost importance for future enhancement of crop productivity in China. Heating benefits gained from increasing temperature would be offset in the north-eastern region, if sufficient irrigation could not be guaranteed during the dry season (Jin et al., 1994; Wen et al., 2005). Some researchers believe that water availability is the primary reason for the fluctuation in grain production (Hu, 1998; Shi, 1997). The model simulation also suggested that incremental climate variability may cause a considerable decrease in wheat yield in north China (Chen et al., 2004). The changing climate variability in future could reduce crop productivity, e.g. in maize (Wang & Lin, 1996), and hence affect the stability of food security.

Table 1-1 Impacts of climate change on food production in China: simulations under SRES scenarios.

	Impacts on crop productivity (% change)				Impacts on welfare (% change)
Kane et al. (1992)	-20 ~ -10%				1.28 ~ -5.48 %
Tsigas et al. (1997)	-17% without CO ₂ fertilizer effect 3% with CO ₂ fertilizer effect				-7.23% without CO ₂ fertilizer effect 0.54% with CO ₂ fertilizer effect
Parry et al. (1999)	-2.5% ~ 2.5%				
Harasawa et al. (2003)	Rice	Wheat	Other grains	Other crops	-0.21%
	-0.25%	-3.97%	-1.39%	0.07%	
Parry et al. (2004)	-30 ~ 0 % without CO ₂ fertilizer effect -5% ~ 10% with CO ₂ fertilizer effect				
		Rice	Wheat	Maize	
	with CO ₂ fertilizer effect	-2.9% ~ 7.8%	4.5% ~ 40%	-2.2 % ~ 20%	
Lin et al. (2005)	without CO ₂ fertilizer effect	-28.6% ~ -1.1%	-21.7% ~ -0.5%	-36.4% ~ 0.2%	

The impacts of climate change on the food system involve food production, and distribution and consumption processes that are critical for effective food access and utilization. Food production is the basis of food availability. However, food security also depends on food access and food utilization. The climate change impacts on food access and utilization are influenced by the uneven changes in climate systems and the disequilibrium in socio-economic systems among regions.

The state of food access mainly depends on food affordability and allocation (GECAFS, 2006). With a potential increase in costs for food production and storage, lower-income groups in both rural and urban areas would face higher risk of inadequate access due to unaffordable pricing during a long period, e.g. studies by Parry et al. (1999; 2004). Simulating global crop production and international trade processes under SRES scenarios, the substantial increases in risk of hunger in poorer nations in future would not only result from regional differences in crop production, but also from economic barriers. The effective access to sufficient food depends on adequate income of households, favourable market infrastructure and affordable price, as well as on physical factors (GECAFS, 2006). The regional difficulty in food supply for a period characterized by unfavourable weather and the inter-regional exchange of different staples among crop belts would put more pressure on transport systems, while climate change would place a further strain on transport infrastructure (IPCC, 2001b). For example, warming climate conditions are expected to reduce the operational lifetime of infrastructures and in turn increase food price, with storms hampering normal circulation of goods (Perry & Symons, 1991, 1994).

Food utilization involves how food is used and processed within households, and the diversity of food consumption (GECAFS, 2006). Since food is produced and consumed locally in many developing regions, food utilization changes with the seasonal climate variation, e.g. there would be copious quantities of food supplied in harvest season, while in the rest of the year food consumption would be reduced due to lower food availability. If droughts or floods occurred in the harvest season, the usual balance of nutrition would be affected through the year as well. Meanwhile, agricultural communities in such regions are also the victims of unstable cash flow and in-kind income. The fluctuation of crop production within one year or between years could lead to reduced purchasing power for food. Therefore the instability of food access and utilization often occur together in this situation varying with inter-annual climate change.

In addition, the coping strategies for other purposes, such as attempts to reduce carbon emissions, would affect food consumption in an underlying manner by rigorously competing for limited capital and natural resources. The promotion of bio-fuels extracted from crops in the United States has a great influence on grain consumption as food resource by causing fluctuation of maize prices in international markets (Blythe, 2007; Cassman, 2007). The interruption of the normal global food trade, which is one of the important options for alleviating shortage of regional food supply, could put regional food access at risk.

1.2.3 Food security and climate change: methodologies and modelling

In the past decades, scientists have made significant advances in modelling in fields related to food security assessment. According to different methodologies, former modelling exercises appear two directional, which can be called the “bio-physically oriented” and “economically oriented”. The first category stresses the ecological and biological sides of crop response to climate change, while the other strand of studies concentrates on the economic mechanism in food systems oversimplifying the natural processes in the food system. However, with the development of computer capacity and software flexibility, larger and more complex modelling frameworks have been built, decreasing some of the boundaries across multi-disciplines. Such integrated assessment models (see Table 1-3) serve to incorporate climatic and environmental conditions, crop growth information and socio-economic situations in a balanced and coherent manner, enabling either a bottom-up exercise by developing sub-models, or a top-down analysis of the overall picture of the system.

In an integrated model system, sector-specific methods and models should be considered at first. An integrated model system for food security assessment taking into consideration climate change and adaptation at least requires crop models for estimating potential food productivity, food economy models for describing

distribution and consumption processes, and a component for describing the responses of the human dimension. The methods and models for simulating crop responses, the food economy and human responses will be discussed in the following.

Treatment of crop response:

1) In terms of scaling direction, there are two categories of methods to describe the changes in crop production under different climatic conditions.

In the top-down approach, which is based on the spatial analogue assumption (which means there is no variation of relationship of climate and crop productivity over relatively large regions), crop productivity is not simulated directly by modelling physiological processes, but is derived statistically by observations at different latitudes or in different periods of a year. The differences in observed yield of the same crop between latitudes and periods could be considered as the crop reaction to changes in climatic conditions (Darwin, 1999; Mendelsohn et al., 1994). However, the representativeness of data used and the ability of statistical tools for this spatial analogue method could be problematical (Schimmelpfennig et al., 1996).

Since they employ different indicators, the predictions produced by bio-physical process based models usually are different. Statistical models are thought to be an alternative tool to provide systematic evaluation of model performance, by just using historical yield and simplified weather variables. Lobell & Field (2007) developed a series regression model of crop yield from FAP statistical database and gridded temperature and precipitation from CRU climate database. Their models showed good capabilities to simulate the inter-seasonal variability of yield, but poor relationships of the aggregated data. Applying the models, a full probabilistic study of crop yield responses to changes in temperature, precipitation and CO₂ were done for wheat, maize, barley under SRES A1B scenario (Tebaldi & Lobell, 2008). Lobell &

Burke (2010) also assessed the agreement between CERES-Maize and three kinds of statistical model (time series, panel, and cross-sectional) in Sub-Saharan Africa under two special climate change scenarios. The statistical models based on multiple-site training performed better than the CERES-Maize in simulation of a large spatial area.

For the bottom-up approach, it is basically grounded on the bio-physical crop model simulating the actual growth process providing a site-based yield, then using different up-scaling methods to form the geographical differentials. One solution is projecting the potential crop distribution by the vegetation distribution model, e.g. MAPPS (Neilson, 1993, 1995), and the LPJ model (Criscuolo et al., 2003). This kind of model is usually ecologically based, and can give the potential crop distribution taking both the climatic variables and soil conditions into consideration. This method is widely used for estimation of the crop production changes in a particular region in assessment studies (Adams et al., 1999; Adams et al., 1995). Another aggregation method relies on results from land use and land cover models. The consideration of soil conditions depends on availability of a consistent soil database. Some studies (Parry et al., 1999; Parry et al., 2004) used the agro-ecological-zone analysis, while other assessments consider the yield without employing aggregation (Alcamo et al., 2007). These methods only capture more average changes for larger scales, and also ignore the possible consequences from farming practices. For more reasonable regional food supply estimations, the effects of farm management and the economic factors need to be added as potential modification factors.

The bio-physically based crop growth models explicitly describe how a given vegetal specimen grows and reproduces when external climatic variables change with the plant physiology models. Such kinds of models have been developed from the primary individual plant model that has its specific structure for a crop, like the CERES family models (Ritchie et al., 1989; Godwin et al., 1989), and SOYGRO (Jones et al., 1988), to crop template models, like the CROPGRO (Boote et al., 1998). Some systematic frameworks, like DSSAT (Jones et al., 2003), incorporating those crop

growth models with proper cropping practices, could simulate the cropping process under approximately realistic conditions, contributing to better decision in field management. Another example is the GLAM model, a general large-area model, developed by Challinor et al. (2004). It is based on large spatial scales rather than the farm or plot scale. So the parameters of GLAM are simpler than the DSSAT group models. Challinor's group using this model studied impacts on crop yield in the tropics (Challinor & Wheeler, 2008; Koehler et al, 2013), the crop genotypic responses to temperature change (Challinor, 2007), and the probabilistic forecasting of crop failure due to uncertainties in climate change. Foley et al (1998) developed a method to simulate climate-vegetation feedback mechanisms, coupling a GCM (General Circulation Model) model, GENESIS, and a dynamic global vegetation model, IBIS. Resorting to the coupling method, they assessed the feedbacks of the vegetation cover and net primary productivity and climate variables, evaluating the carbon cycle of atmosphere-biosphere system (Delire & Foley, 2003).

This group of methods and models can provide the bio-physical productivities of different crops under given climatic and environmental conditions as the initial estimation of yields for further projection of total crop production.

2) In economic-based models, such as IMPACT-WATER (Rosegrant et al., 2005), the crop yield is estimated with respect to rain-fed and irrigated land, with the inherent assumption that water stress is the primary natural constraint on yield. In the CAPSiM model (Huang & Li, 2003), the weather or climate variables are not directly considered, and only the statistical erosion and salinization as the endogenous terms in supply-side equations are used.

Treatment of the economic dimension:

For food supply-demand projections, many economic models have been developed, including partial equilibrium agricultural sector models (also known as macro food economy model), general equilibrium economic models (GEMs), and the international trade simulation system (e.g. IIASA BLS used by Parry et al., 2004; 1999). Although there is a trend in usage from partial sectoral to general equilibrium in recent economic assessments (Bosello & Zhang, 2005), the partial one which is powerful in simulating the substitute process within agricultural sectors and is also characterized by its high disaggregation of crop varieties, is still the optimal frame for food security projection.

The classical model for macro food economy is usually operated in a basic structure with balance between food supply and demand at national or international level. The amount of production and consumption depend on endogenous variables, such as prices of agricultural products, and exogenous variables that could be the shocks from natural systems (e.g. climate variation) or from socio-economic systems (e.g. population growth and policy change). If the balance is broken by any changes in the variables, the price mechanics would drive readjustment in production or consumption until the system evolves to a new equilibrium condition. This partial equilibrium model cannot describe the responses and feedbacks from other economic sectors, such as the relocation of resource and capital. When labour migrates between sectors, it requires a special linkage to describe such cross-sector effects. Examples of such equilibrium models are shown in Table 1-4. Several studies have projected China's food supply and demand based on these models (see Table 2-1), and much research has contributed to comparisons of their assumptions, model structures, database and results (Barney et al., 1999; Zhang, 2003). The conclusions suggest that: a) the natural resource disciplines in economic models simplifying prices and substitution processes, and the alternative use of land and

water, need to be introduced; b) purchasing decisions are also important for final food balance, and more details are required in future food economic models.

The General Equilibrium economic Models (GEMs), which deal with the entire economic part with the optimal distribution of resources when the profit is maximized under perfect competition in all markets, are developed for analysis of international trade policy in the first instance, but could also be used to investigate the explicit results of economic fluctuations due to climate change. Kane et al. (1992) and Reilly et al. (1994) have studied impact assessment on global agriculture by using the SWAPSIM world food model. It is worthwhile noting that the national and partial equilibrium studies report higher impacts than global and general equilibrium studies. For one thing, the substitute procedure between agricultural and non-agricultural sectors and international trade effect smoothen the losses in a certain sector due to regional climate change. Another reason is that the general equilibrium models take account of the welfare of all the agents within the whole economic system, which means the losses of one agent would be balanced out by the gains for another, and the net effect is finally weakened. At the macro scale, the modelling work requires a much larger coverage in sectors of economy as well as a special consideration of effects of international market and trade as the background of regional analysis in terms of economy, and then at a more disaggregated scale the regional impacts of climate change would be incorporated. However, it is difficult to satisfy the large requirement of data in economy for these kinds of model.

An alternative method could be used to incorporate the extensive inter-sectoral effects into food production processes, such as the IIASA BLS framework, which is composed of 35 national level models for food with a particular module for food economy and a simplified module for the rest of the major economic sectors (Fischer et al., 1994; Parry et al., 1999; Parry et al., 2004). It should be noted that the national and partial equilibrium studies report higher impacts with respect to global and general equilibrium studies. The substitute procedure between agricultural and

non-agricultural sectors and the international trade effect smoothed the losses in a certain sector due to regional climate change.

The main emphasis of these economy modelling exercises is on predicting the total amount of food supply and demand, although the processes related to food access and utilization are not well discussed in detail especially the distribution and consumption. Some parts of the existing models indeed could be applied for access and utility assessment. For example, the division of urban and rural demand could detect the effects of different market infrastructure on food access, and a careful consideration of livestock production would help further assessment on food utilization. However, such descriptions on a large scale provide little information about local food security and are powerless in terms of local policy making and adaptation. Therefore, further efforts in the economic dimension should focus on developing modules for food access and utilization for the purpose of regional and local sustainable development.

Because of the difficulty in direct economic evaluation, the methods to incorporate the impacts of climate change on food balance into economic models are usually oversimplified, or not even considered. The simple treatment is to impose the changes in climatic-related variables as an exogenous shock onto the production function. For example, changes in land stock due to disasters, erosion, or salinization, could be added directly into the supply-side equations if the model structure permitted, like in CAPSiM.

Treatment of the human dimension:

The human dimension in this study mainly refers to the adaptation processes. Modelling the adaptation processes relies on two tools, one is a cost-benefit analysis tool to identify possible adaptation options and evaluate their costs and benefits,

and another is a decision making tool which usually consists of a programming decision function and proper rules.

Leary (1999) provided a cost-benefit analysis framework for policy making. Adaptation policies are evaluated with the assumption that future climates were known with certainty (see Table 1-2). At each scenario, the monetary measure of social welfare is calculated from all household welfare, and outcomes compared and ranked. Based on a utility function, social welfare can be transformed represented by money metric. By comparing the differences, the welfare changes in climate scenarios and adaptation policies can be obtained.

Table 1-2 An example of the cost-benefit analysis metric of different scenarios.

Adaptation Policy	Climate state	
	C0	C1
A0	Present climate	Altered climate
	Present adaptation policy	Present adaptation policy
A1	Present climate	Altered climate
	New adaptation policy	New adaptation policy

Another topic on human dimension modelling is also tightly associated with land and water resources management, which refers to land and water resource changes (mainly described by vegetation cover models and hydrological models) and land and water use (simulated by land and water use models).

Constant effort is devoted to simulating climate-related land use and land cover change in food production, leading to three approaches.

1) With the consideration of the fact that land has specific features in different locations due to different climate and soil properties, the form of production function within land use variables depends on the unique agro-ecological zone (Lee,

2004). However, the difference in land value within the agro-ecological zone cannot be identified by this 'climate-inside' method.

2) Instead of that inside method, a direct measure of changes in land value induced by climate variation is attempted and is based on the Ricardian approach with regard to the FARM-GIS system (Darwin, 1999), which, however, fails to fully control the impact of important non-climate-related variables that could also explain the variation in farm incomes. Its assumption of costless adjustment is likely to result in underestimating the damages or overestimating the benefits. The first two methods are both based on the spatial analogous concept.

3) The third possible solution is developed by assembling all the production and economic processes concerned into one autonomous land use model, which could simulate the allocation process of land resources, and this routine is preferred for integrated models, like the land cover in the IMAGE model (Alcamo, et al., 2007, 1998) and the land use management module in the IMPEL model (Rounsevell, 1999; Giupponi et al., 1998). The treatment of land use change is built on more realistic decision processes in this method in which the land resource allocation is determined by land demands and certain land use rules. In existing models, the decision rules are based on the qualified estimation of land values or classification, and the quantitative land value is further required to be included into such rules by estimating the economic value of the outputs from a certain type of land from the food economy models.

For water resource management related to food security, the common treatment of water use and hydrological process in an integrated model system is coupling to a special water model simulating both physical land hydrological processes and artificial water allocation and use, such as the WaterGAP model in the GLASS Model (Alcamo, et al., 1997, 2003b) and the WSM model in IMPACT-WATER (Rosegrant et al., 2005, 2002) for water availability and use. The water use module usually takes into account basic socio-economic factors that lead to domestic regional, individual,

industrial and agricultural water use, and estimates the water use balance, coupling water demand in specific sectors with so-called water supply that is derived from simulations in hydrological models or statistical estimations.

A number of studies contribute to water modelling and assessment both at the global and basin level. These take advantage of recent developments in hydrological science and system modelling technology, as well as the application of remote sensing at multiple scales for data collection, and provide a substantial basis for integrated basin management (PODIUM, IWMI), crop water modelling, and water scenario analysis (WEAP model, Raskin et al., 1992) for irrigation in agriculture. Liao (2004) considered the demand for irrigation due to the growth of grain production by coupling the CAPSiM and PODIUM models, a policy model for water distribution, and highlighted the regional food and water security in the north of China. However, this study only produced possible policies, and did not give further assessment of the applicability and efficiency. Because the modelling for water resource is usually based on river basin levels, the examination of the relationship between water availability and food supply needs an aggregated study at multi-scales. Recently, Gosling & Arnell (2011) proposed a new hydrological method to simulate the global river run off using the Macro-scale-Probability-Distributed Moisture model.09 (Mac-PDM.09). This method is able to produce daily runoff at grid level, a range of hydrological indicators, e.g. average annual and monthly runoff, the coefficient of variation of annual runoff, the annual runoff exceeded in 90% of years, and the parameters of a GEV (Generalized Extreme Value) distribution for annual maximum monthly and daily runoff.

Table 1-3 The frameworks of integrated assessment models and applicable modules.

Integrated system	Integrated scale	Objective	Components
GLASS (Alcamo, et al., 2007, 2003a)	National level	Estimate environment stress	IMAGE- climate driver; GAEZ; WaterGAP (hydrology + water use)
IMPACT-WATER (Rosegrant et al, 2005)	Regional/ river basin	Project food/water security	IMPACT (Economic based food balance); WSM (Semi-physical based water balance)
IMPEL (Rounsevell, 1999)	Regional	Predict land use	EuroSCEN(climate baseline generator); Access (soil-crop process); Impeleuro(land degradation); Land use management module
SIM (Krol et al, 2006)	Regional	Water scarcity in semi-arid area	Hydrological dynamic model; Empirical crop yield function; Agro-economy described by mathematical optimization;

Table 1-3 The frameworks of integrated assessment models and applicable modules (continued).

Agricultural/crop modules	Scale	Features
GAEZ (Fischer et al, 2000)	Global	Agro-ecological zone approach based
DSSAT (J. Reilly et al., 2003; Tsuji et al, 1994)	Site-based	Bio-physical based crop models; uniform soil module; cropping practice supported
AVIM (Ji, 1995)	Site-based	Bio-physical and dynamic; explicit boundary-layer-dynamic process
EuroAccess (Giupponi et al, 1998)	Site-based	Bio-physical and dynamic; explicit soil process (water & nutrition exchange)
LPJ (Sitch et al 2003)	Site-based	Using 10 plant functional types modelled by the rules used in equilibrium biogeography models
GLAM (Challinor, 2004)	Large area	Median complex process of crop growth, simplified for large areas, fixed parameters for sub-regions,
EPIC (Williams et al, 1983)	farm level	Featured soil water process and soil erosion; long-term projection capability
Water Modules	Scale	Features
SWAT (Arnold et al, 1998)	River basin level	Physical based (water exchange, physical/chemical process in soil, crop chemical process); with land use scenarios;
WaterGAP (Alcamo et al, 2003b)	Global	Hydrological module (explicit geographic solution); Water use module (scenario-based/sector-based use intensity)
SWAP (Kroes et al, 2000)		one-dimensional physically based; transport supported; simple interaction with crop growth
Mac-PDM.09 (Arnell et al, 1999)		Physical based; macro-scale; probability distributed; calculated on grid level
PODIUM (IWMI)		Scenario (with respect crop, cultivating pattern) based; limited physical process;
WSM (Rosegrant et al , 2005)		Water supply (limited physical process); water demand
WEAP (Raskin et al, 1992)	River basin level	Water allocation at river basin scale; limited physical process
Economic modules	See Table 1-4	

Table 1-4 Comparison of the macro-partial equilibrium model of the agricultural sector.

Model	Scale	Features	Parameter	Equations	
				Supply	Demand
CAPSiM (Huang & Li, 2003)	National	Partial equilibrium; 12 crops, 7 livestock	Economically estimated	Sown area(Input/output prices; climate & other shocks) Yield (Tech; irrigation; erosion; salinity; ect.)	Food (urban; rural),Feed, Seed, Industrial, Waste
IMPACT (Rosegrant et al, 1995)	National	Partial equilibrium; 35 countries and regions; 17 commodities	Synthetic	Harvested Area (crop prices; harvested area changes) Yield (input/output prices; tech trend)	Food, Feed, Industrial
OECD model (OECD, 1995)	Provincial	Single equation; 30 provinces; 5 major crops	Synthetic	Given assumed Area/ Yield change trends	Food, Seed, Loss (The change rates are assumed from basic level and empirical)
CPPA (USDA ERS, 1994, 1997)	provincial level for China	Partial equilibrium, separated urban & rural demand; 6 region; 34 commodities	Economically estimated	Cropping area (expected prices; expected yields), Yield (trend, input/output prices, research stock, irrigated area)	Food, Explicit Feed, Other demand

Table 1-4 Comparison of the macro-partial equilibrium model of the agricultural sector (Continued).

Model	Scale	Features	Parameter	Equations	
				Supply	Demand
World Grains Model_World Bank (Mitchell et al., 1997)	National	Partial-equilibrium net trade model Wheat, rice, and 7 coarse grains; All sectors demand; 15 countries+9 regions	Economically estimated	Revenues(t-1), ending stock(t-1), trend→Total cropland harvested, commodity revenue(t-1), trend→Harvested area	Trend of total food consumption, net import, and stock
WB_Nyberg Model (GTAP+ water constraints model, Nyberg, 1997)	Global	General equilibrium economic model consideration of climate change (FARM), water constraint; 45 regions; 7 agricultural commodities, and non-food products General equilibrium economic model; world level; 35 regions; annual increment; 9 aggregated agricultural commodities and 1 aggregated non-agricultural commodity	Synthetic (income elasticity derived from function CDE)	Production (calculated by economic factors, i.e. land, labour, and physical & human capital; resources constraints factors; technology change factor, i.e. TFP), and yield growth rate (calculated by water constraints)	Food, feed, seed, and waste
BLS (Parry et al, 1999)			Synthetic	Supply does not adjust instantaneously to new economic conditions ;Yield modelled by only by fertilizer application	Food, feed, and net import; imposed consistent financial flows

1.3 Problem and Objective

1.3.1 Problem statement

In this section, the issues from existing research are discussed, and the research demands are addressed.

Climate change is a global phenomenon, but the impact and the associated adaptation measures take place locally. Hence, regional and local research is required to support adaptation assessment for regional and local benefits. The wide range of conclusions in global assessment studies mainly provide a direction for long-term strategy, but have limited use to reveal the short-term climate change impacts on food production, which is essential for adaptation policy making. Therefore, analyses of potential impacts in the next 10, 20, or 50 years need to be taken into account urgently as well as those over the next 100 years.

Climate change impacts on food security are reflected in both bio-physical and socio-economic dimensions. An explicit description of bio-physical processes of crop growth models under actual climate change over time is the basis at regional and local scale. In order to address the impacts of the economic dimension, it is necessary to consider farmers' responses to deal with different adaptation options at multi temporal and spatial scales, such as the long-term agricultural policy at regional scale, short-term cropping practice at farm level, and long- or short- term disaster-resisting activity.

Temperature, precipitation, and water availability are the most critical factors for local crop productivity. So far, most researchers have been focused on the food availability due to the biophysical consequence of climate change impact. For

example, for the case study in Jilin province, it is necessary to pay attention to water stress on crop growth.

Compared to studies in food availability, fewer quantitative assessments have been conducted to investigate climate change impacts on food access and utilization, which are critical indicators of regional and local food security. Interactions among multi spatial and time scales in food access and utilization need to be highlighted. Analysis tools are required to capture the quantitative information with respect to regional and household levels, such as changes in income and food consumption pattern due to inter-annual climate fluctuations, and allocation changes of food products at regional scale due to shifts in agro-ecological zones in the long term. To assess food utilization, it is necessary to model the changes in dietary and consumption structure due to income increase or other prices or non-price drivers.

In contrast to climate change scenario that has model projections for this whole century, the projection period of economically-oriented studies is usually 5-20 years in steps of 1 year or 5 years. Therefore, the future focus of the projection period, considering the duration of adaptive practice, might range from 5~20 years, and for policy flexibility, to 20~50 years for long term change in natural factors.

In terms of spatial coverage, studies on Chinese food security, generally aim for macro policy for national benefits, ignoring the effects at regional and local level. The food insecurity for impoverished groups of population in specific regions, such as agriculture-dominant and environmental vulnerable regions, should be highlighted for the local capability building and sustainable development with strengthening resilience against increasing risk due to climate change.

In terms of uncertainty, the risk existing in scenario development and in modelling structure should be further analyzed, especially when adaptation strategies are taken into consideration. The climate system is inherently uncertain; hence the

climate change projections are characterized with high uncertainties. In addition, the socio-economic projections and any economic model results also involve uncertainties, since there are many empirical assumptions on both economic parameters and processes. It is important to discuss the range of uncertainty in impact assessments to support the decision-making process in relation to adaptation. On the farm level, it is possible to use the risk analysis of climate change impacts on the crop yield or production to investigate the uncertainties among climate change scenarios. On the national level, an analysis of potential range of projections coupling climate change and socio-economic scenarios could be examined in order to tell the policy makers the possible best and worst status of food security in future.

Numerical studies assessing the impacts of climate change reflect the qualitative effects of adaptation, the empirical studies investigating adaptation behaviours suggest the possible adaptation options under the given situations, and the theoretical studies that build conceptual frames of adaptation provide the general rules to assess the adaptation. However, there is still a research requirement to evaluate the costs and benefits of adaptation options quantitatively to support efficient decision-making and effective adaptation.

To assess the possible adaptation options in a quantitative manner, not only estimations of the costs and benefits are necessary including the analyses of the effects of such options in the short and long terms, but also considering the uncertainties in climate change under different scenarios.

Current efforts mainly attempt to cope with the stresses in the short-term in an immediate manner, i.e., crop switching to reduce the vulnerability of crop production to water shortage, but little attention has so far been devoted to the options for sustainable development in the long term.

More systematic treatment of adaptation activities across scales should be particularly concentrated on, such as how will the regional land use options affect the farmers' land use strategies, and how will the changes in water distribution at regional level influence the farming water management.

1.3.2 Research objective

The overall objective of this research is to assess the potential risk of food security at national and local scales related to future climate change, and to provide possible adaptation options for regional sustainable development, by developing an integrated assessment model system.

In responding to the above objective, the research focussed on answering the following two questions.

Question 1: How will the food availability, food price and the resilience of Chinese food system are affected by climate change?

Question 2: What are the possible adaptation options for reducing the vulnerability and improving the Chinese food security situation at national and farm levels, and how would these adaptations trade-off the climatic change impacts on food availability, price and system resilience?

To answer Question 1, the bio-physical and socio-economic processes involved in the food system were modelled and integrated.

- To simulate crop production, a bio-physical crop production model was developed by improving the DSSAT model (Jones et al., 2003; Tsuji et al., 1994).

- Considering the limitation on time, only the climate change impacts on maize production is considered in this thesis as a case study. The maize is the primary feed resource for meat production in China (China Animal Agriculture Association, 2001). The future meat demands would contribute the most important part to the increase in total food demands, as the income keeps growing for both urban and rural population and their requirements to high protein food (Zhao et al, 2006).
- To simulate the socio-economic processes related to the food security situation at the national scale, an economic model was developed based on a partial equilibrium food economic model, the CAPSiM model (Huang & Li, 2003).
- The integrated model is tested by a case study of China. The impacts of climate change on food security is assessed by three indicators: 1) the availability of grains, which is represented by the supply and demand, 2) the affordability of grains, which is reflected by the prices of main grain commodities, 3) the resilience of food system to sudden disasters.

To answer Question 2, the following adaptation options were considered: crop variety switching, improving water use, increasing the investments in agricultural research, and increasing the investments in irrigation infrastructure by the government.

1.4 Contribution

Though it is expected that the climate change will have significant impact on food security at regional and global levels, there are lacks of tools that integrate biophysical and economic impact consequences and provide quantitative assessment information to support effective adaptation. Food security is one of the basic needs of human beings and is essential for a sustainable economic world. Against the background of accelerating global climate change, the study on food

security assessment in China has its special significance in terms of regional socio-economic development, as well as making contributions to the climate change scientific research field. The main contributions of this thesis are given below.

In terms of methodology, a model framework integrating bio-physical and socio-economic processes of the food system was developed to assess food security on a national scale, in order to provide policy-makers with the required information to achieve sustainable development at both local and national levels.

With respect to the integrated model,

- the information on impacts of climate change at local levels was successfully incorporated into the processes at a large spatial scale, e.g. national level;
- the effectiveness of potential adaptations was measured for both farmers and government to reduce the negative consequences of climate change and socio-economic conditions;
- the food security was assessed in terms of general availability, food price and the resilience on a year-by-year basis;
- the combined effects of multiple climate change, socio-economic conditions, and policy were coupled into one solution, facilitating analysis and comparison of multiple scenarios.

This study also investigated model improvement by:

- improving the site-based bio-physical model to a spatial one that is able to be applied in a spatial simulation with more reasonable planting and irrigation schemes;
- adjusting the food economic model to fix some elasticities automatically in order to simulate the changes in dietary pattern in the long run projections;

- altering the yield equation in the food economic model so that the impacts of climate change can be incorporated into economic processes directly as well as in the calculation of yield.

The integrated framework was developed into one program package, written with Fortran90 language.

With respect to key findings, this thesis focused on the integrated assessment of food security and climate change. Impacts of climate change on bio-physical production of maize were carried out in Jilin province (local level) and the entire China (national level). Integrated assessment of food security of China (national level) was carried out for future decades. The findings of case study included:

- Impacts on maize yield and on its phenology in the long term to the 2070s. By the bio-physical model, the maize yield was projected to decrease 15% or more by 2050 in the major areas of Jilin province, and to reduce 10% on the average over the whole China under climate change without considering the CO₂ fertilizer effects. The reduction in maize yield is likely to be produced by the significant shrink in grain filling period.
- Calculations and discussion of the probabilistic range of the maize yield under six SRES scenarios in three projection periods. 90% of projections on maize yield using 120 climate change scenarios derived from 20 GCM models and 6 SRES emission scenarios supported the conclusion above.
- Quantitative assessment of the effectiveness of adaptation options at farm level. Improving irrigation may maintain the current production level of maize, but in the long run introducing new maize cultivars and adjusting the sowing schedule might be required to offset the influences of warming climate on maize.
- Analysis of the future food security in China for four main grains and seven livestock products with respect to three aspects of food security until the

middle of the 21st century. The supply and demand of the main grains will move towards a tight balance in the future. The self-sufficiency ratio of maize may even reduce to 92% in 2050 due to climate change impacts. The food access is threatened by the rising prices of main grains in the decades. The unstable status of food security due to a sudden shock may last for years longer under climate change.

- Discussion of the resilience of the socio-economic system to the damage of climate change under multiple scenarios. The bio-physical impacts of climate change on a crop might slightly weakened by the socio-economic system.
- Measurement of the uncertainties in food security of China among climate change, socio-economic and policy scenarios. The worst projection of food security would occur under the high growth scenario of both income and population with A1FI emission scenario, while the best occurs under the low growth of income and population with B1 emission scenarios. The difference of these two projections of food prices might be significantly large.
- Trials and testing of the improvements in food security by implementing adaptations through effective agricultural policy. Supplementary investment in agricultural research and irrigation services would help to alleviate the risks on food security due to climate change and the growth of income and population, remaining the prices of grains on the current level.

The improvements in the bio-physical model and the case study on impacts of climate change on bio-physical production of maize in Jilin province (Chapter 3 and Chapter 4) has been published as a Journal paper (Wang, M., Li, Y., Ye, W., Bornman, J. F., Yan, X. (2011) Effect of climate change on maize production, and potential adaptation measures: a case study in Jilin Province, China. *Climate Research*, 46: 223-242).

Some sections in Chapters 1, 2, 3, 4 and 8 contributed to the technical report of the Asian-Pacific-Network for Global Change Research CAPaBLE Project CRP2008-

02MY-Yan (Li, Y., Ye, W., Yin, C., Wang, M. (2008) Integrated model development for water and food security assessment and a case study in Jilin province.).

Chapter 2 Case Study and Methodology

2.1 Case study

Globally, the food security of China plays an important role for world food security. Because of its huge food demand and fast economic growth, China has been a critical player in the world grain markets and will become more influential in future. In China, a large fraction of the population and national output is dependent on natural resources, and is very sensitive to climate change. A challenging issue in regional sustainability is to identify the potential impacts on it associated with climate change.

There has been periodic and recursively growing concern over China's grain security by scholars, national leaders and the public since the middle 1990s (Brown, 1995; Huang & Rozelle, 1995; Haung et al., 1999; He et al., 2004; Huang et al., 2006; MOA, 2004). Academics have expressed different opinions and views on the current policies and the concern about grain security. Several questions have been raised. Is China's grain supply a serious problem? What is the likely situation regarding China's grain security in the next three decades? What are the key determinants of China's future grain security? Can China rely on long-term productivity growth for grain security?

2.1.1 Current food security status of China

Since the beginning of reform and the opening up policy in the late 1970s, China has maintained a steady growth in food production, and achieved a general equilibrium in demand and supply. In the late 1990s, domestic grain production was around 500 million, and the national grain reserves were higher than 95% to be self-sufficient. The increase of grain production is about 1.96% which is faster than the population

growth in the same period (Li, 2013). In recent years, the self-sufficiency of main staples has fallen to 88.4% and the soybean self-sufficiency is only 18.1% (Han, 2013). The latest Global Food Security Index published by The Economist Intelligence Unit (Please see details on their web site <http://foodsecurityindex.eiu.com/Country>) shows that the food security of China has generally good performance, with the 43th place in affordability, the 41th in availability and the 43th in quality and safety by global ranking. In 2002, per capita possession of grain was about 356 kg, and annual average consumption was about 51 kg for meat products, 34 kg for aquatic products and 330 kg for vegetables per person. The everyday per capita nutritional intake has surpassed the world average of 2750 kilocalories, with more than 70 g protein and 52 g fat per day (MOA, 2004). After six successive years of falling grain prices, the grain price increased in late 2003 and in the spring of 2004. It is also noted that the food demand of the immigrants from rural is growing very significantly, about 119.14 kg higher than the rural residents and 51.04 kg higher than the urban residents in a survey in 2013 led by the Development Research Center of the State Council of China (DRC) in 2013 (Han, 2013).

Many agricultural officials and scholars claimed that China's grain supply was facing a great challenge and predicted that China would encounter grain crises in the coming years. The underlying factors affecting food supply of China include the rapid income growth, changes in food preference, the land use competition, the shortage of water resource, intensive climate change, and the uncertainties in international food markets. The urbanization rate in 2012 is about 53% and would be rising to the peak of 70%~75% in 2030s (Han, 2013). In response to these concerns, the government recently launched several policies to promote grain production. An income transfer scheme with more than 100 billion RMB was implemented in 2004 through a "Grain direct subsidy" program that distributed cash to farmers in grain production areas (Xiao, 2005; Sun et al, 2012). Much stricter control of non-agricultural land use is underway. Maize export subsidies were completely eliminated in April 2004. New contracts to import grain were signed in

late 2003 and early 2004 despite world cereal prices being higher than the domestic prices. The “Grain for Green” program (Li, 2004) was scaled down substantially in 2004 (Xu et al, 2006; Liu & Wu, 2010).

During the past decades, the purchasing power of Chinese consumers increased rapidly with the annual GDP increase rate at more than 7%. The total poverty population was also reduced to about 29 million by 2001 (Huang & Yang, 2006), and the Engel coefficients of rural and urban family have declined to 46.2% and 37.7% in 2002 (MOA, 2004; Zhang, 2005). This indicates a significant improvement in the aggregate household food security of China in recent years. However, the section of the population in poverty is thought to be increasing to 128 million under the new standard in 2011 in the report of Chinese Academy of Sciences (CAS, 2012).

2.1.2 Future food security of China

China has enormous potentials for food production growth in the coming years. The improvement of medium and low yielding farmlands that are about 2/3 of the total area of farmland will promote the rise in both yield and total production of grains.

However, there is still the challenge to ensure food security over long periods of time.

The population of China is projected to grow from about 1.3 to 1.5 billion in 2030, and the urbanization rate would also increase to about 60% by 2020 (MOA, 2004). Increased population, urban populations in particular, and improved income will boost a considerable increase in food demand including animal products, vegetables, fruits, and oil (Huang & Bouis, 1996). The projections of grain production and consumption based on food economic models are shown in Table 2-1. Besides this upgrading trend in consuming structure, the food quality and safety levels need to be improved in future. On the supply side, China is facing severe constraints for

grain production: the shortage of cultivated land and water resources have been deteriorating through heavy degradation, e.g. 20% of farmland, 50% of grassland and 33% of fresh water area have degraded (MOA, 2004).

A study by Zhang (2005) indicated that in the coming 20 years the import of not only cash crops (such as oilseed and sugar) but also grains will increase greatly due to China's fast-growing consumption. It is predicted that China will import about 560 Mt of maize in 2020, which is about 10% of global maize production in 2006, a large volume uneasily buffered by the world grain market nowadays or even in the future (Huang & Yang, 2006). As one of the most important food production areas in the country, the Northeast of China produces more than 15% of the grain and about one third of the total marketable grains and soybean (Zhou, 2005), and will thus become a sensitive region for food security in China.

Table 2-1 The projected grain production and consumption in China based on using economic models without considering the factors related to climatic change.

		Production (Mt)	Consumption (Mt)	Net Import (Mt)
Huang et al. (1999)	2002	442	460	17.9
	2004	456	468	19.6
	2005	464	484	19.8
USDA (ERS, 1994, 1997)	2002	397	418	9.9
	2004	412	436	12.0
	2005	419	445	13.8
Mitchell et al. (1997)	2005	445	460	15.6
	2010	482	503	21.6
OECD (OECD, 1995)	2005	503	572	69.1
	2010	511	648	136.0
Nyberg et al. (1997)	2005	493	516	23
	2020	662	731	69
Rosegrant et al. (1995)	2020	707	739	32
Chen (1997)	2000			15
	2020			35
	2030			50
Kang (1998)	2000			33
	2010			83
	2020			138
	2030			91

Table 2-1 The projected grain production and consumption in China based on using economic models without considering the factors related to climatic change (continued).

Liao and Huang (2004)	2020	496	511	
Ma and Niu (2009)	2010		516	
	2015		532	
	2020		547	
Lu et al (2010)	2015	537	571	
	2020	536	595	
Zhang (2012)	2020	550	570-660	
			Self-sufficiency	Net import (Mt)
Han (2013)	2020	Rice	101%	
		Wheat	99%	
		Maize	92%	19.87
		Soybean	20%	69.06
	2035	Rice	102%	
		Wheat	100%	
		Maize	84%	50.36
		Soybean	17%	89.28

China is facing the threat of food insecurity to different degrees with similar socio-economic changes and natural problems. The low level productivity in the agriculture sector, transition of economy, degradation in the environment, and climate change are likely the main reasons that could lead to unstable food production and increased rural poverty (Alcamo et al., 2003b; FAO, 1997; MOA, 2004; Zhou, 2005). During recent years, its grain production has been unsteady against agricultural structural adjustment and disaster shocks (Liu & Chen, 2000; Shi, 1997); and with the rapid development of the economy and continual growth in population, the increasing demand for the quantity and quality of food will require greater output from the food system (Huang et al., 1996, 1999). That will place heavier pressure on both limited natural resources and transforming of agricultural sectors than ever before (Barney et al., 1999; Huang et al., 1995).

The weak anti-disaster capability due to insufficient agricultural infrastructure accounts for large losses in grain production (Yang et al, 2006; Jiang et al, 2006; Lu et al, 2009; "Assessment Report on", 2011; Jia et al, 2011; Zhang & Wang, 2011). In half of Chinese provinces, the grain loss due to natural disasters is larger than 10% in the past (Zhang & Wang, 2011). There are also small-scale and scattered food production units that are economically more vulnerable with respect to marketing (Ma & Cui, 2005; Wang, 2005; He & Wang, 2012). The frequent extreme climate events and climate change over longer time periods would impose negative influences on the already burdened environment for agriculture, and result in negative effects on agriculture (Fu et al, 2002; Deng et al, 2002). In addition, climate and environmental changes at both global and regional scales will have significant impact on the food security for this country (Lin & Wang, 1994; Liu et al, 2010; Zhao et al, 2010, Wu & Luo, 2010; Yuan et al, 2011; Pan et al, 2011).

Firstly, the changes in average climate conditions, such as the warming trend, could affect crop production directly and indirectly. The site-based observation records over China in the last 20 years show that no matter what crop managements that

were practiced or what cultivars adopted, the increase in temperature has reduced the main staple yields, particularly in the north where unfavourable precipitation in the growing season exacerbates losses (Tao et al., 2006); also, global warming will induce stronger surface evaporation and plant transpiration, which would increase irrigation demand and contribute further to the water scarcity in semi-arid regions (Rosenzweig et al., 2004). Such as in the northeast plain in China, the agricultural water demands have been increasing due to the soil drying trend and the significant changes in soil-moisture variability in the last half century (Tao et al., 2003a). In future, the agricultural sector might encounter heavy impacts on the economy with the large competition for water resource from other sectors.

Secondly, the changes in variability of extreme events have produced more frequent severe disasters in this region (Qian & Zhu, 2001; Zhai et al., 1999), such as droughts, floods, spread and incidence of pests and diseases, increasing agricultural loss (Liu & Chen, 2000; Shi, 1997; Zhu & Yang, 2001). According to the historical data, the annual average loss of grain production caused by agro-meteorological disasters (including droughts, floods, wind and hail, low temperature) increased from 2.1% of total production in the 1950s to about 5% in the 1990s (Hu, 1998). The multi-annual droughts, besides the decline in material inputs into agriculture, might be the first critical threat for Chinese grain production in future, particularly in semi-arid areas such as the northwest part of Jilin Province (Wang et al., 2003).

Agricultural production is not only the major resource of food but also the principal source of people's income, so food security has very close connection with the local economic development. Considering that agriculture in China largely depends on natural resources and climate conditions and because of poorer resilience of local economy, the food system in China would be highly vulnerable to climate change in the next decades.

As Krol et al. (2006) stated, the assessment studies on the impacts of climate change in developing semi-arid regions called for an integrated approach. Because of

climate change and its consequent strong restrictions on utility of land and water resources as well as few short-term options available for local communities in such regions, the study should include not only the understanding of climate impacts on bio-physical food production, but also analysis of agricultural economy, natural resources management, and social impacts. The integrated model system has the ability to analyse the associative consequences of possible adaptation options by coupling the bio-physical and the socio-economic information, as suggested by the IPCC report (IPCC, 2001b). This would become a useful tool to link climate change science with food security assessment and sustainable development.

2.1.3 Current food security status of Jilin province

Jilin Province (N 40°52' ~ 46°18', E 121°38' ~ 131° 19') is located in the middle part of Northeast China. The total area of Jilin is 187,400 km², which is about 2% of the total area of the country (Figure 2-1). The last 60 years have seen remarkable growth in agricultural production and food security improvement of Jilin (He et al., 2003), but at significant expense to the environment and natural resources. It has been widely recognised that this unsustainable development mode cannot continue. Furthermore, it is evident that drought, the biggest agriculture disaster for Jilin, has become more severe with the changing climate.

As one of the most important grain production regions of China, Jilin has less than 2% of the national population, but since the 1980s produced more than 4% of the national total grains. Although the amount of grain production in Jilin takes a little proportion of the total country production, it produces the biggest trade grains for exporting to other provinces in China. In fact, Jilin's grain production has a steady trend of assimilating higher shares of the national grain production in the last three decades. At around 1,000 kg per capita, Jilin's grain production is the highest in China.

Maize is the most important grain crop in Jilin and also the one that historically has had the fastest development, from less than 1.5 Mt during the 1950-1960s to increasing 10 times and more to 15 Mt after 1980, peaking at 19.24 Mt in 1998, and consistently above 70% of Jilin's total grain production since the 1980s. On average, it has accounted for 13.25% of the national maize production during 1981-2005.

The total grain production in Jilin Province was 25 Mt in 2005, about five times that as in 1949 (Figure 2-2) with the dramatic increase in yield contributing largely to the increase rather than the change in sown area. In general, after the low level evolvment during the 1950s to 1960s with the weak agricultural infrastructure and technology, the trend in average yield of all grains—including maize, wheat, rice, coarse grains, legumes and tuber, have gone up rapidly in the late 1970s, and reached a stable high level around 5700 kg/ha in the 1990s (Figure 2-3), because of a steady improvement in investment in agricultural sectors, land ownership reform and other agricultural policy changes.

The fast increase in grain production in Jilin was achieved mainly through the improvement of agricultural management, i.e., irrigation and fertilizer utilization, without significant change of the grain sown area (Figure 2-6, and Figure 2-7). Starting at around 4.5 million ha, the total sown area decreased slightly up to the late 1990s, but regained all the lost area after that. However, the irrigated area was almost doubled from 0.087 million ha in 1949, to 1.63 million ha in 2006, while fertilizer use increased 50 times more from 0.06 Mt to 3.2 Mt for the same period. Correspondingly, the average grain yield in Jilin stayed at a relative low level during the 1950s and 1960s, but went up very rapidly and reached a stable high level of 5,800 kg/ha after the 1990s.

The annual natural disaster affected ratio is defined as the area affected by disasters divided by the total sown area of grains and usually treated as the integrated estimation of the main agro-meteorological disasters (including flood, drought,

heavy wind and hailstorms, and low temperature damage). Figure 2-5 shows the ratio for historical data, which demonstrates a significant influence of climate related disasters on grain production. On average, the natural disaster affected area due to abnormal climatic conditions increased from less than 30% of the total sown area before 1980 to about 45% over the past 25 years, increasing the risk of grain production in Jilin Province. It is also noted that intensive drought became the major disaster especially in recent decades along with the aridification of this region.



Figure 2-1 The county map of Jilin province, China.

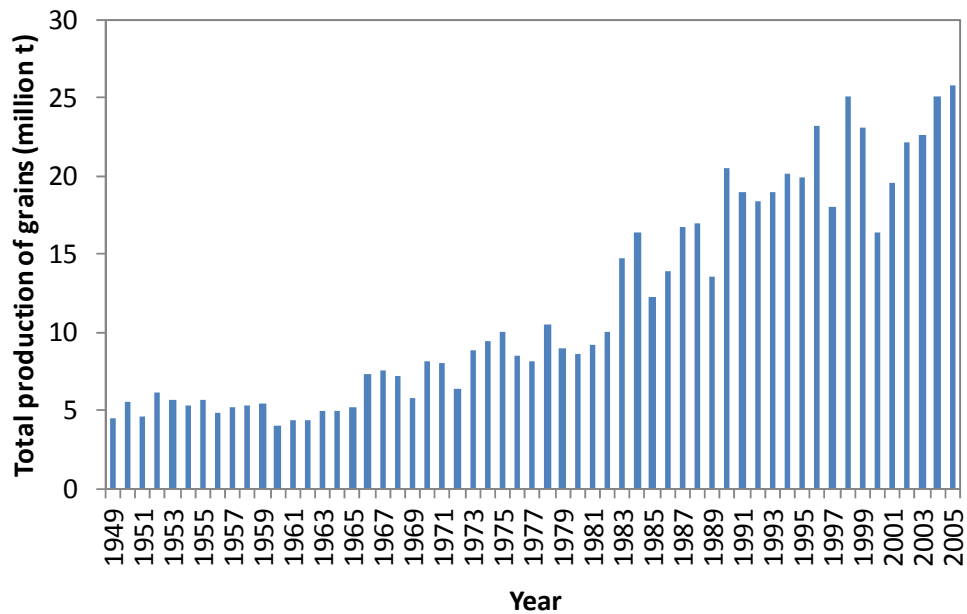


Figure 2-2 The annual series of total grain production of Jilin Province from 1949 to 2005.

Sources: the crop database developed from the statistical yearbooks published by the National Bureau of Statistics of China and China's agricultural Database by the Ministry of Agriculture of China (<http://zzys.agri.gov.cn/nongqing.asp>)

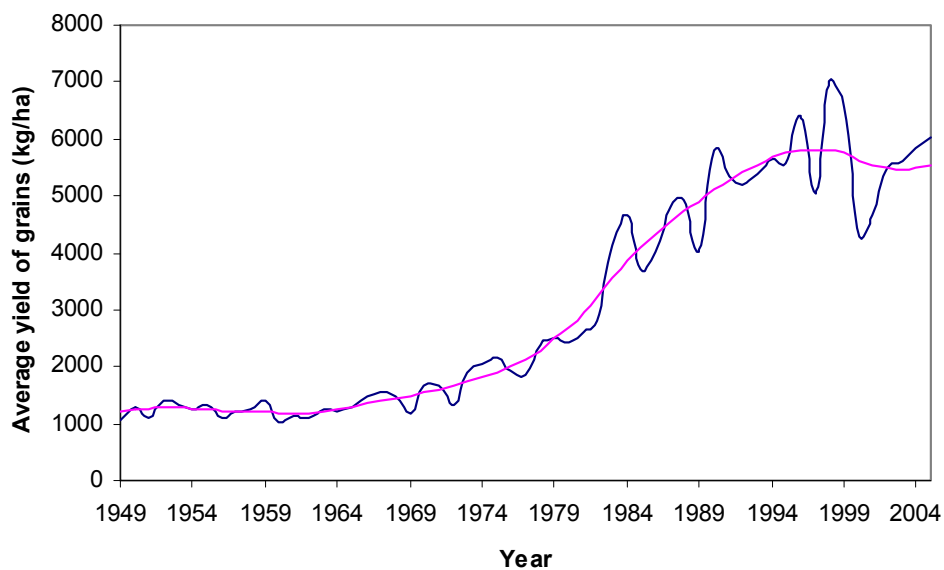


Figure 2-3 The annual series of the average yield of grains during 1949-2005 in Jilin Province.

The blue line is the original average yield of grains, and the purple one is the trend.
 Sources: the average yield of grains is derived from the crop database developed from the statistical yearbooks published by the National Bureau of Statistics of China and China's agricultural Database by the Ministry of Agriculture of China (<http://zzys.agri.gov.cn/nongqing.asp>).

The annual turbulence and time trend are separated from the census of yield using the linear moving average method (Xue et al., 2003), and then the stability of the yield and the risk of variation can be calculated through the probability analysis tools. This time trend of yield, often called the trend yield, could be considered as the agent of the food production capability in a certain period, and its variability, called the meteorological yield, would represent the yield mainly attributable to climate-related factors. Then the relevant meteorological yield can be defined as the increase or reduction ratio of meteorological yield to the trend yield can be introduced to measure the climate risk of food production. Ten kinds of crops have been selected in this analysis, including main grains, coarse grains, soybean, tuber and cash crops.

Despite the increasing trend of intensity of natural disasters, the meteorological yield, calculated by the method of Xue et al. (2003), varied more after 1980 than before (see Fig. 2-3). The variability of annual trend yield did not increase between 1980 and 2005, according to the above analysis. The changes in the relevant meteorological yield between the two periods, i.e. 1949-1979 and 1980-2005, show that the probability of yield reduction seems smaller in the latter periods, especially the risk of 20% and 30% losses that were reduced in the latter period (Table 2-2).

Table 2-2 The occurrence of risk probability of yield reduction caused by climate related disasters.

Reduction ratio of yield	Occurrence probability	
	1949-1979	1980-2005
> 30%	0.08%	0%
> 20%	3.24%	0.09%
> 10%	13.08%	6.11%
> 5%	27.31%	22.33%

* Occurrence probability: the probability of the occurrence of four reduction levels, i.e. larger than 30%, 20%, 10% and 5%. Firstly, the reduction events in history were obtained based on the statistics from 1949 to 2005. Secondly, the numbers of these events under 4 different levels were calculated. Thirdly, the probability of the occurrence of reduction events were calculated for 4 different levels separately. Finally, the probabilities of the occurrence of reduction event in two periods, 1949-1979 and 1980-2005 were compared by their reduction levels.

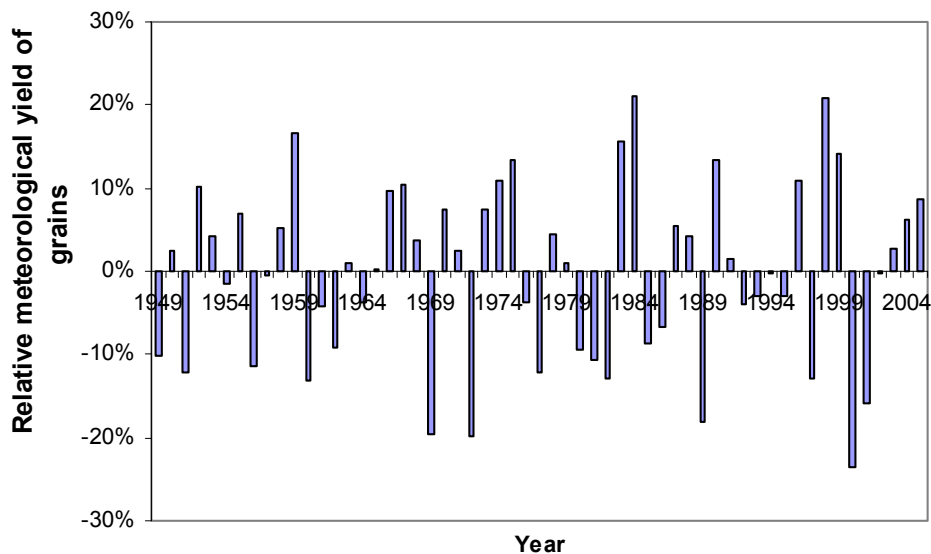


Figure 2-4 The annual variation of meteorological yield of grains during 1949-2005 in Jilin Province.

The stabilization of the yield of main grains in Jilin in recent decades could be largely explained by the increased financial and resource investment in the agricultural sector. The statistical data (Figure 2-6) show that fertilizer input increased more than 10 times during 1965 to 2005, from less than 50 t/ha to 700 t/ha; a similar trend appears in the series of rural electricity consumption; there was also an increase in agricultural machinery after the late 1970s; and the effective irrigated area grew rapidly during the late 1970s and the late 1990s (Figure 2-7) as the result of human response to the intensive droughts in those periods.

Further analysis of each of the staples shows that the reduction risk of maize (Figure 2-8-a), the major crop in Jilin Province, behaves differently from other main grains, such as wheat, soybean and rice (Figure 2-8-b, c, and d), which might be caused by the larger instability of input into maize production because of the higher commercialization of maize than the other grains in Jilin Province. It indicates that the turbulence of yield due to climate factors could be smoothed or amplified by

economic factors such as the transfer of agricultural investment and labour related to crop price variation.

To sum up, the results of the background analysis show that for food security, it is vital to address the instability of food supply due to the climate-related risk in food production, especially the risk due to intensive droughts. However, the statistical tools used in the above analyses are unable to identify the respective contribution of each of the input variables, and the data on the affected area are not precise enough for quantifying the intensity of disasters in practice. Thus the turbulence of yield or production due to climate variation cannot be separated from the entire variation in a quantitative manner. A modelling method might be a possible solution to the problems. Also, a higher resolution database needs to be constructed, from which the new indices for measuring impacts of disasters on crop yield or production can be derived.

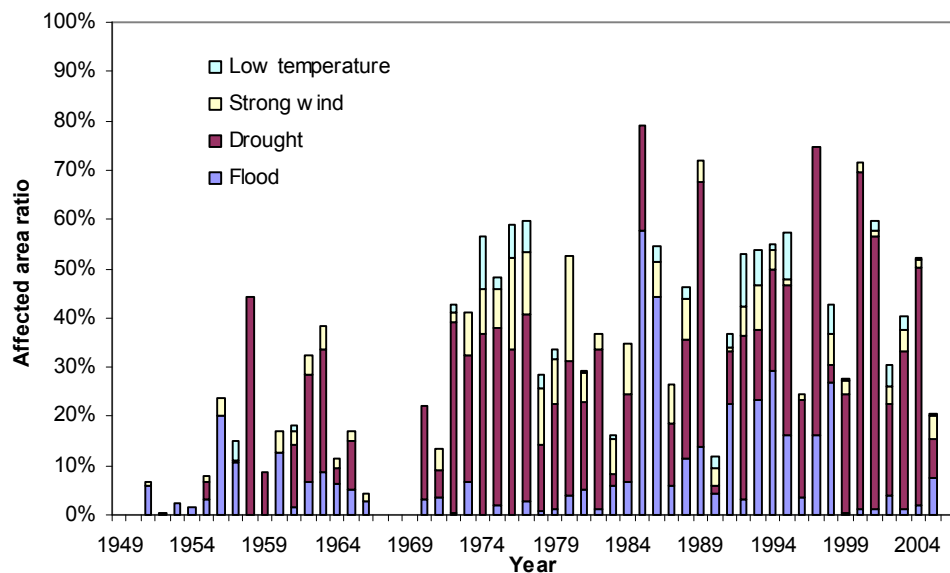


Figure 2-5 The series of climate disaster-affected area ratio during 1949-2005 in Jilin Province.

The affected area, defined as the area that experiences more than 10% reduction of yield due to natural disasters, is derived from China's agriculture Database where the records from 1966-1968 are absent.

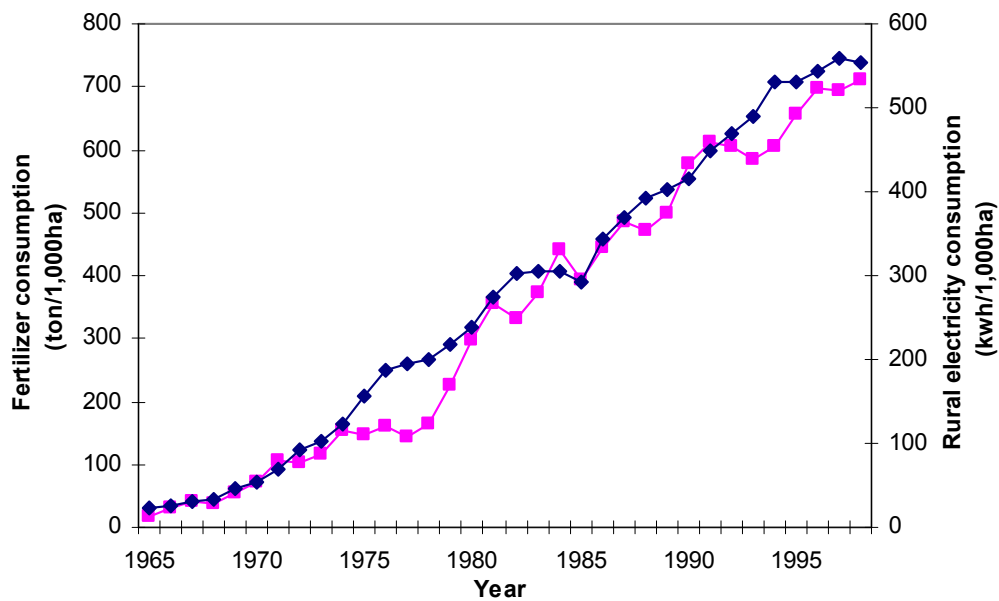


Figure 2-6 The series of fertilizer and rural electricity consumption during 1965-1998 in Jilin province.

The blue line is fertilizer consumption in unit of sown area of crop, and the purple one is the rural electricity consumption in unit of sown area of crop.

Source: China's Natural Resource for Scientific Research Database.

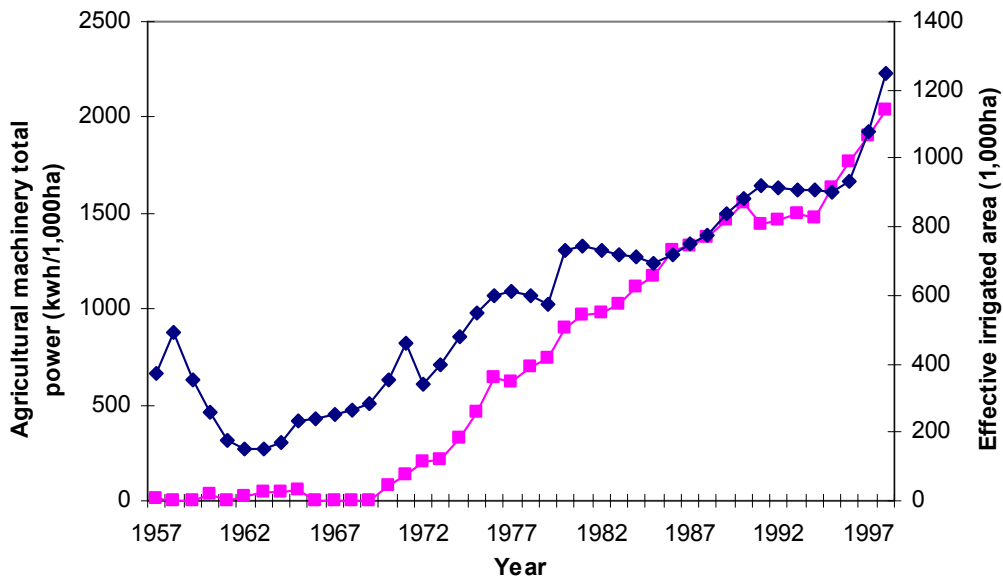


Figure 2-7 The series of agricultural machinery total power and effective irrigated area during 1965-1998 in Jilin province.

The purple line represents the agricultural machinery total power in unit of sown area of crop, and the blue one is the effective irrigated area.

Source: China's Natural Resource for Scientific Research Database.

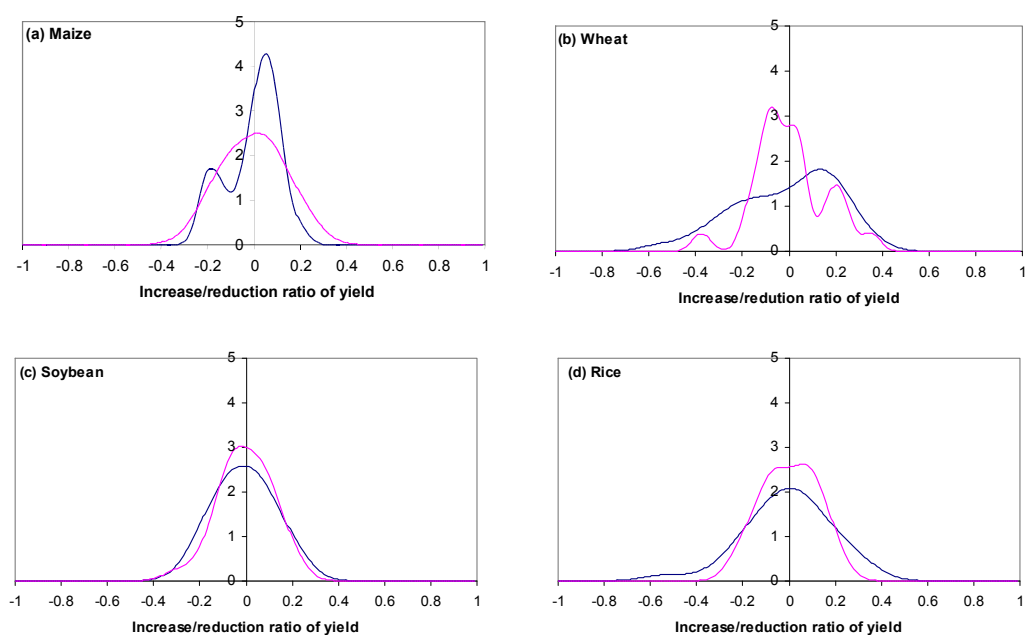


Figure 2-8 The probability density function of the yield’s increase or reduction ratio for maize (a), wheat (b), soybean (c), and rice (d), during two periods, 1949-1979 and 1980-2005.

The blue lines represent the functions in the first period, and the purple lines are those in the second period.

In conducting climate change impact assessments and sustainable development evaluation in China, two essential questions need to be addressed: (1) the impacts of climate change scenarios on various aspects of food security in the selected region; and (2) the effects of the various adaptation options available to reduce the adverse consequences of climate change and to improve sustainability. Finding answers to these two questions can be approached through integrated modelling.

2.2 Methodology

In this section, I provide my integrated framework for the assessment of food security, and briefly introduce two built-in specific models in that framework.

2.2.1 Overall model structure

The aim was to integrate climatic, biophysical, environmental, and socio-economic information for food security assessment under the concept frame as shown in Figure 2.9.

The integrated model system included

- a bio-physical crop model to capture the impact of climate change
- a macro-scale partial food economic model

The physical climate change scenarios produced by SimCLIM (Warrick, 2005), were incorporated into the integrated system as the climatic driver. The effects of the socio-economic changes on food are described in three inter-connected components— food availability, access and utilization. The adaptation options will be proposed and assessed for both regional and local government and farmers. The links of drivers, food security, and adaptation options across spatial scales within the integrated system are shown in Figure 2-9.

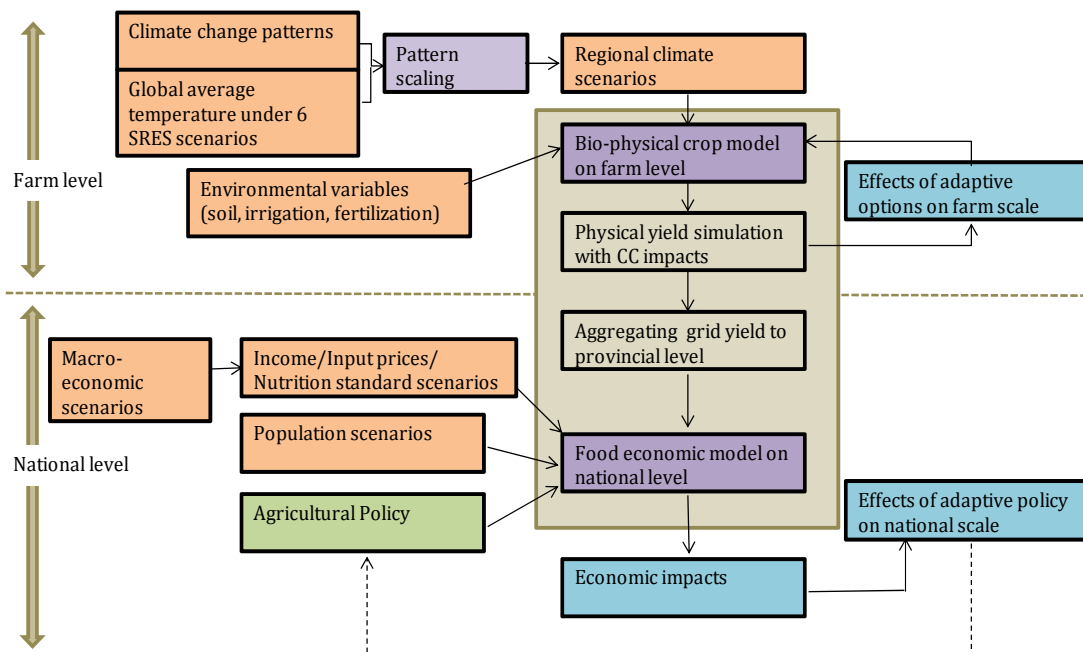


Figure 2-9 The integrated framework developed in the thesis.

2.2.2 Modelling the bio-physical process of crop production

The bio-physical crop production model was developed based on the well-known DSSAT model (Jones et al., 2003; Tsuji, 1998; Tsuji et al., 1994) which can simulate crop growth based on bio-physical processes, development and yield of a crop growing on a uniform area of land under simulated management, changes in soil water, carbon, and nitrogen over time.

The DSSAT-CSM (the Decision Support System for Agrotechnology Transfer-Cropping System Model) is composed of 7 modules. The core is the bio-physical dynamic modules of crop growth, CROPGRO crop template module and individual plant modules. The CROPGRO approach has a common source code for different species, while each of the individual plant modules is developed for specific crop varieties, such as the CERES-Maize, and Wheat and Barley model. The weather

module can read or generate daily weather data. The information on soil water, temperature, carbon and nitrogen, and dynamics is integrated in a single soil module, and the exchange processes of energy, water and nutrition within the soil-plant-atmosphere system are simulated in SPAM (Soil-Plant-Atmosphere Module). Field operations, like planting and harvesting, inorganic and organic fertilizer application, and irrigation, are determined in a management module. The system also includes a pest module to process pest and disease damage on crop growing in a semi-empirical way. In the latest version of DSSAT, the crop growing process and environmental control process are connected through a single interface, the land unit module, integrating the outputs from the rest of the modules, such as weather and soil conditions, Leaf Area Index (LAI) and phenological information, in a uniform area.

The improvement of DSSAT required for this study, involved correcting the parameters of bio-physical process and soil properties for water-stress areas, improving model to apply in spatial simulation, modification on irrigation scheme and sowing scheme.

The DSSAT model was selected for five reasons: 1) it provides a detailed process of crop growth based on bio-physical mechanism, 2) the model runs at grid level, so it is possible to do high-resolution spatial analysis, 3) the cropping managements, i.e. irrigation, fertilization, and plant schedule, are modelled very well, which is the most important characteristic required in assessment of adaptation quantitatively, 4) the model has been verified widely for many locations in China and many other countries in the past, and 5) it also supports to simulate a group of plants (i.e. rice, wheat, beans, sugarcane, potato and sunflower) except maize, so that the study framework is probably extended to other plants, which is necessary to do full assessment of food security.

Details of the bio-physical model are in Chapter 3.

2.2.3 Modelling the food economic system

The development of a macro-scale partial food economic module was based on the partial equilibrium model, CAPSiM (Huang & Li, 2003). CAPSiM is a typical agricultural economy model for long-term economic policy planning and agricultural commodity projection. It has a clear conceptual structure including specific components for presenting the domestic production, demand, trade and market clearing. All cross-price impacts are considered in both demand and supply functions. The structural change in Chinese economy is projected by explicitly modelling the rural and urban demand in separated equations. The model development was initiated in 1989 and has been continually updated with new demand and supply elasticities estimated by CCAP's primary survey and secondary data resources.

The basic frame of the macro-scale food security module is built on a partial equilibrium economic model, in which crop production was estimated as the product of crop yield and sown area related to producers' prices, investment and environmental constraints. Grain demand was calculated as the sum of food, feed, seed and other demand mainly depending on consumers' prices, population and income level, and the supply and demand equations will be finally linked by price variables. Some equations would be slightly modified to stress the impacts of climate change and variability on food economy.

The driving force and detailed function form are shown in Figure 2-10 at national level. The national level, the climate change and extreme events, agricultural policy, income and population growth will play a role as the exogenous shocks that will drive the changes in food supply-demand balance. The sown area is determined by the input and output prices and shocks due to changes in land use. The yield is specified economically as functions of technology stock, the effective irrigated area, and shocks due to climate change simulated by the bio-physical model. The climate change effect would be directly incorporated into food production at the national

level. Also, the impacts of extreme climate on yield will be identified by the statistical disaster in the historical census. The output of the national level food security model provides the volume of supply and demand of grains and livestock products and the national equilibrium prices of main grains on a yearly basis.

Details of the food economic model are in Chapter 6.

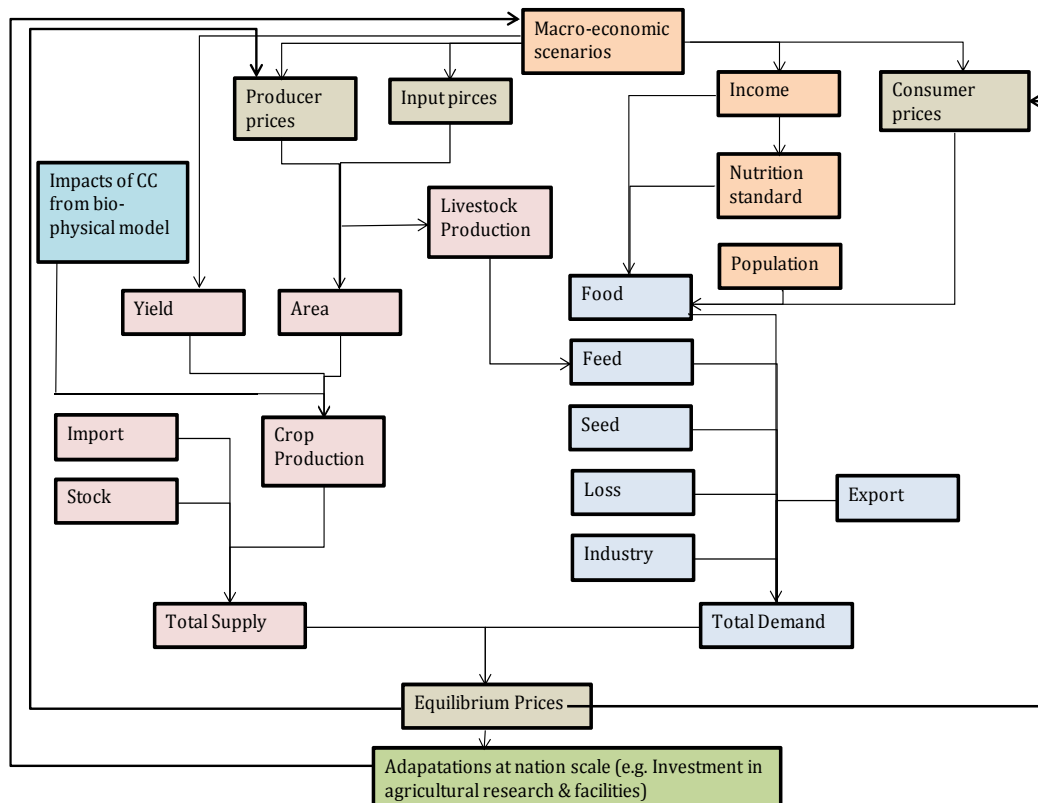


Figure 2-10 Structure of the economic model assembly in the thesis.

Chapter 3 Improved DSSAT Model: Model and Modification¹

3.1 Introduction

Maize production is the mainstay of agriculture in Jilin Province as well as for China nationally. Therefore the producing capacity of maize concerns the food sufficiency as well as the rural income in this region. This section investigates the climate change impact on maize production in the coming decades. The spatial distribution of maize yield and its temporal variation under the baseline climate and future change scenarios are simulated by a physically based crop model. A bio-physical model is selected because the objective of this study was to identify adaptation options by assessing impact due to climate change. Hence, it was essential that the change signals in the maize growing period (e.g. planting date, maturity period, etc.) could be detected and the maize response to cropping practices (such as planting density, irrigation and fertilization) could be quantitatively examined.

The CERES Maize was selected in this study after reviewing a number of crop models. The CERES Maize site-based crop model built in DSSAT (Decision Support System for Agrotechnology Transfer, Hoogenboom et al., 2004) is operated on a daily time step and takes into account the effects of cultivar, cropping management, weather, soil moisture and nutrition on maize in its simulation (Jones & Kiniry, 1986). In addition, the cultivar is modelled with explicit genotype coefficients. Therefore, the CERES Maize has the ability to provide information on the changes in essential signals (e.g. planting date and maturity period) under different climate change scenarios and the quantitative crop response to cropping practices (such as

¹ Chapter 3 has been published as a part of a Journal paper (Wang, M., Li, Y., Ye, W., Bornman, J. F., Yan, X. (2011) Effect of climate change on maize production, and potential adaptation measures: a case study in Jilin Province, China. *Climate Research*, 46: 223-242).

planting density, irrigation and fertilization), which is required for adaptation option identification.

In addition, the model has been widely validated across different climates and soils for different varieties (Wu et al., 1989; Maytin et al., 1995; O'Neal et al., 2002; Gungula et al., 2003; Soler et al., 2007; Braga et al., 2008). In Jilin, Jin et al. (1996; 2002) used it in the projection of maize yields at specific locations based on a double CO₂ climate scenario derived from three GCMs, and suggested several adaptation options. It was also employed by Xiong et al. (2005; 2007) to predict the future maize production in China under 2 emission scenarios with the daily outputs of PRECIS regional climate model at 50×50 km resolution. In this chapter, the description is given of the CERES Maize model that was employed for simulating maize growth, development and yield by using improved weather generator and climate scenarios.

3.2 DSSAT model

The DSSAT (Decision Support System for Agro-technology Transfer) model was originally developed for assessing the impacts of agro-technology applications on agricultural systems under different environmental conditions by integrating information of crop, soil, weather, and cultivating applications, and now has collected 16 kinds of crop models simulating crop growth, development and yield and diverse models describing water and chemical transfer in the soil-atmosphere-plant system with special consideration of diverse cultivating methods and the applications of irrigation and fertilization. The model is coded by Fortran90.

3.2.1 Model structure

The components of the DSSAT model as shown in Figure 3-1 chiefly include 5 modules: a weather module for reading or generating daily weather variables driving the crop growth module; a soil module, which calculates and integrates the state information of water and chemicals (mainly carbon and nitrogen) in soil; a crop module, which is the key module of DSSAT for simulating crop growth by computing the photosynthesis rate on leaf or canopy scale (CERES or CROPGRO modules); a soil-plant-atmosphere module (SPAM), which processes the water exchange among soil, plant and atmosphere, and computes the impacts of soil evaporation and plant evapotranspiration on crop development; and a management module, controlling the cultivating operations conveyed to crop models, e.g. planting schedules, fertilization, and irrigation.

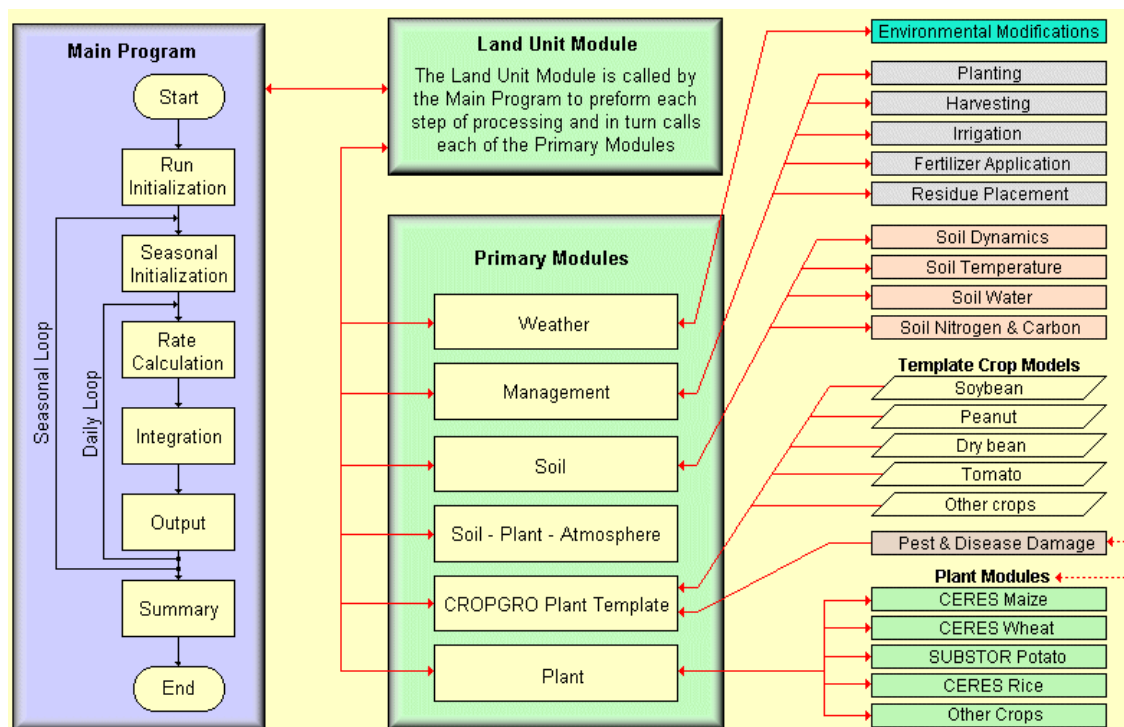


Figure 3-1 The structure of the DSSAT model (Source: http://www.stoorvogel.info/tradeoffs/course/course_4.html).

3.2.2 CERES-Maize model

The CERES-Maize model in DSSAT simulates plant growth by phenological stages (including germination, emergence, juvenile, floral induction, silking, grain filling, and maturity), which are determined by thermal periods (in growing degree days, i.e. GDD). The daily dry matter production is calculated based on the intercepted photosynthetically active radiation (400-700 nm), which is a function of the leaf area index (LAI), and is also modified according to the water, nitrogen, and temperature stress. The final grain yield depends on the plant population, kernel number per plant, and kernel weight. The GDDs in the key stages, kernel numbers and potential kernel growth rate are defined by the genotype parameters of a specific cultivar calibrated by the local observations.

3.2.3 Input requirement and output

3.2.3.1 Input requirement

The minimum input data set for the operation of the DSSAT model discussed by Jones et al. (2003), requires 5 aspects of the contents about the geographical information, weather data, properties of soil, cultivar types, initial conditions of environment and management of planting (e.g. the planting schedule and method, applications of irrigation and fertilizer). The details about required inputs are shown in Table 3-1.

3.2.3.2 Output

The output variables include the daily and seasonal simulations of weather, soil water, carbon and nitrogen content in soil, plant biomass and grain yield, and N uptake by plants.

Table 3-1 The input data sets for the DSSAT model.

	Input variables
Initial conditions	Initials of soil water, nitrate and ammonium
Cultivar	Genotype coefficients
Geographic information	The latitude, longitude and elevation of the site; The major obstruction to the sun;
Weather	Daily solar radiation, maximum and minimum air temperature, precipitation
Soil	Average annual soil temperature and its amplitude; Soil surface albedo, the coefficients associated with evaporation, hydraulic conductivity, and drainage; Soil texture, water release characteristics, organic matter, soil pH and drainage class by layer;
Management	Planting and harvest date, planting depth and method, row spacing, plant population; Irrigation (date, method, amount and depth); Inorganic fertilizer type; date, method and amount of application; Residue (organic fertilizer) and its application; Tillage; Environmental adjustments

3.3 Data and construction of the input dataset

3.3.1 Geographical information

The latitude of the site is the main geographic parameter required in the model in order to calculate and adjust the variables related to weather. Some parameters such as slope and coefficient of the obstruction to the sun (e.g. nearby mountains)

can also affect the simulation at a single field, but in this study they were not considered because it focused on the overall picture of crop production in a region and its changes over time, not on a single site simulation.

3.3.2 Weather

The DSSAT requires daily weather to drive the crop growth process, however, if the daily data is not available, it also allows using built-in weather generation to produce daily weather, given monthly data (i.e. the monthly total solar radiation, maximum and minimum air temperature, and precipitation). In this study, only climate data is available for both baseline and future period. In this section, the method how to produce the baseline and future climate variables for DSSAT input is introduced.

The baseline climate data of 1961 to 1990 were obtained from the CRU (Climate Research Unit, University of East Anglia) and the global climatology dataset (New et al., 2002) through linear interpolation of the spatial resolution from 10×10 minutes to 5×5 minutes grids. The solar radiation was estimated from the CRU sunlight hours following the method of Tong et al. (2005), and the max and min temperature were calculated from the mean temperature and its diurnal range (New et al., 2002).

Generally, the solar radiation cannot be obtained directly from the climatic database, so it needs to be calculated from the daily sunshine duration by the following equations:

$$R = Q_n[a + b \cdot (n/N)] \quad (\text{Eq. 3-1})$$

where R is the daily total solar radiation, Q_n (W/m^2) is the maximum daily solar radiation, n and N are daily sunshine duration and daily duration of possible

sunshine, respectively, and the parameters, a and b , are related to atmosphere quality. The empirical value of the sum of a and b is 0.75. The maximum daily solar radiation, Q_n , is computed based on

$$Q_n = \frac{TI_0}{\pi\rho^2} (\omega_0 \sin \varphi \sin \delta + \cos \varphi \cos \delta \sin \omega_0) \quad (\text{Eq. 3-2})$$

where $T = 24 \times 60 \times 60$ s, I_0 is the solar constant (1367 W/m^2), ρ^2 is the sun-earth distance, and ω_0 is the sunset hour angle, $\omega_0 = \cos^{-1}(-\tan \varphi \tan \delta)$, where φ is the latitude and δ is the declination of the sun.

The climate change scenarios are obtained from the projections of 20 General Circulation Models (GCMs) and 6 SRES emission scenarios by using the pattern scaling method. The scenarios of future monthly temperature and precipitation are generated as follows:

$$Temp_1 = Temp_0 + \Delta Temp \cdot \Delta GMT \quad (\text{Eq. 3-3})$$

$$Prec_1 = Prec_0 \cdot (1 + \Delta Prec/100 \cdot \Delta GMT) \quad (\text{Eq. 3-4})$$

where $Temp_0$ (or $Temp_1$) and $Prec_0$ (or $Prec_1$) are the baseline (or future) temperature and precipitation; $\Delta Temp$ (or $\Delta Prec$), the change pattern, is the localized change in temperature (or precipitation) to per unit global warming, generated through standardizing the GCM simulation outputs to the corresponding global mean temperature changes; ΔGMT , the scalar, is the change of global mean temperature increase in a future time slice.

The 20 GCM change patterns in the IPCC AR4 Climate Model Inter-comparison Project (CMIP) (Covey et al., 2003) and 6 SRES scenarios (Special Report on Emissions Scenarios, IPCC, 2000), i.e. A1B, A1FI, A1T, A2, B1, and B2 were used for the ensemble, with a total ensemble size of 120 scenarios. The GCM change patterns were interpolated from the original resolution of 2.5×2.5 degrees to 5×5 minutes in order to simulate the crop change with high resolution, and years 2020, 2050 and

2070 were selected to reveal the impacts of climate change on maize production at different future times. The SRES dataset offers different global warming projections (Figure 3-2) corresponding to different GHG emission scenarios and the low, mid, and high climate sensitivities (Wigley, 2003). Only the SRES global temperature projection with middle climate sensitivity was used to generate the spatial mean changes. The middle climate sensitivity is the median value of the future global warming range predicted by the GCMs (refer to IPCC 2010 for more detail). The area average changes of temperature and precipitation of 6 SRES emission scenarios from baseline climate for Jilin is shown in Table 3-2. Detail of the pattern scaling method can be found in Mitchell et al. (1999), Mitchell (2003), Wigley (2003) and Li et al. (2009).

Table 3-2 The area average changes of temperature (°C) and precipitation (% of baseline precipitation) of the 6 SRES emission scenarios from the baseline climate for Jilin province.

Scenario	A1B	A1FI	A1T	A2	B1	B2
	Temp.	Temp.	Temp.	Temp.	Temp.	Temp.
2020	0.58	0.62	0.79	0.57	0.63	0.74
2050	1.82	2.03	1.97	1.59	1.41	1.64
2070	2.67	3.46	2.59	2.63	1.94	2.23
	Prec.	Prec.	Prec.	Prec.	Prec.	Prec.
2020	2.71	2.79	3.1	2.98	2.98	3.06
2050	3.84	4.54	5.07	5.3	5.42	5.6
2070	6.13	6.85	7.2	7.52	7.61	7.76

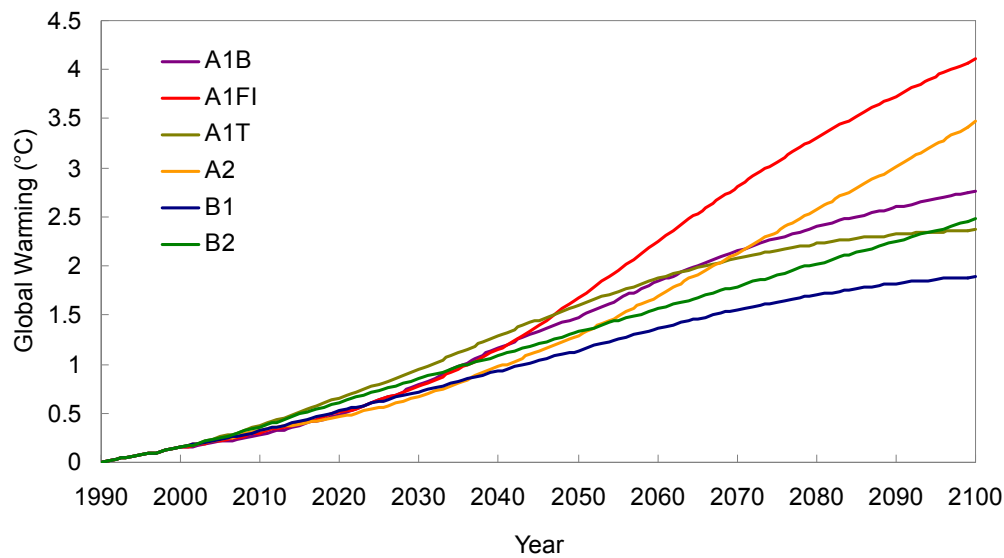


Figure 3-2 Global average temperature under IPCC illustrative 6 SRES (medium) scenarios.

3.3.3 Soil

The input soil data for the DSSAT involves 6 coefficients describing the properties of the whole soil profile, and 14 coefficients of soil properties at each layer (see the Table 3-3).

The spatial soil parameters are derived from two datasets: 1) the ISRIC-WISE (WISE, Batjes, 2006) database (5×5 arc-minutes) which provides a lot of essential parameters required by DSSAT within the 100 cm deep five-layer soil profiles (see Table 3-3); and 2) Soil and terrain database for China which is based on the Soil Map of China at a scale 1:1 million (Shi et al., 2004; Zhang & Zhao, 2008). Some parameters that these datasets do not offer directly were produced using the rules and methods described in Section 4.1.1.1.

3.3.4 Cropping management

The major cropping practice considered in DSSAT includes planting density, sowing date, fertilizer application, and irrigation application. The applications of fertilizer and irrigation are needed to setup the date and amount to be applied. Details of cropping management in Jilin and China are introduced in Chapters 4 and 5, respectively.

Table 3-3 The main soil parameters required.

Code	Property	Unit	WISE
SALB	Soil surface albedo		
U	First stage evaporation coefficient	mm/day	
SWCON	Whole profile drainage rate coefficient		
CN	Runoff curve number		
DMOD	Factor to adjust the mineralization rate for atypical soil		
SLPF	The relative reduction of growth due to poor soil fertility		
DS (I)	Depth of the layer I	cm	*
LL (I)	Lower limit volumetric moisture content of the layer I	cm ³ /cm ³	
DUL (I)	Drained upper limit moisture content of the layer I	cm ³ /cm ³	
SAT (I)	Field saturated moisture content of the layer I	cm ³ /cm ³	
WR (I)	Root hospitality factor		
SWCN (I)	Saturated hydraulic conductivity of the layer I	cm/h	
BD (I)	Bulk density of the layer I	g/cm ³	*
OC (I)	Organic carbon content of the layer I	%	*
TOTN (I)	Total nitrogen content of the layer I	%	*
CLAY (I) #	Percentage of clay in the layer I	%	*
SILT (I) #	Percentage of silt in the layer I	%	*
STONES (I) #	Coarse fraction in the layer I	%	*
PH (I)	pH in water of the layer I		*
CEC (I)	Cation exchange capacity of the layer I	cmol/kg	*

It accepts the USDA (United States Department of Agriculture) definition of particle size in the DSSAT model, i.e. sand (0.05~2 mm), silt (0.002~0.05 mm), and clay (0.001~0.002 mm). The particles with the size larger than 2 mm are known as stones (or gravels).

Asterisk (*) in the last column indicates that the parameter can be obtained directly from the database.

3.3.5 Genotype parameter

The CERES Maize model in DSSAT requires 6 coefficients to describe a crop genotype that are essential factors for crop growth and yield formation. Four of them (P1, P2, P5, and PHINT) control the timing of phenological stages, and the other two (G2 and G3) characterize the potential yield under optimal conditions.

P1 is the thermal duration (the degree days above the base temperature of 8°C) in the juvenile phase and characterizes growth when the plant does not respond to changes in photoperiod. The value of P1 for the late maturing varieties is larger than that for the early varieties.

P2 describes the photoperiod sensitivity associated with delayed growth under unfavourable long, daylight condition. It is expressed by the delayed ratio of growth due to a one hour increase over the threshold photoperiod (supposed to be 12.5 h).

P5 is defined as the cumulative period when the environmental temperature is above 8°C during the mature stage, indicating the duration of the reproductive phase. The coefficient should probably be set as the higher value for late-maturing cultivars than for the early-maturing types.

G2 is the potential kernel number per plant under the optimal condition.

G3, the kernel growth rate (mg/day), shows the filling rate under the optimal condition. For most of the Chinese cultivars, the range of G3 is from 8 to 11.

In addition, the phyllochron interval (PHINT) defines the interval in thermal time between successive leaf tip appearances.

Details about how to calibrate genotype parameters of current maize cultivars will be discussed in the next Chapter (see Section 4.2).

3.4 Modification

3.4.1 Weather generation

For the purpose of spatial impact analysis, the CERES Maize model was further developed with spatial simulation capability. The stochastic weather generator – SIMMETEO embedded in DSSAT, was used to produce daily weather for each grid cell from the monthly climate data, including maximum and minimum temperature, monthly precipitation, monthly numbers of wet days and solar radiation.

The stochastic weather series generated in SIMMETEO is associated with the random seed used in each run. The simulations with the same monthly climate data but different random seeds produce very different yields. Experiments using 1000 random seeds indicated that the mean of the cumulative simulated yield will become less variable as more runs were being taken into the sample. Four tests with different groups of random seeds (the first 120 results of the 1000 runs are given in Figure 3-3) suggest that the mean value of the cumulative simulations converged

after 100 random seed runs. Therefore, the average of 100 cumulative runs with different random seeds was used in this study.

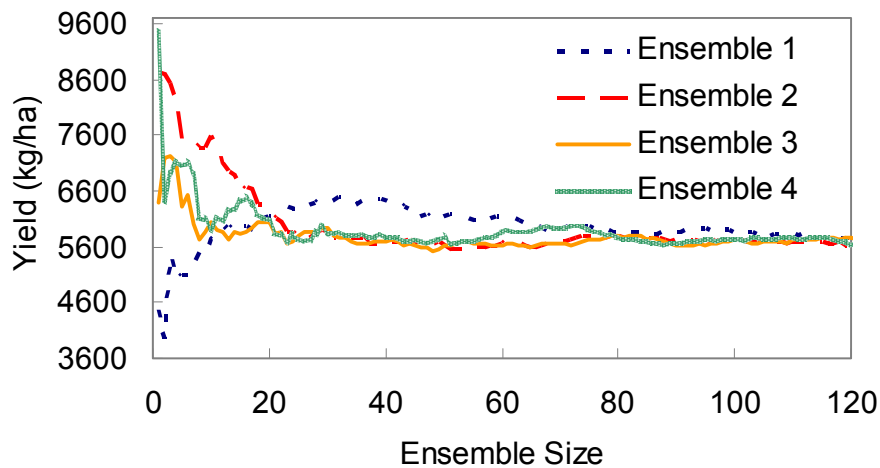


Figure 3-3 The cumulative mean simulated yield of 1000 runs at a site with 4 groups of 1000 random seeds. Only the first 120 runs are shown.

3.4.2 Irrigation scheme

The irrigation practice was also re-organized, in order to examine the effect of the total irrigation and application frequency on maize growth and production. Irrigation in DSSAT was originally applied in two ways: 1) automatic irrigation that provides optimal water covering the estimated soil water deficiency, and 2) scheduled irrigation based on presetting of application date and amount. In practice, the automatic irrigation method may require an irrigation amount exceeding the official quota, the maximum irrigation amount allowed for maize production by the local government (Provincial water quota, 2010). In the meantime the scheduled method is also not applicable for the spatial simulation, because it does not take into account the actual climate and soil conditions.

Therefore, a 2-run process was designed in this study for each grid to assign the irrigation date and apply water amount properly. In the first run, the automatic irrigation feature in DSSAT was employed to estimate the total water requirement (Q_1 in mm) and irrigating frequency (F_1) for four growth stages (i.e. before emergence, juvenile, tasseling and flowering, filling), and the ratio of water demand (Ratio, %) for each stage. In the second run, the given irrigation quota (Q_f in mm), which was likely less than Q_1 , was assigned into four stages according to P1s, then the irrigation amount in each phase (Irr2-phase in mm) was obtained. In order to irrigate evenly in each phase, the maximum amount for each irrigating in a certain phase (Irr2_max in mm) was calculated by the F_1 and the Irr2-phase.

$$\mathbf{Ratio}_{iphase} = \mathbf{Irr1}_{iphase}/\mathbf{Q1} \quad (\text{Eq. 3-5})$$

$$\mathbf{Irr2}_{iphase} = \mathbf{Ratio}_{iphase} \cdot \mathbf{Q}_f \quad (\text{Eq. 3-6})$$

$$\mathbf{Irr2_max}_{iphase} = \mathbf{Irr2}_{iphase}/\mathbf{F1}_{iphase} \quad (\text{Eq. 3-7})$$

The real irrigation is applied when the available water in the top soil is less than 60% of saturated volumetric water content, and the applied amount is between the soil water deficit estimated in DSSAT and the Irr2_max. This 2-step method has the advantage of allowing the irrigation water to be properly allocated, depending on the specific growth condition. Irrigation application efficiency applied in this study, which is the ratio of the volumetric water available for crop to the quota, is 0.4 for the furrow irrigation system in China as suggested by Su & Liu (2006).

Chapter 4 Impacts of Climate Change on Maize: a Case Study of Jilin, China²

4.1 Introduction

In this chapter, the impacts of climate change on maize in Jilin province were predicted by applying the improved DSSAT model. Firstly, two cultivars used in Jilin were calibrated. Then the impact on yield and phenology in the 2020s, 2050s, and 2070s is discussed. Uncertainties in maize yield among six climate change scenarios are also projected. In the last section, three adaptation options at farm level are assessed.

4.1.1 Data

To meet the data requirements of DSSAT, the input dataset of soil and management for Jilin province were constructed. The parameters of soil properties were produced based on the ISRIC-WISE dataset. Most of the management data was derived from NBS yearbooks and the rest is the empirical estimation from local contacts. County location in Jilin province is given in Figure 2-1.

4.1.1.1 Soil

In Jilin, the soil parameters derived from the ISRIC-WISE (WISE, Batjes, 2006) database (5×5 arc-minutes) were used, providing most of the parameters required by DSSAT within the 100-cm deep five-layer soil profiles (see Table 3-3).

² Chapter 4 has been published as a part of a Journal paper (Wang, M., Li, Y., Ye, W., Bornman, J. F., Yan, X. (2011) Effect of climate change on maize production, and potential adaptation measures: a case study in Jilin Province, China. *Climate Research*, 46: 223-242).

There are 14 soil classes of WISE classification for the case region (Table 4-1), and the soil distribution is shown in Figure 4-1. Other parameters not provided in the WISE database were estimated, depending on the following guidelines.

Table 4-1 Categories of soil profile in WISE database.

ID	Code
3964	Be
3992	Kh
4195	Gm
4225	Lo
4286	Bc
4234	Lg
4312	Ch
4343	Hg
4346	Hh
4364	Bk
4400	Kl
4429	We
4444	Zm
6997	WR

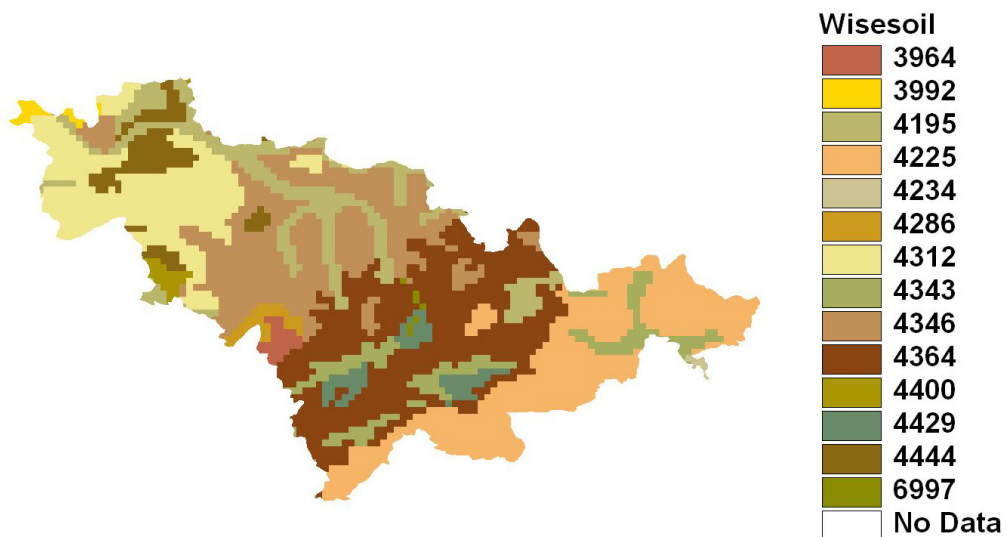


Figure 4-1 The soil profiles of ISRIC-WISE in Jilin Province.

SALB

The value of the soil surface albedo (SALB) can be estimated from the colour of the surface soil layer (Gijsman et al., 2007), shown in Table 4-2.

Table 4-2 SALB under different soil colours.

Colour	SALB
Black	0.09
Brown	0.13
Grey	0.13
Red	0.14
Yellow	0.17

U

The value of U, the first stage evaporation coefficient, is speculated from the soil texture of the 1st layer (Iglesias, 2006). In this case, the value is determined by the texture and the percentage of particles of the 1st layer (Table 4-3).

Table 4-3 U value according to soil texture.

Texture	Properties of 1st layer	U (and its range)
Coarse textured	Sandy and >30% sand	7 (5 ~ 8)
Medium textured	Loams and <30% clay	9 (8 ~ 11)
Medium textured	Loams and >30% clay	11 (8 ~ 11)
Medium - heavy textured	Clay	12 (10 ~ 12)

Note: in order to identify the differences among soil classes, the value of U adopted is distinctive for each texture class.

SWCON

The drainage coefficient (SWCON) is associated with the soil drainage class provided. In the WISE database, the drainage capacity is classified into 7 levels (see Table 4-4).

Table 4-4 SWCON estimation for different drainage class.

Drainage class	Code in WISE	SWCON
Excessively	E	0.8
Somewhat excessively	S	0.8
Well	W	0.6
Moderately well	M	0.4
Somewhat poorly	I	0.2
Poorly	P	0.05
Very poorly	V	0.005

CN

The runoff curve number (CN) describes the runoff potential of the soil, depending on both the infiltration and permeability of the whole soil profile and the slope as stated in the USDA technique release. Because of the insufficient description of such properties in the WISE database, it has to be estimated by the drainage class and the 1st layer texture instead (Table 4-5 and 4-6). The impact of the slope on runoff potential is not considered here.

Table 4-5 CN in USDA references.

Soil group	0~5%	5~10%	> 10%
A	64	68	71
B	76	80	83
C	84	88	91
D	87	91	94

Table 4-6 CN estimated based on the drainage class and the 1st layer texture.

Texture (1)	Drainage class	CN
Sandy, >30% sand	W	76
Clay	I	84
Clay	P	87
Other		76

Note: The 14 soil classes in Jilin province only refer to 3 levels of drainage, so only the corresponding CN value is given here.

SAT, LL, DUL

The saturated moisture content (SAT) and the two threshold parameters of the moisture content, LL and DUL, can be calculated from the texture at layer I (Saxton, 1986). Considering the relation between the soil texture and SAT, LL, or DUL developed by Gijsman (Table 4-7), the SAT is set by the average of the upper and lower value for each texture, and the lower (or upper) threshold value was obtained as the input LL (or DUL).

WR

The WR refers to the root distribution weighing factor that reflects the relative root growth in each soil layer. This parameter is supposed to be an exponential function of the centre depth of the I-th layer, shown as the following equation:

$$WR(I) = \exp(-4 \times Z(I)/200) \quad (\text{Eq. 4-1})$$

where $Z(I)$ is the depth (cm) to the centre of the I -th layer.

Because the above relation usually applies to deep and well-drained soil without chemical and physical stresses, the WR was modified to a smaller value according to soil constraints, e.g. it declined by 70% for the stone-based soil with the organic

carbon less than 0.3 extreme restrictions in the soil environment. In the surface layer, the WR was set as 1.00.

SWCN

The saturated hydraulic conductivity (SWCN) of the I-th layer was calculated using the software SPAW (Saxton & Rawls 2006, Saxton & Willey 2005).

Table 4-7 Estimated BD, LL, DUL, and SAT based on soil texture (Gijssman, DSSAT 4.02 Manual, 2004).

Texture	Code	LL	DUL	SAT	BD (g/cm³)
Clay	C	0.22~0.346	0.33~0.467	0.413~0.488	1.129~1.512
Clay loam	CL	0.156~0.218	0.282~0.374	0.417~0.512	1.243~1.502
Loam	L	0.083~0.156	0.222~0.312	0.415~0.501	1.245~1.483
Loamy sand	LS	0.059~0.11	0.137~0.185	0.355~0.416	1.353~1.629
Sand	S	0.055~0.085	0.123~0.158	0.374~0.4	1.446~1.574
Sandy clay	SC	0.195~0.294	0.276~0.389	0.376~0.409	1.501~1.593
Sandy clay loam	SCL	0.132~0.191	0.213~0.304	0.36~0.418	1.475~1.636
Silt	SI	0.096~0.099	0.299~0.307	0.442~0.488	0.978~1.464
Silt clay	SIC	0.224~0.326	0.379~0.456	0.455~0.489	1.307~1.446
Silt clay loam	SICL	0.155~0.219	0.324~0.392	0.448~0.511	1.248~1.464
Silt loam	SIL	0.082~0.152	0.24~0.333	0.439~0.547	0.968~1.464
Sandy loam	SL	0.066~0.133	0.164~0.243	0.348~0.499	1.142~1.647

4.1.1.2 Cropping Management

In this case, the planting density (6 plants/m²) was set to the same value for the whole area; and the fertilizer application was obtained from the county statistical data. Only the ammonium nitrogen fertilizer is considered in the fertilization. The total nitrogen application (kg/ha) in each county is the average annual chemical fertilization consumption derived from the county agriculture census (Statistics Jilin, 1998-2007), and applied evenly during the growing season. The sowing date is determined by the revised sowing scheme described below. The irrigation is applied following the scheme introduced in Section 3.4.2, and the local water quota for agriculture is 350 mm (Provincial water quota, 2010).

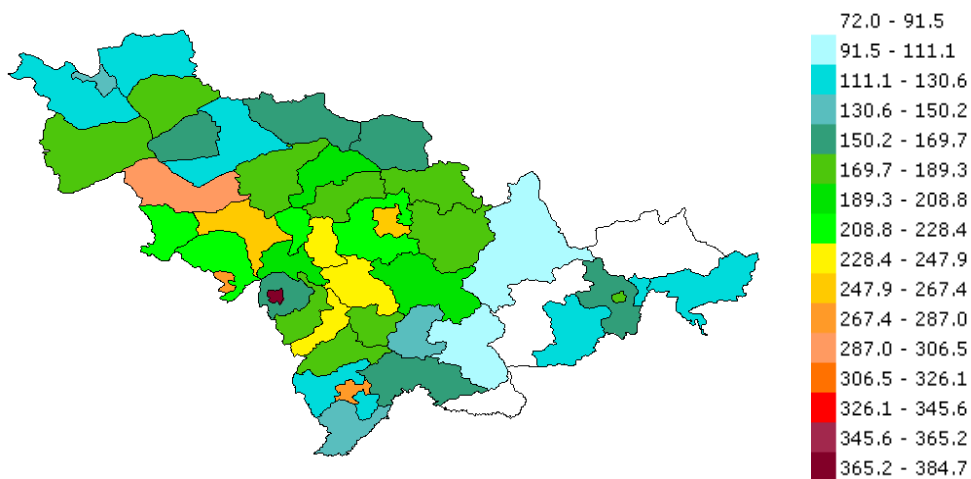


Figure 4-2 The amount of N fertilizer applied by county in Jilin Province (kg/ha).
Source: Jilin statistical yearbooks from 1998 to 2007.

Sowing scheme

The planting management was changed slightly for the Jilin case study. In the original CERES maize model, maize is automatically sown if both soil temperature and soil moisture exceed a given threshold. This rule is not appropriate for large areas of Jilin, where the required soil water condition could not be fulfilled in the

normal dry spring in spite of the appropriate soil temperature. Therefore the planting date was revised, based mainly on the soil temperature conditions: once the average soil temperature was higher than 7°C in 5 successive days, which is the lower limit of soil temperature for maize emergence (Song et al., 2006), an irrigation was applied on the planting day if the soil water content was below the threshold of 20% of saturated volumetric water content and then the seed is sown.

4.2 Calibration of maize cultivars

4.2.1 Issues in the simulation in a large area

The CERES Maize model was widely calibrated and validated in China, but in most of them the genotype parameters were estimated from single observation site experiments (Yang et al., 2006; Yu et al., 2006). Some studies expanded the spatial scale to provincial (Wu et al., 1989) and country-wide (Xiong et al., 2007; Cui, 2005), relying on the site-observed genotype as the representative for a large region, such as Cui (2005) who universalized the genotype estimated by the observed data at Dunhua to the whole Jilin province. Xiong et al. (2007) examined the accuracy of one representative cultivar in Jilin by comparing the simulation derived by the nearest weather station with the county census in 50 × 50 km grids, and pointed out a significant uneven overestimation of the mean annual yield. Such biases in spatial simulations may be caused by the homogeneous application of the cultivar obtained from a site to a region, where the actual maize cultivars in the eastern area (including Panshi, Baishan, and Tonghua) are quite different from those in the western and middle area (including Tongyu, Changling, Shuangliao, Changchun and Siping), corresponding to the different solar radiation and thermal potentials (Luo et al., 2000).

Because the mismatch of using data from single agricultural experimental stations to the regional census data for generating spatial distributions of crop genotype for

a process-based crop model like CERES-Maize requires extensive observed stations that cover the spatial area of interest, such a requirement is seldom satisfied for most crop production research. An alternative approach is to classify the area into different zones based on pre-defined crop production related factors, such as identifying the crop zones based on specific agro-ecological characteristics (AEZ) (Xiong et al., 2008) and for each classified zone, single and/or multi observed station data can be used to generate its crop genotype. Since this study is focused on the climate change impact, it appears that it would be much more appropriate to classify the zoning of maize cultivar based on climate characteristics. However, there are not enough available observation stations in Jilin to support a selection of maize cultivars for each conventional climate zone (Luo et al., 2000). Consequently, only two distinctive maize cultivar zones are found through calibration, and based on these zones, cultivars are selected and the maize model is calibrated, as described below.

4.2.2 Solution

Considering the spatial-heterogeneity of the maize cultivar, the genotypes used for the thesis study were calibrated and validated by multi-year observation (including yield, planting date and harvest date) at 11 agro-meteorological stations located in the different regions of Jilin (in Table 4-9). The required data, including daily weather records (maximum and minimum air temperature, precipitation, sunlight duration, and relative humidity) and the observed crop data from 1996 to 2006 (annual yield, planting date and harvest date), were obtained from the China Meteorological Data Sharing Service System (<http://cdc.cma.gov.cn/index.jsp>).

The evaluating indicator (I_e) was a combination of two indexes, which are used for genotype selection. The mature date index (I_m) defines the difference in

physiological stage between simulation and observation, and the yield index (I_y) is used to evaluate the fit of the simulated yield to the observations:

$$I_e = I_m + I_y = (1 - M_{sim}/M_{obs})^2 + (1 - Y_{sim}/Y_{obs})^2 \quad (\text{Eq. 4-2})$$

Thus, a smaller I_y or I_m indicates a better estimate of yield or mature date using a certain cultivar.

An iteration method is applied to obtain the optimal cultivar (Figure 4-3). Firstly, 30 trial genotypes were sampled within the reference range using the uniform design method (Zhang et al., 2004) at each iterative step. The initial reference ranges of P1, P2, P5, G2, and G3 are from DSSAT documents (Table 4-8). Secondly, a new narrower range for sampling trial genotypes is decided from the cultivars with the two smallest I_e s from the 30 trials; and the iteration was completed when the difference between the upper and lower range of genotype coefficients was less than the 5% of its magnitude.

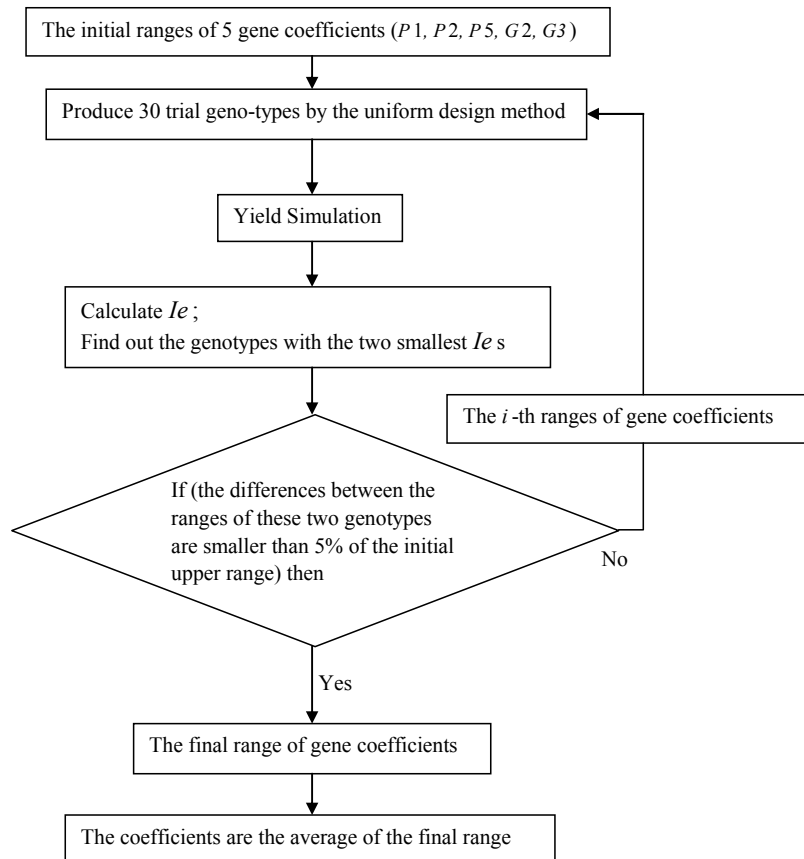


Figure 4-3 Iteration steps to get the optimal genotypes using the spatial observations.

Taking account of the average I_e at 11 stations in 11 years (from 1996 to 2006), it was found that the range of physiological coefficients (P1, P2 and P5) at the stations located in the west and middle areas shows a different trend from those in the southeast. Therefore, two groups of genotype coefficients (Table 4-8) were estimated for two different areas, with 5 calibrated sites for the late cultivar and 6 sites for the slightly early cultivar, respectively (Table 4-9). The bias of the simulated yield (or growing seasons) at most stations drops in the $\pm 10\%$ of its observed value (provided in Table 4-9)

Table 4-8 The maize genotype coefficients.

Genotype coefficient		Initial reference range	Cultivar	
			Late	Early
P1	The thermal time from seeding emergence to the end of Juvenile stage (degree days above the base temperature of 8 °C in juvenile stage)	125~400	280	270
P2	The photoperiod sensitivity associated with the delayed growth under the unfavourable long-daylight condition	0.1~0.8	0.3	0.3
P5	The thermal time from silking to physiological maturity (degree days above base temperature of 8 °C in mature stage)	500~900	790	700
G2	The potential maximum number of kernels per plant	500~850	720	720
G3	The kernel filling rate under optimum conditions (mg/day)	5~12	8.5	8.5
PHINT	The interval in thermal time between successive leaf tip appearances	35~75	38.9	38.9

Table 4-9 Calibration at 11 agro-meteorological stations.

Station	Long. ^a	Lat. ^a	Alt. ^b	Cultivar	Y_{sim} / Y_{obs} ^c	M_{sim} / M_{obs} ^c
Changling	123.97	44.25	190.4	Late	0.55	0.94
Nongan	125.16	44.41	190.0	Late	0.92	1.03
Yushu	126.53	44.83	206.0	Late	0.87	1.06
Lishu	124.3	43.35	160.0	Late	1.05	1.05
Jian	126.15	41.1	177.7	Late	0.94	0.96
Shulan	126.93	44.42	252.0	Early	0.87	1.06
Yongji	126.56	43.7	232.4	Early	0.99	0.95
Dunhua	128.2	43.37	523.7	Early	1.23	1.13
Liaoyuan	125.08	42.92	254.0	Early	1.05	1.01
Meihekou	125.63	42.53	341.5	Early	0.94	0.94
Huadian	126.75	42.98	264.2	Early	0.9	1.0

^a Latitude north and longitude east in degrees and decimals

^b Altitude in metres

^c The 11 year mean ratio of simulations to observations

4.2.3 Maize cultivars in Jilin

The boundary between the late and early cultivar (shown by the bold curve in Figure 4-4) was decided on the following criteria: 1) the calibration at 11 agro-meteorological sites; 2) the maize variety distribution in Northeast China estimated from the local climate temperature conditions by Luo et al. (2000), which suggests that the optimal maize varieties in the eastern area (including Panshi, Baishan, and Tonghua) are quite different from those in the west and middle areas (including Tongyu, Changling, Shuangliao, Changchun and Siping); and 3) the conformability of the annual yield simulation to its statistic with respect to the two cultivars in each county. Basically, the cultivar selection based on the 11 sites that have reliable observed daily weather data and crop records is the top criterion among the three in determining the boundary, followed by local observations, and finally the comparison of yield simulations obtained by gridded-climate data with county census of yield.

To validate the model for spatial simulation, the census yields and simulations at county level were compared. The annual yield was simulated with the CRU time-series climate data from 1990 to 2002 (Mitchell & Jones, 2005), the two cultivars obtained, as well as the soil properties and crop management mentioned above. The county level yield was obtained by aggregating the yield simulation for grids where maize is sown. The percentage of maize sown area in 5×5 minutes grid (Figure 4-4) was obtained from the Global 18 Major Crops dataset in 1992 (Leff et al., 2004). The annual county maize yield data is the census data from 1990-2002 (Statistics Jilin Province, 1990-2002).

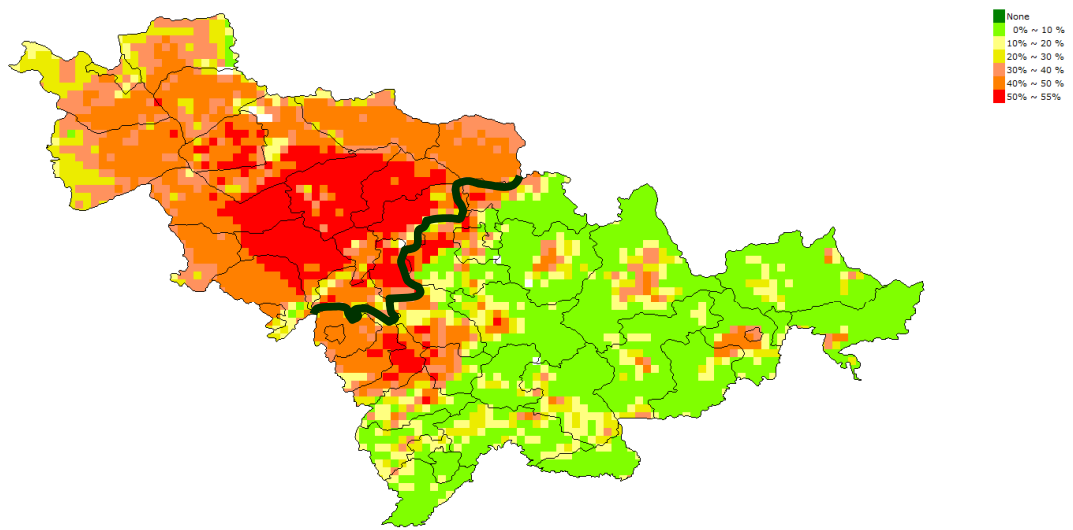


Figure 4-4 The maize sown area percentage of each grid in Jilin Province. The boundary of early and late maize cultivars is marked by the bold curve, on the left of which the late cultivar is sown, and on the right is the early cultivar.

Table 4-10 Comparison of mean bias in yield simulations to county census under two cultivars.

Region	County	Mean bias ^a		Cultivar ^b
		Early	Late	
Baicheng	Baicheng	-5.7%	-9.2%	Late
	Daan	18.4%	-2.5%	Late
	Taonan	-6.5%	23.4%	Late
	Tongyu	40.9%	71.1%	Late
	Zhenlai	-0.7%	16.6%	Late
Songyuan	Changling	28%	12.1%	Late
	Fuyu	24.4%	-8.7%	Late
	Qianan	13.1%	-5.8%	Late
	Qianguo	10.9%	-7.8%	Late
Changchun	Changchun	10%	-7.05%	Late
	Dehui	15.9%	-1.8%	Late
	Jiutai	21.5%	-4.9%	Late
	Nongan	32%	17.4%	Late
	Yushu	23.1%	-8.1%	Late
Siping	Gongzhuling	43.2%	30%	Late
	Lishu	48.1%	36.3%	Late
	Shuangliao	24.7%	7.9%	Late
	Siping	54.2%	44.4%	Late
	Yitong	34.5%	19.5%	Late

^a Mean bias is the average difference between the simulated yield and the county census from 1990 to 2002.

^b The cultivar in each county finally used in the present study.

Table 4-10 Comparison of mean bias in yield simulations to county census under two cultivars (continued).

Region	County	Mean bias ^a		Cultivar ^b
		Early	Late	
Jilin	Huadian	14.5%	-4.8%	Early
	Jiaohe	10.1%	-1.7%	Early
	Jilin	11.3%	-7.7%	Early
	Panshi	-0.8%	16.2%	Early
	Shulan	16%	-3%	Early
	Yongji	-2.1%	18.4%	Early
Liaoyuan	Dongfeng	-9.9%	10.2%	Early
	Dongliao	25.3%	-7.7%	Early
	Liaoyuan	22.1%	51.3%	Early
Baishan	Baishan	18%	24.7%	Early
	Changbai	53.1%	56.9%	Early
	Fusong	-8.8%	10.7%	Early
	Jingyu	-9.2%	21.5%	Early

^a Mean bias is the average difference between the simulated yield and the county census from 1990 to 2002.

^b The cultivar in each county finally used in the present study.

Table 4-10 Comparison of mean bias in yield simulations to county census under two cultivars (continued).

Region	County	Mean bias ^a		Cultivar ^b
		Early	Late	
Tonghua	Huinan	14.6%	-1%	Early
	Jian	20.8%	35.7%	Early
	Liuhe	21.5%	-5.5%	Early
	Meihekou	14.8%	-2.8%	Early
	Tonghuashi	42.6%	69.7%	Early
	Tonghuaxian	19.9%	41.2%	Early
Yanji	Antu	23.1%	17.6%	Early
	Dunhua	15.9%	15.5%	Early
	Helong	25.4%	32.1%	Early
	Hunchun	49.8%	53.2%	Early
	Longjing	31.2%	34.9%	Early
	Tumen	35.3%	39.3%	Early
	Wangqing	15.1%	14.6%	Early
	Yanji	26%	33.2%	Early

^a Mean bias is the average difference between the simulated yield and the county census from 1990 to 2002.

^b The cultivar in each county finally used in the present study.

A comparison was made of the mean and standard deviation (SD) from the 12-year simulations to the county census yields (Figure 4-5). The mean yield simulations are about 10% lower on average than the reported county statistics. The relative bias in the central part, ranging from -18% to 11%, is moderate, which indicates that the model performed a reasonable estimation of mean yield in the major maize sown area. However, there was a significant overestimation in low level yield counties (e.g. Tongyu in the west dryland area, and counties close to eastern mountains) and a slight underestimate in the high level yield area (Figure 4-5-a), i.e. the Siping region. The spatial correlation coefficient of the aggregated simulations with the 47-county census reaches 0.6 (passed the 99% confidence level, two-tailed *t*-test). With regard to the SD of the 12-year yield, the simulated values are much smaller than that of the census for most counties, except those where mean yields are overestimated (Figure 4-5-b).

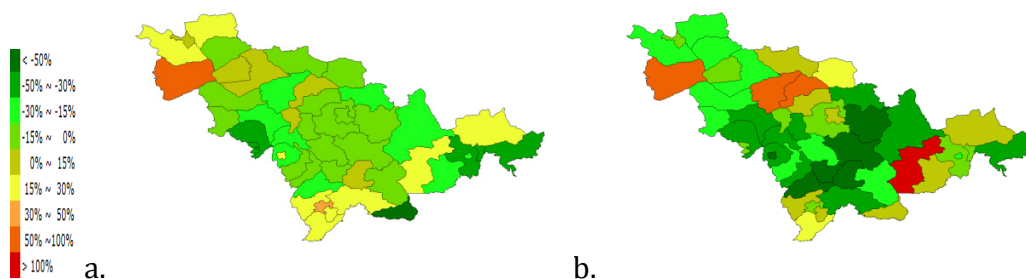


Figure 4-5 The bias of the mean(a) and SD(b) of yield simulations to the county census. The annual county yield is derived from the Yearbooks of Jilin Province from 1990 to 2002.

In general, the former simulation in the literature significantly overestimated the mean yield, while a slightly lower estimation was found in this study. This is probably attributed to the differences in daily weather resource and aggregation approach.

- In contrast with the daily observations, the SIMMETEO stochastic weather generator used in the present study, and as suggested by Soltani et al. (2003), has some weakness in reproducing maximum and extreme temperatures, as the result of which the final simulated yield sensitive to the daily temperature amplitude (Dubrovský Žalud et al., 2000) may be lower than the observed.
- In addition, the gridded simulations were aggregated to country level in the current study, which may have introduced some errors due to this rescaling process.

4.3 Impacts of climate change on maize production

This study was mainly focused on the impact from the changes of the monthly mean temperature and total precipitation, with other climate variables, such as solar radiation and wind speed, being kept at the baseline level. The possible fertilization effect of the rising CO₂ concentration is not included in our model, because of its uncertainty in the field experiments considering the contemporary temperature increase and the limits of water supply (Elliott, 2013).

The median value of climate change projections shows a consistent warming trend and increased precipitation during the maize growing season (Apr. – Sept., Figure 4-8). The temperature increases to a little above 0.6, 1.6 and 2.4°C in the years 2020, 2050 and 2070, respectively, with slight spatial variations, and the total precipitation increases around 2.3, 6.2 and 9.0%, correspondingly. The warming trends in April, August, and September are moderately higher than in the other 3 months (May, June and July), whereas 85% of the precipitation increase happens in May, August, and September.

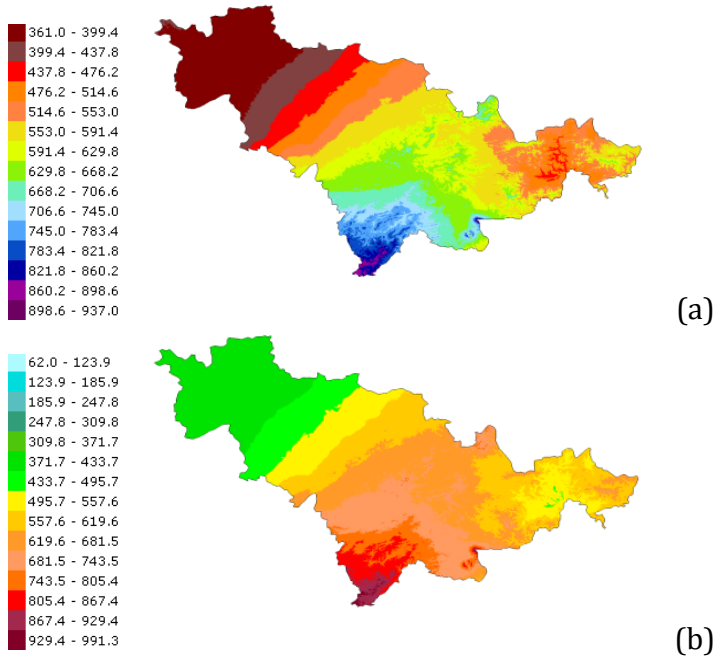


Figure 4-6 The total precipitation (mm) during the growing season (from April to September) in the baseline (a) and in the year 2050 (b).

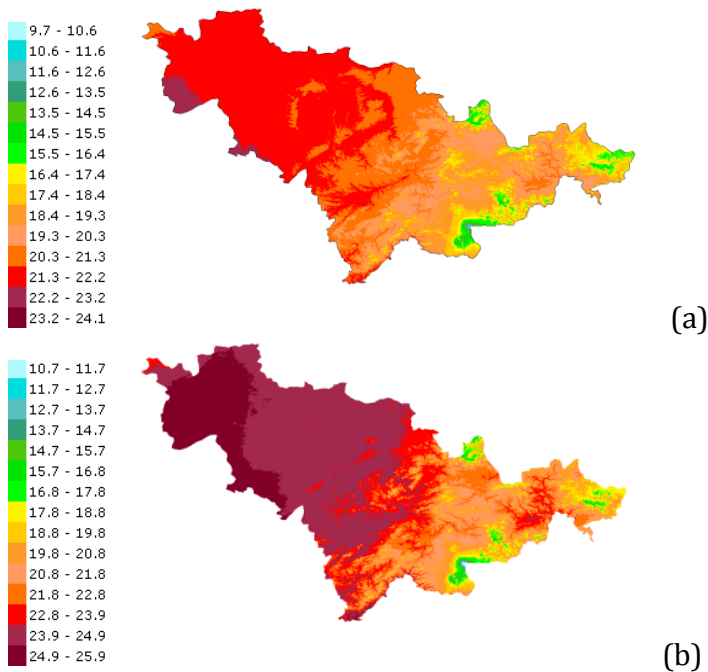


Figure 4-7 The average of maximum temperature (°C) during the growing season in the baseline (a) and in year 2050 (b).

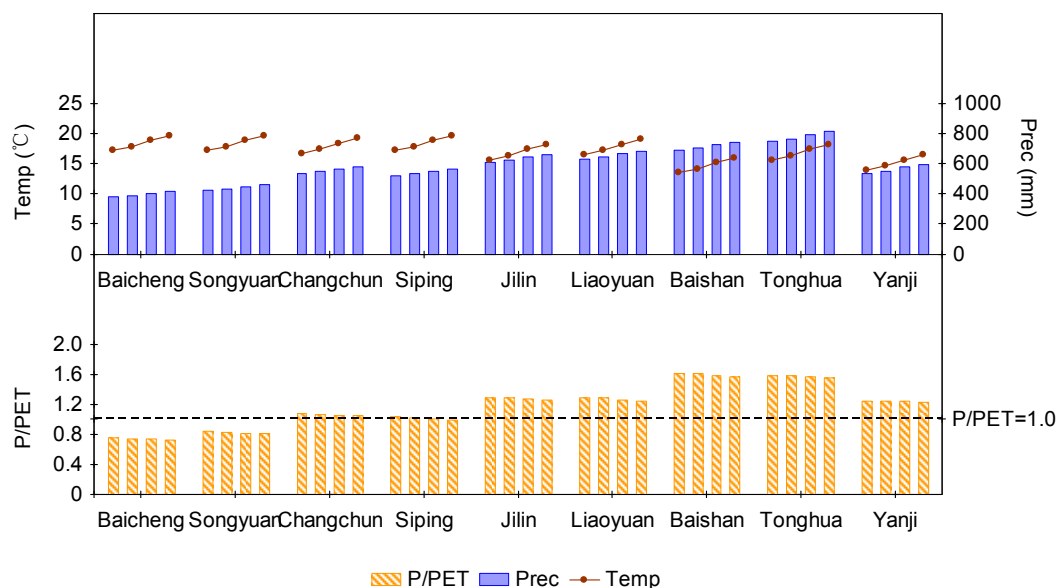


Figure 4-8 The baseline climate and the median climate change scenarios in Jilin Province in 2020, 2050, 2070.

Temp. (°C) is the average monthly temperature during the maize growing season (from Apr. to Sep.); Prec. (mm) is the total precipitation during the growing season; and P/PET is the ratio of total precipitation to the potential evaporation in maize during the growing season.

Although both temperature and precipitation increase, it is the change of the dry or wet status that is more pertinent to crop yield. The change in dry or wet status in the growing season was measured by looking at the ratio of precipitation (P) to potential evaporation (PET), i.e. P/PET. The monthly potential evaporation was calculated using the monthly average temperature by the Thornthwaite method (Ma et al., 2005). There is a clear correlation between maize yield and P/PET for the central and western areas (Baicheng, Songyuan, Changchun, and Siping). For all the regions in Jilin province, the P/PET ratio is projected to decrease in the future. The PET is mainly decided by temperature. In Jilin, the decrease means that the magnitude of PET increase due to high temperature is bigger than the rainfall increase. In the middle area, the total PET from April to September surpasses the precipitation, which implies an enhanced aridification trend for all regions of Jilin.

The current semi-dry area in the central region is likely to become even drier, and the present dry west may undergo a larger water deficit in the coming decades.

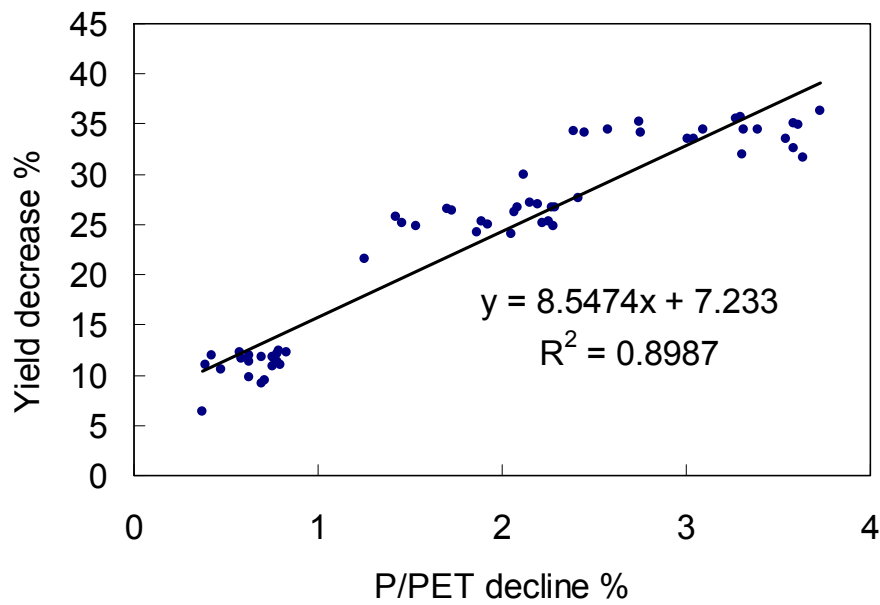


Figure 4-9 The change in maize yield responding to future decline in P/PET during the growing season (form Apr. to Sep.) in Baicheng, Songyuan, Changchun, and Siping.

The yield change (each point) is aggregated at county scale.

4.3.1 Impact on yield

In general, the future yield is projected to decrease in the main sown area, but increase in a few counties in the eastern area. The wide western and central regions, including Baicheng, Songyuan, Changchun, Siping, and parts of Liaoyuan and the Jilin District, are likely to experience a significant yield reduction due to the increasing dryness. The largest reduction tends to be about 1.1, 2.1 and 2.7 t/ha in the years 2020, 2050 and 2070, respectively, for the central cropping area that covers Changchun, most of Songyuan and the northern part of Siping (Figure 4-10).

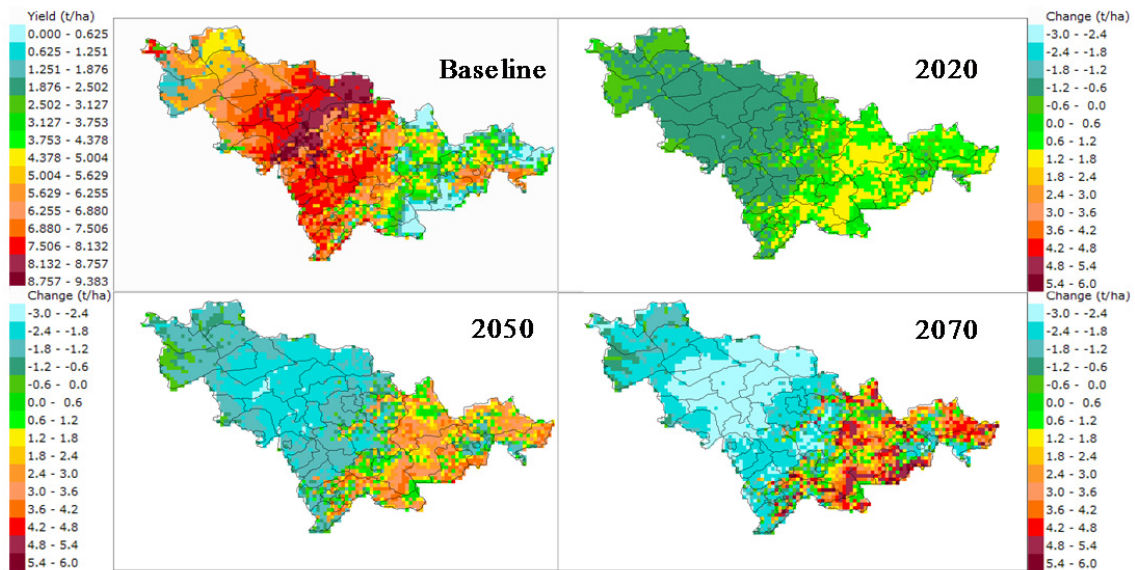


Figure 4-10 The simulated maize yield (t/ha) at baseline and its change in 2020, 2050, and 2070

In contrast, a favourable rise in yield emerges for the current marginal maize-growing regions in the eastern mountainous areas. Some unsuitable areas at present could have a doubled maize yield in 2050. It is worth noting that in the southeast of Tonghua and part of Yanji, the future change in yield is initially projected to go up in 2020 but fall again by around 2.0 t/ha towards the end of this century.

Temporally, the projected yield change suggests a significant difference from one region to another in the evolvments along with climate change.

In the regions with the downward trend, the reduction of regional average yield in central counties (Songyuan, Changchun, Liaoyuan, and Siping) is projected to be about 10% in 2020 but more than 20 and 30% in 2050 and 2070, respectively (Table 4-11). For the Jilin District and Tonghua, the reduction is less obvious

initially but becomes significant towards the middle and end of the century. For the two eastern regions, Yanji and Baishan, there appears to be a large benefit in maize production during the first fifty years. However, the gains are likely to be retarded towards the end of the century because the potential productivity of the existing cultivar would have been fully exploited in line with the corresponding local temperature increases.

Table 4-11 The maize yield projections (t/ha) in 2020, 2050 and 2070 using 20 GCMs under 6 SRES emission scenarios.

Region		Baseline (t/ha)	2020	2050	2070
Baicheng	Median ^a	5.08	4.34 (-14.6%)	3.66 (-27.9%)	3.26 (-35.9%)
	Range ^b		3.80 ~ 4.55	2.60 ~ 4.17	1.85 ~ 3.92
Songyuan	Median	6.94	6.33 (-8.7%)	5.27 (-23.9%)	4.66 (-32.8%)
	Range		5.67 ~ 6.64	3.92 ~ 5.85	3.00 ~ 5.45
Changchun	Median	8.15	7.33 (-10.0%)	6.02 (-26.2%)	5.33 (-34.6%)
	Range		6.77 ~ 7.68	5.00 ~ 6.72	4.03 ~ 6.22
Siping	Median	7.14	6.35 (-11.0%)	5.26 (-26.4%)	4.64 (-35.0%)
	Range		5.76 ~ 6.64	4.07 ~ 5.86	3.21 ~ 5.38
Liaoyuan	Median	7.14	6.46 (-9.5%)	5.43 (-23.9%)	4.88 (-31.6%)
	Range		6.04 ~ 6.71	4.66 ~ 5.93	3.89 ~ 5.48
Jilin District	Median	6.98	6.76 (-3.2%)	5.96 (-14.6%)	5.33 (-23.6%)
	Range		6.50 ~ 6.90	5.12 ~ 6.50	4.09 ~ 6.13
Baishan	Median	4.23	4.75 (12.2%)	5.60 (32.3%)	5.71 (34.8%)
	Range		4.51 ~ 5.03	5.27 ~ 5.86	4.85 ~ 5.97
Tonghua	Median	7.06	7.04 (-0.3%)	6.39 (-9.6%)	5.73 (-18.9%)
	Range		6.86 ~ 7.13	5.49 ~ 6.79	4.41 ~ 6.45
Yanji	Median	4.16	4.62 (11.1%)	5.18 (24.6%)	5.15 (23.9%)
	Range		4.45 ~ 4.82	4.79 ~ 5.34	4.05 ~ 5.43

^a The median yield of 120 projections by 20 GCMs under 6 SRES scenarios, and the reduction ratios to baseline yield are given in parenthesis.

4.3.2 Uncertainty in yield projection

Figure 4-11 displays the predictions under each scenario in order to identify the uncertainty within specific SRES. In the yield reduction areas, the biggest reduction is projected by the A1T scenario in 2020, but is overtaken by the A1FI scenario in 2070. The projection of the B1 scenario has the smallest reduction for most of the area in most future periods. With regard to the positive change areas of Baishan and Yanji, the differences among six SRES projections are much less than those in the areas with reduced yield. The lowest yield is projected by the B1 group simulations for Baishan in 2050, but is again overtaken by the A1FI group simulations in 2070. For Yanji, the A1FI group simulation consistently has the lowest forecasting for all time periods.

The probabilities of six reduction levels (5, 10, 20, 30, 40, and 50% reduction relative to the baseline yield) to quantify the likelihood of yield change were investigated. The probability density distribution of 120 regional yield simulations (from 20 GCMs under 6 SRES) was estimated by the Gauss kernel method (Parzen 1962), and then the cumulative probability of each reduction level was calculated (Figure 4-12). Results showed that Baicheng is most vulnerable to climate change. For the same reduction rates, this region demonstrates the highest probabilities for all future time periods simulated. In contrast, the Jilin District has the most resilience. Its 2020 reduction was projected to be less than 10% for all simulations, and a relative small probability that it would have a 50% reduction by 2070. Apart from the Jilin District, other maize-growing regions all gave more than 90% probability to have a 10% reduction for 2050, and a 20% reduction for 2070.



Figure 4-11 The projected range of maize yield of 9 regions under 6 SRES (A1B, A1FI, A1T, A2, B1, and B2). The black cross is the median yield of 20 projections, and the colour bar shows the 10th and 90th percentile range. The baseline yield is shown as the black line.

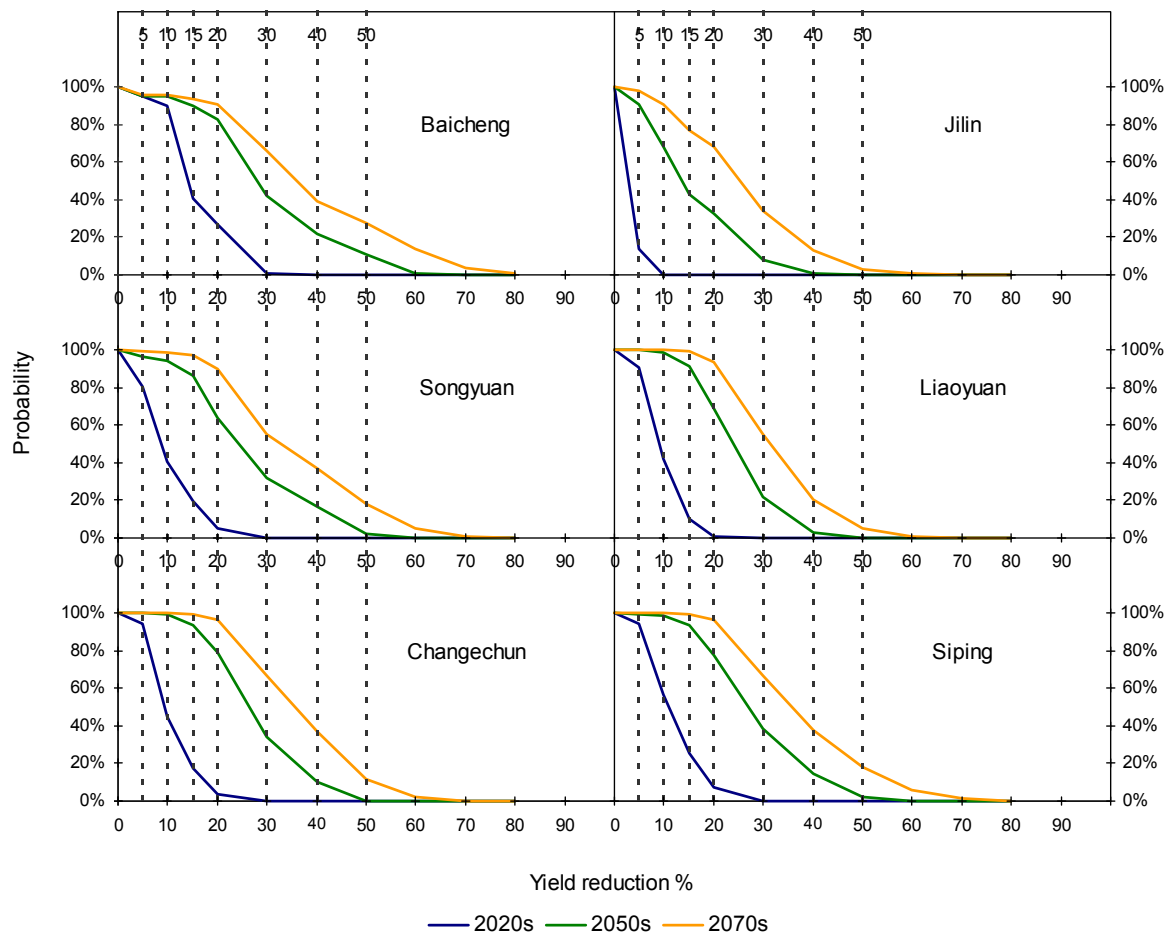


Figure 4-12 The probability of maize yield reduction of 6 regions in 2020, 2050 and 2070.

4.3.3 Impact on phenological features

Climate change also has an impact on the maize phenology, since the temperature change influences the schedule of maize sowing, flowering and grain-filling.

4.3.3.1 Planting date

Spatially, the sowing date of maize will slightly advance in future due to the warming trend in spring. The average result of 100 runs under the median projection of climate change reveals that the sowing date will be 1.5, 3, and 4 days earlier in 2020, 2050, and 2070, respectively, than the baseline for the main cropping areas, and the advance in the eastern regions even exceeds one week after 2050 but with quite high spatial variability (see Figure 4-13). The advances in the eastern regions are due to the comparatively lower sowing temperature threshold of April and May that could be easily surpassed in future warming. Phenologically, the early sowing helps to prolong the maturity season of the current early maize cultivar in the east and is a favourable change for maize yield.

4.3.3.2 Flowering date

Similar to the sowing date changes, there is also an advance in flowering date but with a more homogeneous pattern for the whole province. The flowering dates are 2, 3 and 4 days earlier for 2020, 2050 and 2070 (see Figure 4-14).

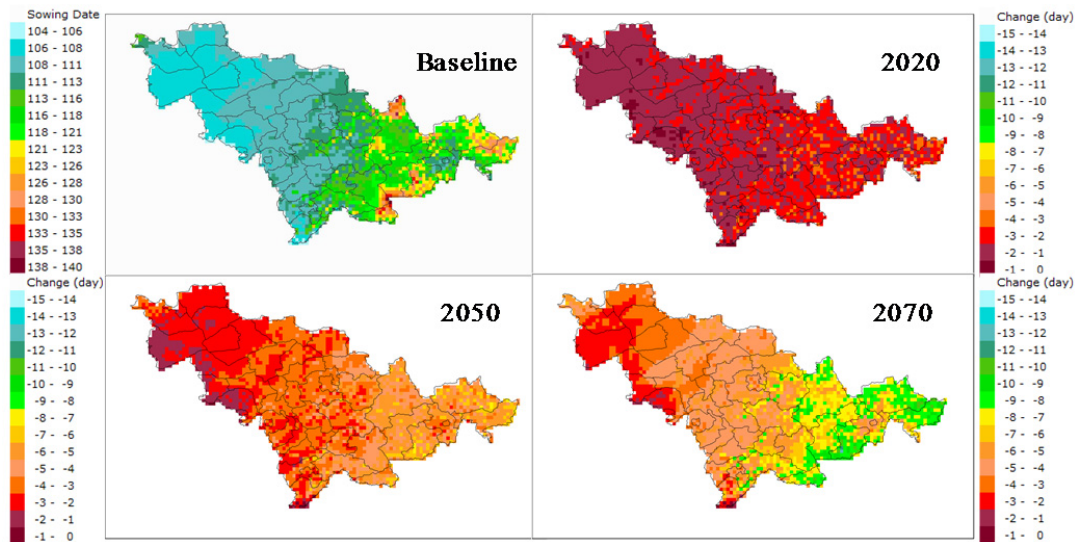


Figure 4-13 The maize sowing date at baseline and its changes in 2020, 2050 and 2070 (negative value means advanced date).

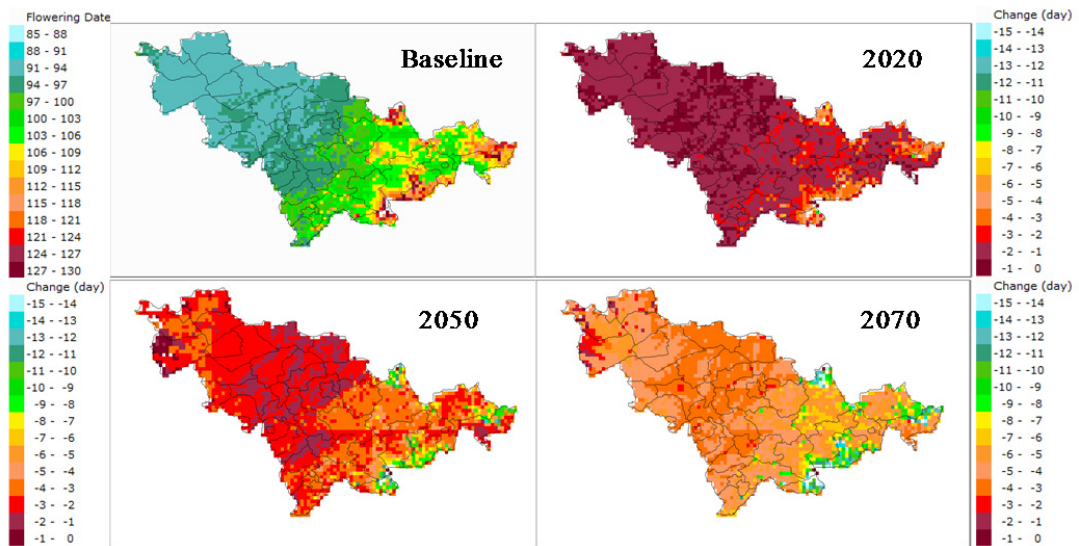


Figure 4-14 The simulated flowering date (days after being sown) at baseline and its probable advances (in earlier days, negative) in 2020, 2050 and 2070.

4.3.3.3 Maturity period

As distinctive from the changes in sowing and flowering phases, the entire number of maturity days (from sowing to harvest) is predicted to shrink in the central and western plains, ranging from about 10 to 30 days shorter in the next few decades, but be lengthened by 8~22 days in the eastern mountainous areas covering Yanji, Baishan and part of Tonghua (see Figure. 4-15).

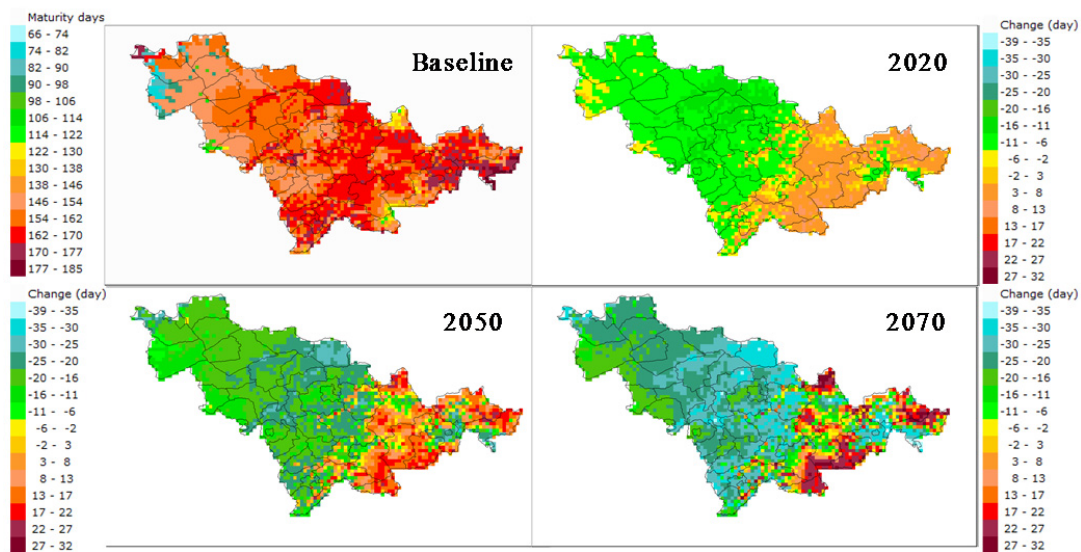


Figure 4-15 The simulated number of maturity days (days after being sown) at baseline and its probable advances (in earlier days, negative) in 2020, 2050 and 2070.

4.3.3.4 Grain filling period

Despite the advance in both sowing and flowering dates (1 to 5 days earlier), it is the changes in the reproduction phase (periods after flowering, including tasseling and grain-filling) that may contribute to most of the changes in maize phenology (10~30 days shorter in middle-western areas and 8~22 days longer in the east). Hence, it is likely that the varied length of the reproduction phase may link with

yield changes. In this part of the study, the single run simulation of both yield and growth phases at selected sites was calculated and analysed.

Four sites were chosen for this experiment, two in the far west (Baicheng and Tongyu), and two in the east (Dunhua and Huadian). Three periods of growing phase are considered: the period from sowing to tasseling, from the first tasseling to the beginning of grain-filling, and from grain-filling to maturity.

Evidently at both Baicheng and Tongyu, the shrinking of the maize-filling period takes more than half of the overall reduction of the growth season, while the simulations at Dunhua and Huadian show performance in the reversed manner: the grain-filling is prolonged despite the shortening trend in the periods from sowing to flowering (Figure 4-16). We may conclude that the possible increase in maize yield in eastern cold counties is mainly attributed to the improvement of local thermal conditions, as the regional warming develops, which could significantly extend the grain-filling phase. The physiological mechanism for the prolonged period of grain filling in Dunhua and Huadian in DSSAT is: the increased temperature in these sites prolongs the period when temperature is above the threshold temperature at which the grain filling would start.

It is also worth noting that, since the maize yield in some western counties is likely to decrease in the future, even in the automatic irrigating test, in which the irrigation supplies enough water for maize growth, such a reduction in yield is probably not caused by the deficient water supply, but induced by the shortened grain-filling period.

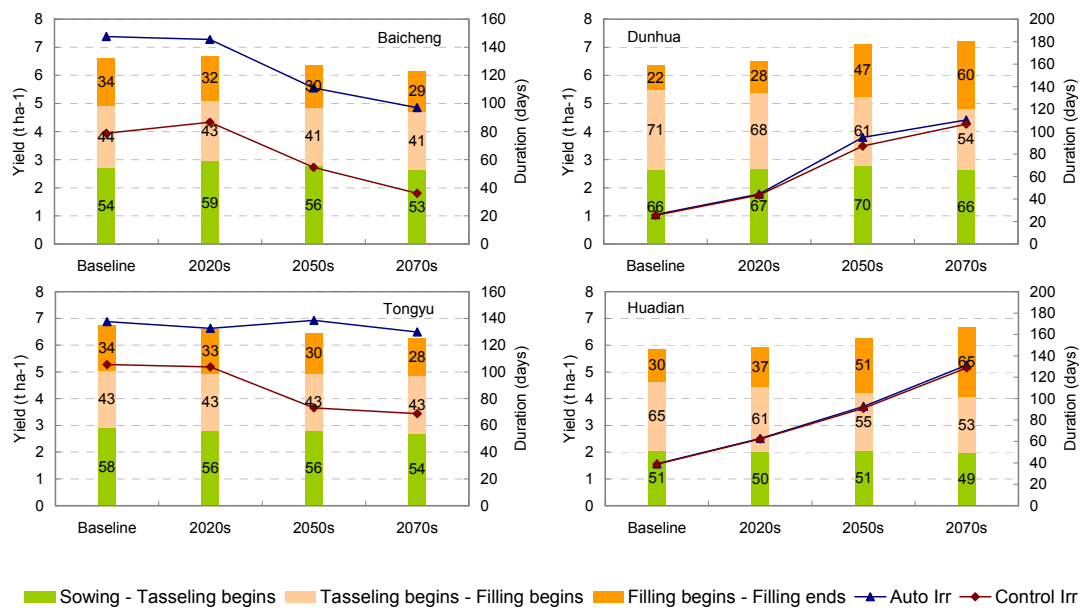


Figure 4-16 The maize yield and phenological indicators under two irrigating strategies at four selected sites. The line and symbols show the simulated yield obtained using automatic and controlled (in blue and red) irrigation.

4.4 Adaptation options at farm level

As discussed previously, the changes in dryness and length of grain filling are the two main factors that have major influences on the future maize yield change in Jilin province. Therefore any effective adaptation options need to have these two factors properly addressed. Alteration of the current irrigation practice, such as adding to the total applied water, is the most obvious measure against the dryness trend, and the assessment of this option is now discussed in detail.

4.4.1 Improving irrigation strategy

A test of the gradual increase of the total water supply by raising the irrigation quota from the present 350 to 750 mm with an increment of 50 mm was carried out for sites Baicheng and Tongyu, both in the western areas. It is evident that the increase in total irrigation helped to maintain the present maize yield with climate change for western regions (Figure 4-17). For Baicheng, the irrigation quota is required to increase approximately 30% in 2020, and be nearly doubled in 2050, in order to acquire the baseline level yield. However, in 2070, even the largest irrigation level cannot produce the baseline level yield. The situation seems to be worse in Tongyu, where the yield lost cannot be compensated for by the increased irrigation quota after 2050, as the yield is limited by the current genotype due to the shortened grain filling period. The positive effect is more significant initially with the irrigation quota increasing from 350 to 550 mm, but less so for higher levels of irrigation.

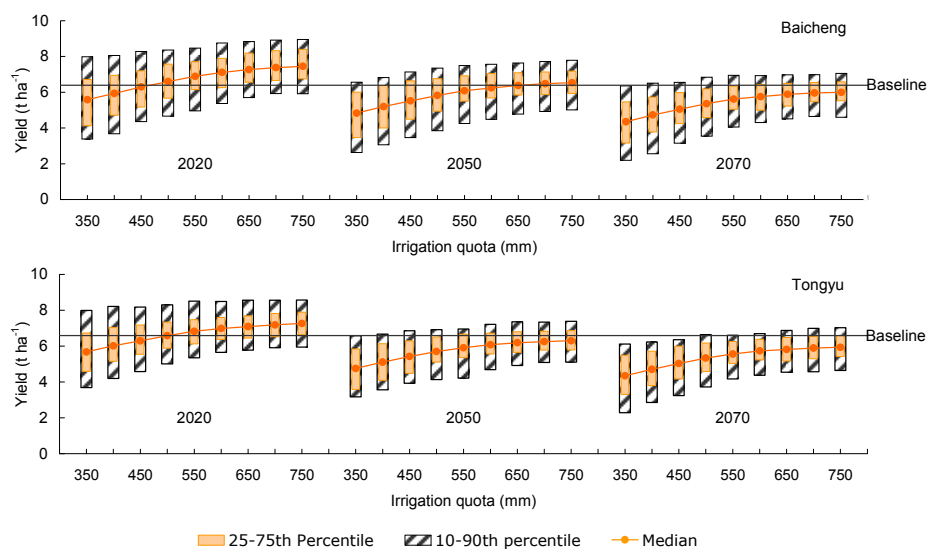


Figure 4-17 The effects of total irrigation enhancement on maize yield at Baicheng and Tongyu.

The experiments were carried out 100 times for each site under the median climate change scenario. The median result of those runs is in the yellow line and symbols, and the ranges between the 1st and 3rd quartiles and between the 10th and 90th percentile are respectively marked by the grey and orange bars.

4.4.2 Introducing new cultivars or changing the planting schedule

Since the yield reduction in the western area likely resulted from the fact that the current cultivar cannot take advantage of future warmer temperatures even with sufficient water supply, experiments were carried out to investigate the performance of a series of maize cultivars that are adjusted to the longer growing season as global warming develops. The experiments excluded the influences of soil water and nutrition on yield by assuming optimal irrigation and fertilization conditions, in order to limit the study to the phenological effect only.

As mentioned in Section 3.3.5, the phenological timing in the CERES-maize model is controlled mainly by the coefficients P1, P2, and P5. In our experiments, P1, P2 and P5 are assigned with 7, 3 and 8 different levels, respectively (Table 4-12), so in total 168 cultivars ($7 \times 3 \times 8$) were tested. The genotype coefficients, G2, G3, and PHINT, were kept on the same current level. Therefore, the differences among the simulated yields are attributed to the alterations in phenological coefficients (P1, P2, and P5) of maize cultivars. The yield and length of the juvenile and reproduction phase were simulated using 168 new cultivars at Baicheng, which is located in the dry western area.

Both the effects of increasing a single coefficient and changing multi-coefficients were examined. Increasing the photoperiod sensitivity to unfavourable daylight (with larger values of P2) had little impact on the maize growth with whatever levels of P1 and P5 were used. If only the juvenile phase was elevated, the yield was projected to increase slightly in future and the period from flowering to maturity was extended. The yield projection of all these cultivars appears as a downward time trend in the future, except the case in which P1 is 360 and P5 is 1100 or 1150. An increase in P5 has a clear positive effect on yield, particularly with low P1

(Figure 4-18, P1=280). For about every 50 GDD change in P5, the grain filling phase has a one week extension before 2050 and a 3-day extension after 2050. The combined effect of increasing P1 and P5 improves the maize yield even further as shown in Figure 4-18, P1=320 and P1=360. Within the suggested range in the DSSAT document, the maximum yield in year 2020 occurs when P1 is 320 and P5 is 1000 or 1100, if the seed-breeding technology becomes available. For 2050, the cultivar that has the highest yield is the one with P5 at 1150.

Table 4-12 Genotype coefficients sensitivity experiments for selecting potential maize cultivars.

Genotype coefficient	Value
P1	280, 300, 320, 340, 360, 380, 400
P2	0.3, 0.5, 0.7
P5*	790, 850, 900, 950, 1000, 1050, 1100, 1150

* The value of P5 suggested in the DSSAT document, ranges from 0 to 1000; however, 3 values of P5 larger than 1000 were tested in order to identify any possible cultivars with the best yield in the future.

In addition to the genotype coefficient sensitivity experiment, five existing cultivars calibrated in previous studies on Chinese maize were tested. There are three alternative cultivars which were originally cropped in warmer climate regions, and which might slow down the maize reduction trend in the coming decades in Jilin province, as shown in Figure 4-18-d. In the control run, the spring maize, JilinLate, which is calibrated in Section 4.2.3 (P1=280, P2=0.3, P5=790, G2=720, G3=8.5, PHINT=38.9) was used. The alternative cultivars include: Jiao3danjiao (Xiong et al., 2007), a spring cultivar from Southwest China, with P1=320, P2=0.3, P5=900,

G2=700, G3=9.2, PHINT=38.9; Huangbao1 (Yang et al., 2006, P1=300, P2=0.3, P5=640, G2=740, G3=14, PHINT=60) and Luyu13 (Nakayama et al., 2006, P1=320, P2=0.3, P5=620, G2=720, G3=11, PHINT=45), which are summer cultivars maturing faster than the spring maize JilinLate now planted in Northeast China. All these alternative cultivars tested are originally cropped in the area quite far away from Jilin province. More realistic alternative cultivars should be the spring cultivars from the southern part of Northeast China. However, the genotype coefficients in the related studies are unavailable.

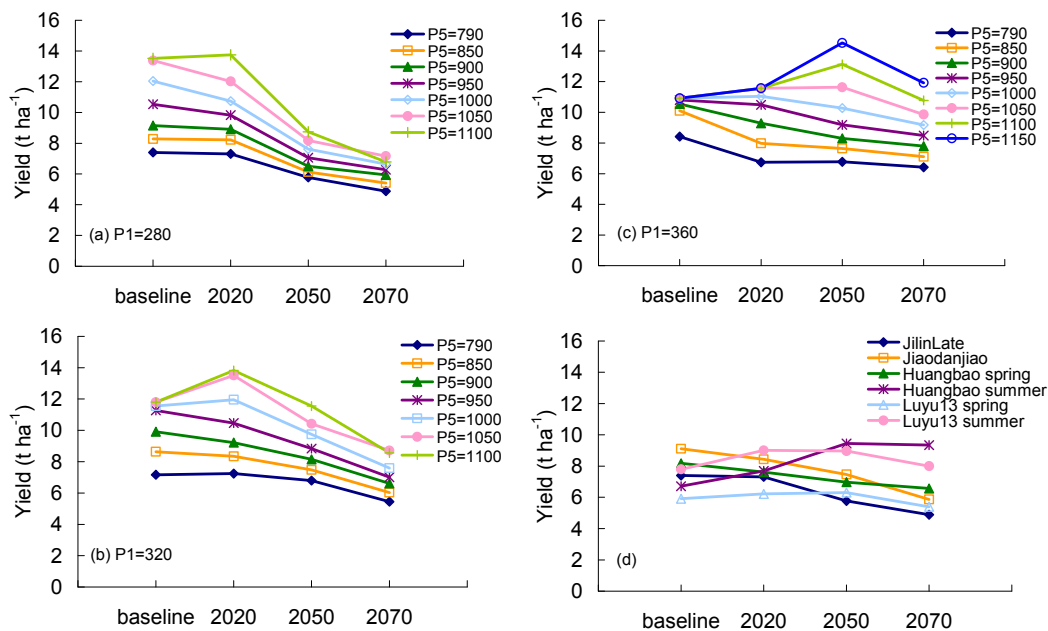


Figure 4-18 Yield projections of possible maize cultivars at the Baicheng site under the baseline, 2020, 2050 and 2070 climates using different genotype parameters. Cultivars in (a), (b), and (c), have different values of P1 and P5 with the same values of P2, G2, G3 and PHINT (P2=0.3, G2=720, G3=8.5, PHINT =38.9); (d) represents planting the cultivar in spring/summer. The genotype parameters in (d): JilinLate, P1=280, P2=0.3, P5=790, G2=720, G3=8.5, PHINT=38.9; Jiao3danjiao, P1=320, P2=0.3, P5=900, G2=700, G3=9.2, PHINT=38.9; Huangbao1, 2006, P1=300, P2=0.3, P5=640, G2=740, G3=14, PHINT=60; and Luyu13, P1=320, P2=0.3, P5=620, G2=720, G3=11, PHINT=45.

If using a revised automatic sowing scheme in which maize is sown in spring, the production potentials of the spring cultivar Jiao3danjiao are higher than JilinLate for all of the test periods, under optimal irrigation and fertilization schemes, because it requires much more thermal accumulation. Huangbao1 produces a higher level of yield than the JilinLate for its large values of G2 and G3, which determine the grain numbers and potential daily growth of grains. Introducing Luyu13 generated a slight yield improvement in 2050 and 2070, given its high G2, G3 and P1.

The two summer cultivars (Huangbao1 and Luyu13) produce significant yield increase in the future if sown in summer, on Jun 10th, the present normal sowing date in the North China Plain. However, for the baseline period, only Luyu13 produces higher yield compared to JilinLate. This means that in future summer maize may be cropped well in Jilin province. But the potential of changing cropping schemes needs to be carefully investigated in future research.

4.5 Summary and discussion

In the case study of Jilin, which is the most important grain-producing province, the maize yield is highly likely to decline in the western and central regions but to increase in the east in future under climate change. The growing season will be reduced in the central and western parts, leading to a shortened grain-filling period. The average maize yield in the west and central regions is thus projected to decrease 15% or more by 2050 as predicted by 90% of the 120 projected scenarios. Two potential adaptation strategies, i.e. improving irrigation facilities and introducing cultivars, were identified from the vulnerability assessment and further tested for the reduction areas. The results reveal that the increase in effective irrigation by upgrading the irrigation system would help to maintain the current

production level, but in the long run, maize cultivars need to be introduced in line with the future warming climate to maintain the current yield level.

The CO₂ fertilization effect resulted in quite different simulations of maize production when different irrigation strategies were used.

I added a CO₂ fertilization effect in the DSSAT simulation, which resulted in quite different simulations of maize production when different irrigation strategies were used (see B.8 and B.9). With sufficient irrigation (automatic irrigation setup in DSSAT, and water demand is fully satisfied), the CO₂ effect is about 2-3% on average for the whole Jilin province. When irrigation is limited (with irrigation quota considered and irrigation is applied as that described in Section 3.4.2), in the dry western area of Jilin, the CO₂ fertilizer effect is shown quite large, while in eastern area where the water demand could be fulfilled even by limited irrigation, the fertilizer effect is still small. For example, in Baicheng (a western county), the reduction in maize yield during 2050s is 30.5% in A1FI without CO₂ considered, but only 5.5% with CO₂ considered. But in Baishan (a county in east Jilin), the CO₂ effect resulted in about 3% increase in maize yield under the same scenario.

Higher CO₂ level is thought to increase the leaf stomatal resistance, and thus the water loss in crop transpiration is reduced. In the limited irrigation run, which can only provide about 50% of the ideal water demand, water stress on biomass production are reduced significantly because of the CO₂ effect on stomatal resistance.

To explain how does CO₂ influences maize growth under different irrigations in this model, we did the single-run simulations at 123.46E longitude and 45.6N latitude

(in the dry western area) where the CO₂ fertilization effect is 40% with limited irrigation, using 1) the automatic irrigation which provides as much water as demand (called “well irrigation condition”) and 2) the irrigation method in this study (described in Section 3.4.2), in which the total amount of irrigation is limited, as referred as “limited irrigation”.

In the automatic irrigation run, the crop was very well watered, and the simulated daily biomass productions with or without CO₂ effect had only small differences from each other (bottom left in B.6). But in the limited irrigation run, which can only provide about 50% of the ideal water demand, water stress on biomass production (the sudden drop in top left of B.6) are reduced significantly because of CO₂ effect on stomatal resistance. Higher CO₂ levels are thought to increase the leaf stomatal resistance, and thus the water loss in crop transpiration is reduced.

The Fig. B.7 gives an example of sudden drop in daily biomass production caused by water stress under insufficient irrigation experiments. Given the same irrigation, the water stress on the 52-nd day, the biomass production with concerning CO₂ effect is larger than that without CO₂ effect. Similar case also happens on the 55-th, 64-th, and 67-th day. Such a difference in daily biomass is cumulated day by day, and then results in great differences of the total biomass production and yield formation. Whether this significant CO₂ effect under insufficient irrigation regime is realistic needs to be tested both by model design and field experiments.

Chapter 5 Impacts of Climate Change on Maize: a Case Study of China

5.1 Introduction

The simulations by the improved DSSAT model were also carried out for the whole of China (10 km×10 km) in order to reveal the impacts of climate change in the main maize growing areas, e.g. the Northeast spring maize area, the North China Plain (NPC) summer maize area, and the Southwest area spring maize area.

The provincial average of the simulated yields was calculated by

$$Yield_{iprov,it} = \left(\sum_{igrid} Yield_{igrid} \cdot Wt_{igrid} \right)_{iprov,it} \quad (\text{Eq. 5-1})$$

where $Wt_{igrid} = \frac{Area_{igrid}}{\sum_{igrid} Area_{igrid}}$. The $igrid$ is the number of grid, $iprov$ ($iprov=1, \dots, 31$)

denotes the province, and it presents the it -th year. The $Area_{igrid}$ is the maize cropping area of the $igrid$ -th cell. The simulated national yield ($Yield_{0,it}$) was obtained by

$$Yield_{0,it} = \sum_{iprov=1}^{31} \left(Yield_{iprov,it} \cdot \frac{Area_{iprov,it}}{\sum_{iprov=1}^{31} Area_{iprov,it}} \right) \quad (\text{Eq. 5-2})$$

where $Yield_{iprov,it}$ is the provincial average yield obtained above, $Area_{iprov,it}$ is the sown area of maize in the $iprov$ -th province at year it . $Area_{iprov,it}$ is derived from the China statistical yearbooks (Statistics NBS, 2007).

5.1.1 Input data and climate scenarios

In this chapter, the same input data and climate scenarios were used as for Jilin province, except for the soil and management data.

5.1.1.1 Soil data

In the simulation of China, the soil data derived from the Soil Map of China at scale 1:1 million (Shi et al., 2004; Zhang & Zhao, 2008) were used. The soil profile in this soil map offers most soil properties required by DSSAT, and the rest of the properties were estimated by the methods described in Chapter 4.

5.1.1.2 Cropping management data

The management data for sowing date, irrigation quota, total fertilization and maize cultivars were obtained by province, as shown in Table 5-1, and the genotype parameters of maize cultivars are given in Table 5-2. The planting density (6 plants/m²) was set to the same value for the study area. Only the ammonium nitrogen fertilizer was considered in the fertilization and applied evenly during the growing season. The irrigation was applied following the scheme described in Section 3.4.2. The province location in China is given in Figure 5-4.

Table 5-1 Management and cultivar settings in the whole-of-China simulation.

No.	Province	Sowing date (Julian day)	Irrigation quota* (mm)	Fertilization** (kg/ha/year)	Cultivar code
1	Beijing	160	150	428	1
2	Tianjin	160	180	357	1
3	Hebei	160	300	317	1
4	Shanxi	160	300	234	1
5	Inner Mongolia	116	350	151	2
6	Liaoning	106	315	303	2
7	Jilin	110	350	265	2
8	Heilongjiang	116	310	135	2
9	Shanghai	109	570	357	3
10	Jiangsu	109	570	431	1
11	Zhejiang	109	52.5	296	3
12	Anhui	109	570	301	1
13	Fujian	109	52.5	453	3
14	Jiangxi	109	52.5	215	3
15	Shandong	160	265	395	1
16	Henan	160	210	338	4
17	Hubei	109	90	358	3
18	Hunan	109	90	240	3

*The provincial irrigation quota was collected from the official water consumption quota determined by specific province governments (Provincial water quota, 2010).

**The annual fertilizer use was calculated by the total consumption of chemical fertilization and the cropping area, both of which are derived from the China statistical yearbooks (Statistics NBS, 1995-2005).

Table 5-1 Management settings used in the whole-of-China simulation (continued).

No.	Province	Sowing date (Julian day)	Irrigation quota* (mm/year)	Fertilization** (kg/ha/year)	Cultivar code
19	Guangdong	109	68	389	3
20	Guangxi	109	180	278	3
21	Hainan	109	68	361	3
21	Hainan	109	68	361	3
22	Chongqing	116	90	211	5
23	Sichuan	106	97.5	223	6
24	Guizhou	106	97.5	155	5
25	Yunnan	106	97.5	215	7
26	Xizang	158	510	142	8
27	Shaanxi	160	375	317	1
28	Gansu	116	750	185	1
29	Qinghai	158	510	138	1
30	Ningxia	116	510	232	1
31	Xinjiang	148	510	258	1

*The provincial irrigation quota was collected from the official water consumption quota determined by specific province governments (Provincial water quota, 2010).

**The annual fertilizer-use was calculated by the total consumption of chemical fertilization and the cropping area, both of which are derived from China statistical yearbooks (Statistics NBS, 1995-2005).

Table 5-2 The genotypic parameters of maize cultivars used for the whole-of-China simulation.

Cultivar Code	P1	P2	P5	G2	G3	PHINT
1	280	0.3	850	700	8	38.9
2	280	0.3	790	720	8.5	38.9
3	280	0.3	750	700	8	38.9
4	280	0.3	900	700	8	38.9
5	320	0.3	750	700	8	38.9
6	320	0.3	900	700	8	38.9
7	280	0.3	650	700	8	38.9
8	320	0.3	650	700	8	38.9

5.2 Impacts of climate change on maize production in China

Figure 5-1 gives the simulation of maize yield under the baseline climate (1960-1990), corresponding to an obvious maize zone in China from the northeast plain to the southwest areas. Comparing the census yield, as shown in Figure 5-2, the baseline simulation performs moderately well in the North China Plain (NCP), Northeast areas, and central south areas. In the main cultivating provinces of maize, i.e. Jilin, Heilongjiang, Liaoning, Shandong, Hebei, Henan, Inner Mongolia, and Sichuan (those provinces contribute about 70% of the total maize production of China, see Figure 5-2), the bias of simulated yield to the statistics is about 17% on average. The model does not produce qualified simulations in the minor cropping areas of maize like Fujian and Jiangxi, and in those small provinces like Tianjin and Chongqing. The worst simulations appeared in Xizang, Qinghai, Xinjiang, and Ningxia, which were extremely lower than the statistical yield. The model

performance to simulate the maize yield in major maize-cropping regions (i.e. Jilin, Shandong, Hebei, Heilongjiang, Henan, Liaoning, and Inner Mongolia) was moderately well for both spring and summer cultivars, except for the overestimation of the spring cultivar in Sichuan province, Southwest China.

The underestimation in some provinces, i.e. Xinjiang, Xizang, Qinghai, is likely to have been caused by 1) the unsuitable cultivars employed, 2) the inaccurate daily weather generated, and 3) the unsuitable sowing date. The parameters of current cultivars used were originally calibrated in other spring maize areas. The daily weather was generated rather than actual observations. The weather generator was not tested for Xizang and Qinghai at their higher elevations, so it may produce extreme values that would affect the growth process. The sowing date is fixed in this simulation, thus if the initial weather condition is not suitable, the growth will stop quickly and no grain will be produced, which would cause the extremely low yield. However, considering the planting area of maize (see Fig. 5-4) in these three provinces, the maize is rarely planted, so this underestimation may not affect the final results at a country level.

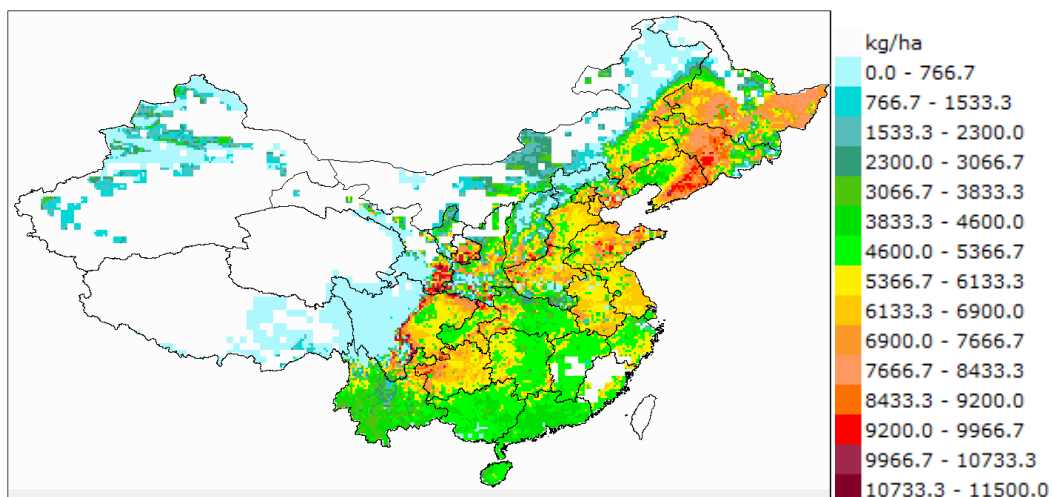


Figure 5-1 The simulation of maize yield in China under the baseline climate.

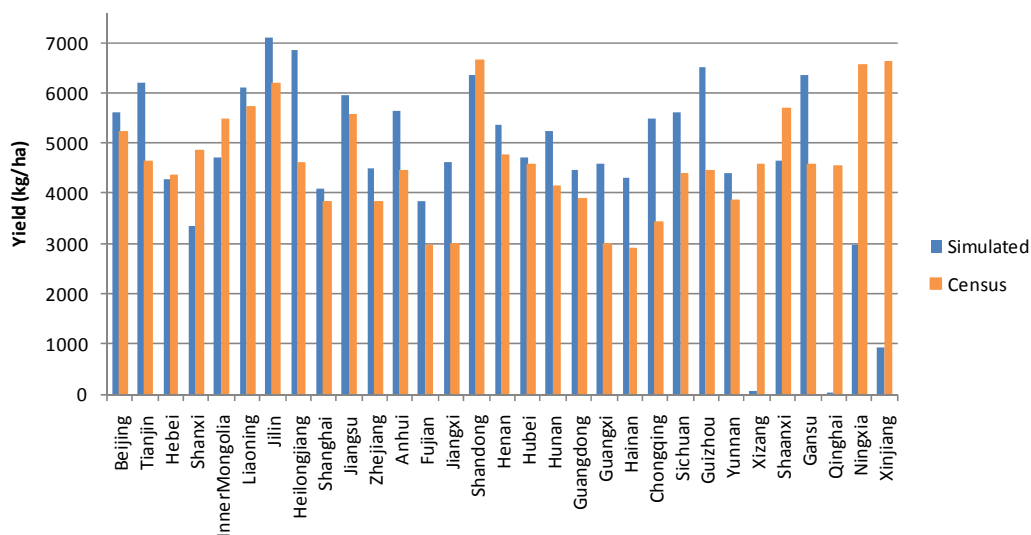


Figure 5-2 The provincial average yield (blue bars are the simulated yields and orange bars are the census yields from 1995 to 2005).

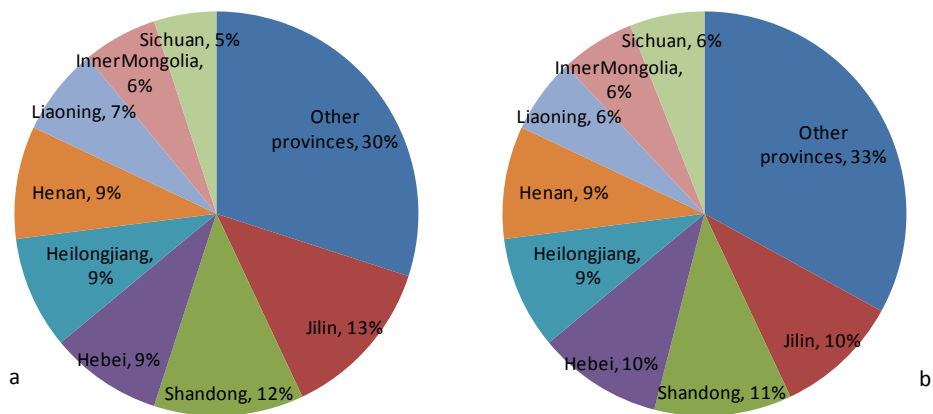


Figure 5-3 The share of provincial (a) maize production and (b) sown area historically (1995 - 2005).

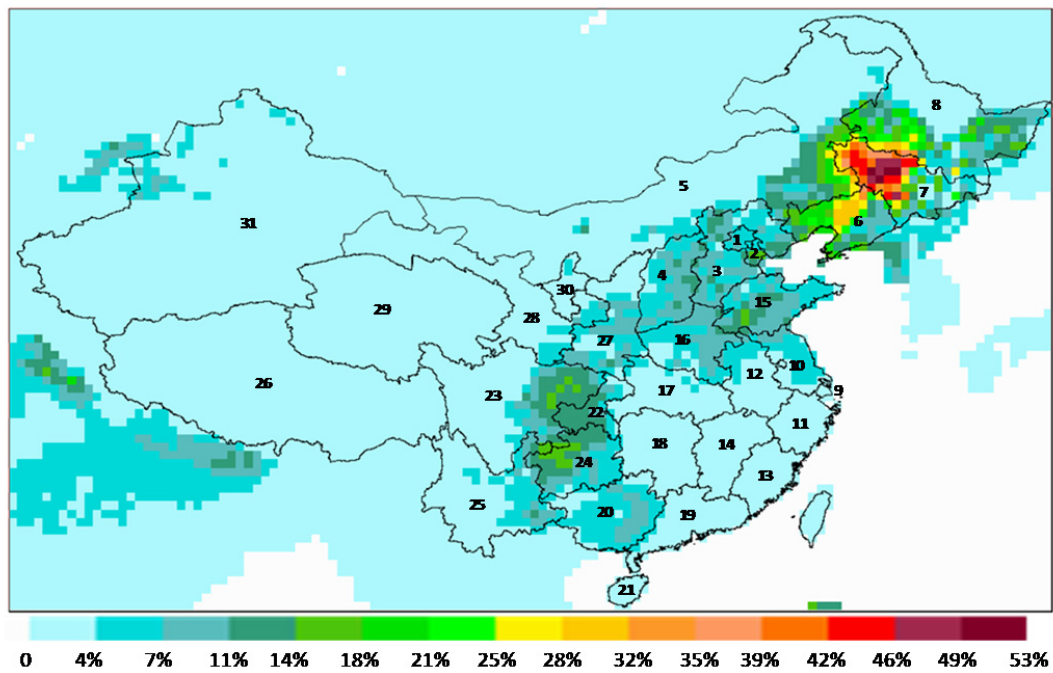


Figure 5-4 The percentage of sown area in maize in each grid. The percentage in grid is the ratio of maize-cropping area to the total area of that grid.

5.2.1 Impacts on yield and maturity period

The projection of maize production was then carried out for the years 2020, 2050, and 2070. All the settings of model were as exactly the same as mentioned in Chapter 3 and Chapter 4 except those proposed in section 5.1. And no adaptations were applied in projection.

The maize yield in major cropping areas is projected to fall significantly in the coming decades, i.e. 2020s, 2050s, and 2070s. The average reduction of yield over the whole of China is about 3% in the 2020s, 10% in the 2050s, and 14% in the 2070s, respectively, under the median climate change scenario. In general, the northeast spring maize and the north summer maize may decline by about 15%, 20% and 25% in 2020, 2050, and 2070, respectively. The absolute reduction in yield is about 600 kg/ha in the Northeast and NCP areas, and 300 kg/ha on average in the Southwest provinces. The most important provinces for maize production, Jilin and Shandong, may suffer the largest reduction, about 30% of the baseline yield by the year 2070. In contrast, future climate change has favourable effects on maize yield in the areas along the northeast to southwest maize zones, including the marginal areas of Northeast China, northern parts of Hebei, parts of Shaanxi and Shanxi, and the boundary areas of the Chengdu plain in Sichuan.

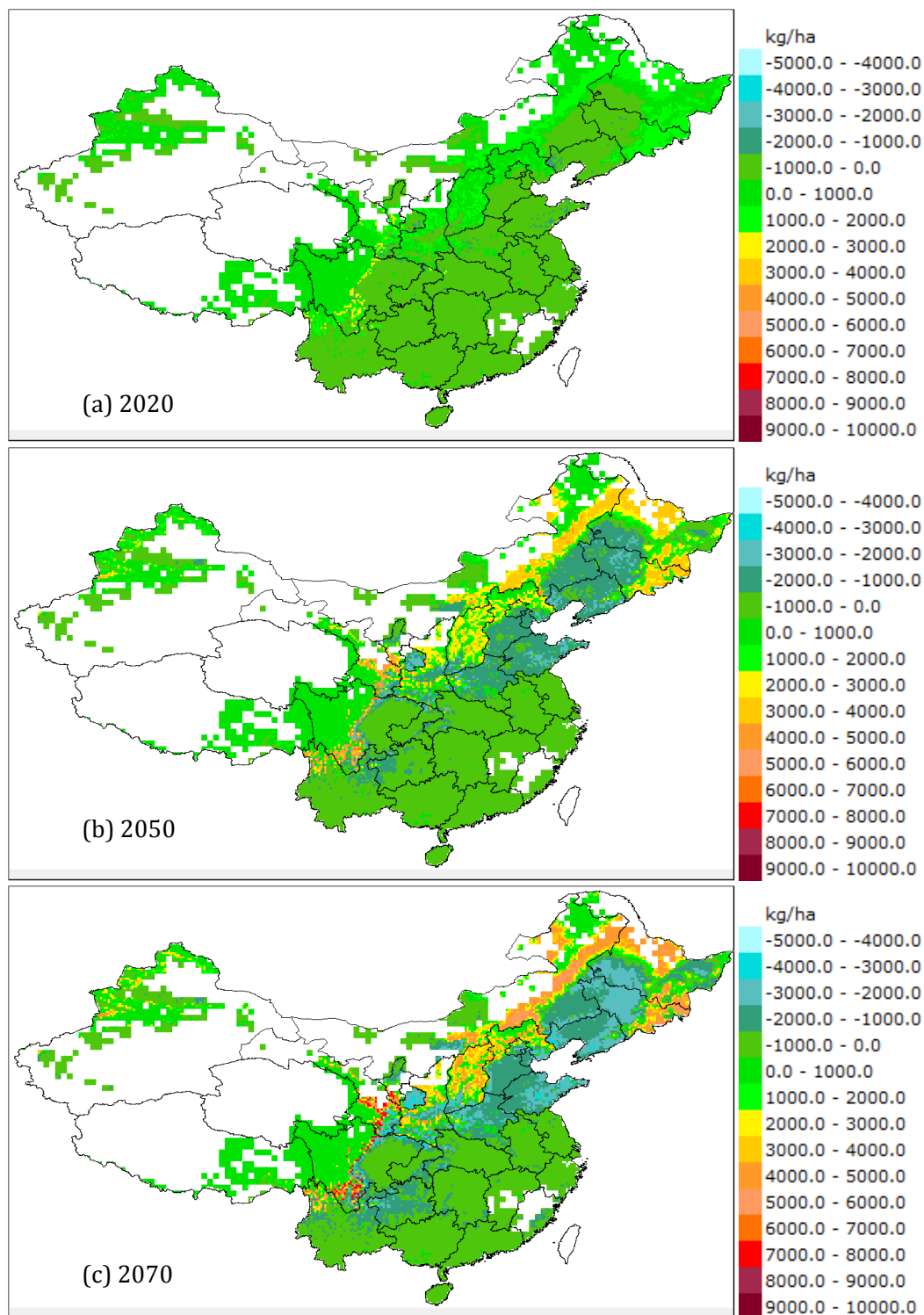


Figure 5-5 The changes in simulated maize yield in (a) 2020, (b) 2050, (c)2070 under the median climate change scenario.

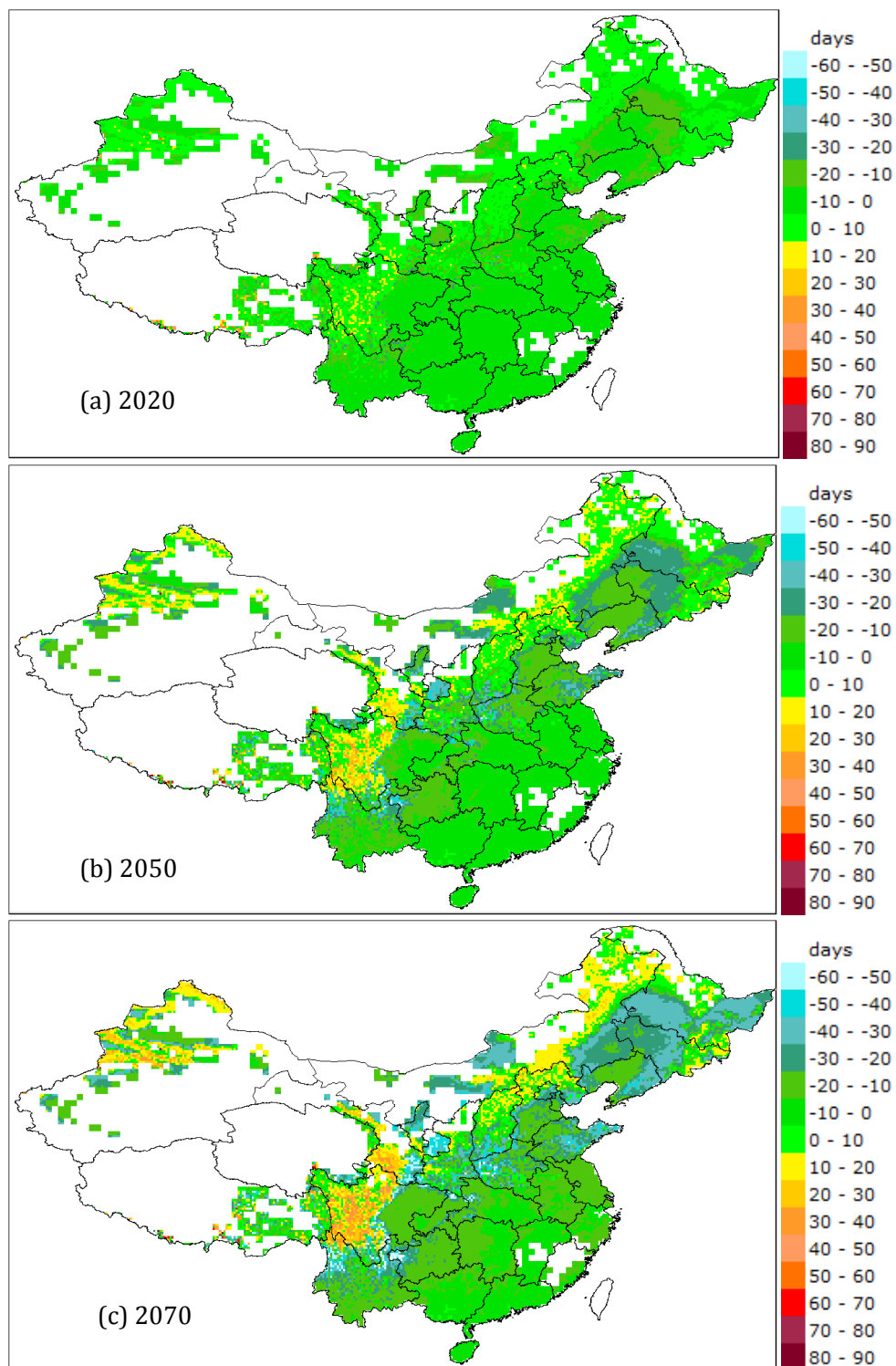


Figure 5-6 The changes in days to maturity in (a) 2020, (b) 2050, (c) 2070. The negative values mean that the maturity period is shortened, and the positive values shows increased maturity period.

The change in maturity periods has a quite similar spatial pattern to the yield variations: in those areas where maize yield is likely to decline, the growth days to maturity are also shortened significantly, and the significant shrinking in growth days spatially matches the large falls in maize yield. The spring maize area in the Northeast suffers the biggest reduction in maturity period. The growing season of maize is likely to increase just in the neighbouring areas of the Chinese maize zone where the thermal condition is the key factor limiting maize cropping, such as the western mountain areas of Sichuan and Xinjiang, and the border land between Hebei and Inner Mongolia. The growing season in DSSAT was decided by the cumulative temperature above a base value and the parameters P1, P2, and P5 of genotype. When the cumulative temperature is calculated to satisfy the requirement on P1/P2/P5, the crop growth will move to the next phase, and if temperature below a certain lower criteria, the growth will cease. So with warming climate, the crop has longer period with temperature above the base before the falling temperatures prevent growth. The improvements in thermal conditions induced by warming climate in those areas may produce a prolonged growing season synchronous with the increasing yield of maize. For example, an extension of 10~20 days in maize growth will bring about 1000 kg/ha increase in western Sichuan in the year 2020. The maturity days will be increasing rapidly from 2020 to 2070, whereas the rise in yield is projected to vary very slightly in different time slices, remaining at the 1000~2000 kg/ha level through the coming decades. This indicates that the profitable effect on maize production produced by a warming climate is not only narrowed in a quite small spatial scope, but also limited in particular time periods.

5.2.2 Uncertainty among six climate change scenarios

As mentioned in Chapter 3, six emission scenarios and 20 GCMs were used to generate full scale climate change scenarios in China. In this section, the climate

change pattern under a specific emission scenario is only the median one produced by all 20 GCMs. The national average yield of projections was calculated by the method described in Section 5.1, considering the historical contribution of each province to the total maize production.

On average, the national yield is projected to keep falling in all provinces through the 21st century, especially if the rapid reduction occurs under the A1FI scenario after 2020s (Figure 5-7). The total reduction in 2020, 2050, and 2070 is 3%, 9% and 14% of the baseline level, respectively. The projections under A1B, A1T, and A2 are very close to the median projection by the year 2070, and the B1 and B2 emission scenarios may produce smaller reductions in the long run. The six emission scenarios could result in quite different projections of maize yield in the whole country. The difference between the worst prediction of maize yield under A1FI and that under B1 will be more than 10% of the baseline yield in year 2070.

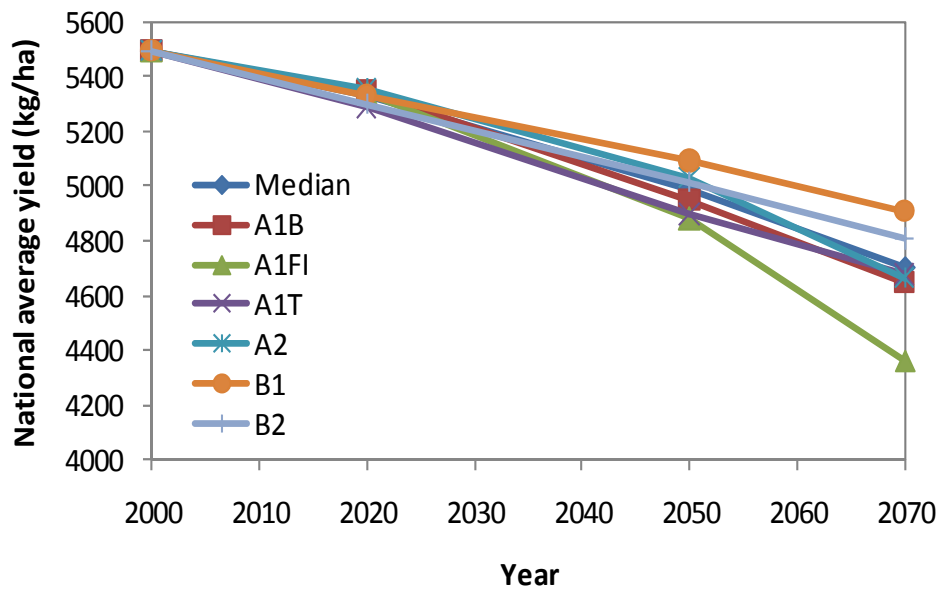


Figure 5-7 The average simulated maize yield of China under the six climate scenarios and their median in years 2020, 2050, and 2070 (time series).

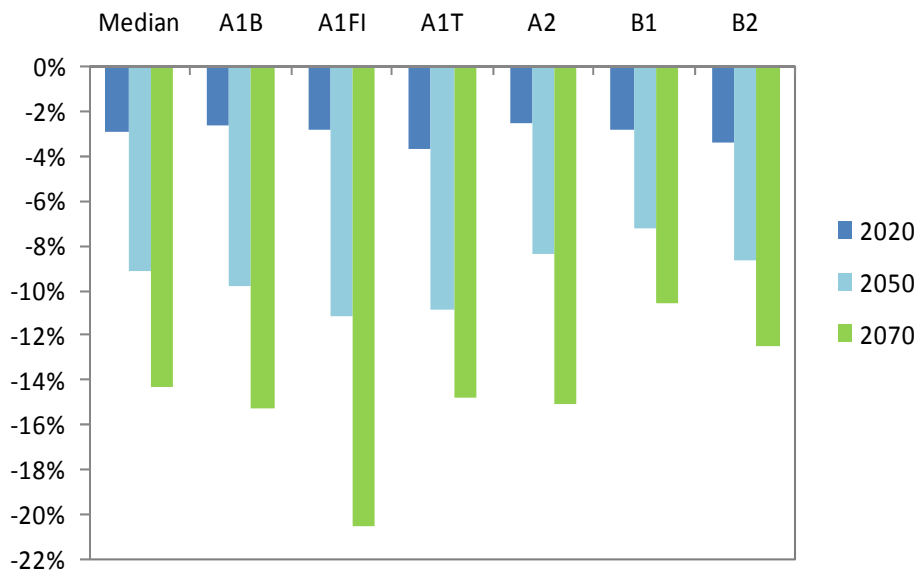


Figure 5-8 The reduction ratio of average simulated maize yield of China under the six climate scenarios and their median in years 2020, 2050, and 2070.

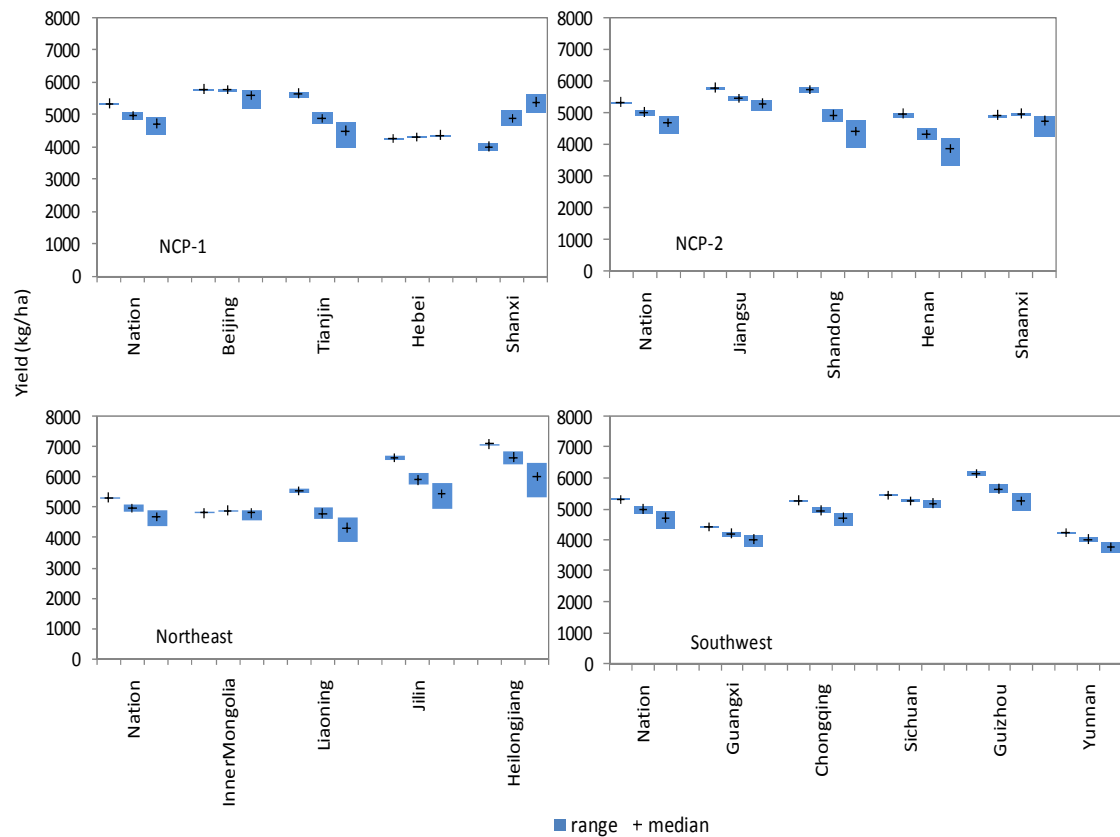


Figure 5-9 The range of maize yield projections under the 6 SRES emission scenarios in 2020, 2050, and 2070 by 20 GCMs. The projected yield under the median climate change scenario is marked by the crosses.

The responses of provincial average yield to the six emission scenarios are very different from those at the national scale. Seventeen provinces were chosen that were located in the main areas of maize production which are the northern and southern parts of the North China Plain (NCP-1 and NCP-2, summer maize area), the Northeast spring maize area, and the Southwest spring maize area. The yield projection of Hebei province in NCP-1 varies in a much smaller range than the national average, while the yield of Shanxi increases with a bigger variation. The different climate change scenarios may produce greater variances in the provinces of NCP-2, except Jiangsu, than in the whole country. The largest variances of provincial yield among climate change scenarios appears in the Northeast areas, and the average variance of Heilongjiang, Jilin and Liaoning is about 938 kg/ha, 14% of

the baseline yield. Compared to the other three areas, the Southwest area is likely to keep a considerably stable level of maize yield in the future. Figure 5-9 reveals that the spring maize in the very northern area of China is seriously affected by the local warming climate, but the influences on spring maize in the southwest area are quite small. The summer maize in the northern parts of NCP seems to benefit from the positive effects of climate change with a higher irrigation level (300 mm), and that in the southern parts of NCP with irrigation of only about 200 mm, is probably stressed by the rising temperature.

5.3 Summary

When the climate change impact is considered, maize yield is likely to drop significantly in the main cropping provinces of China. In major cropping areas (i.e. Jilin, Heilongjiang, Liaoning, Shandong, Hebei, Henan, Neimeng, and Sichuan), there will be a significant drop in yield for either spring or summer cultivars. The average reduction of yield is about 3% in the 2020s, 10% in the 2050s, and 14% in the 2070s, respectively, under the median climate change scenario. In the first two important areas of maize production (Jilin and Shandong), maize yield is predicted to decline by about 30% of the baseline yield in the year 2070. The future climate change has favourable effects on maize yield in the areas along the northeast to southwest maize zone, including the marginal areas of Northeast China, northern parts of Hebei, parts of Shaanxi and Shanxi, and the boundary areas of the Chengdu plain in Sichuan.

In those areas where maize yield is likely to decline, the growth days to maturity are also shortened significantly. The spring maize area in the Northeast will suffer the biggest reduction in maturity period, about 20 days shorter in the worst case by the

year 2070. The improvements in thermal condition induced by a warming climate in those areas may produce a prolonged growing season synchronous with the increasing yield of maize. But the profitable effect on maize production produced by a warming climate is not only narrowed in a quite small spatial scope, but also limited in particular time periods.

The difference between the lowest prediction of maize yield under climate scenario A1FI and that of the highest yield under B1 will be more than 10% of the baseline yield by year 2070. The responses of the provincial average yield to the six emission scenarios are very different from those on the national scale.

The impacts on maize production due to climate change in the entire China are predicted to be considerably significant in future decades by the bio-physical crop model, potentially raising the risk of food insecurity in China. How would the socio-economic system respond to the possible yield reduction of a crop? Are there any strategies that the government can take to slacken or offset the negative consequences? In the next two chapters, a food economic model is developed in order to model the food economy taking climate change impacts into account to answer these questions.

Chapter 6 Food Economic Model

6.1 Introduction

Due to its large population and fast economic development, China's food security has attracted intensive and extensive research during the last decades, both nationally and internationally, because such an issue has significant implications for global food security. Most research was concerned mainly with economic reactions and consequences under the assumption of stable crop productivity with normal climate status. Recently, there has been increasing demand for assessments of the impacts of climate change on China's food security, in order to support potential adaptation planning. Although some researchers (Tao et al., 2003b; Lin et al., 2005; Xiong et al., 2007a; Xiong et al., 2007b; Li et al., 2011) have investigated physical impacts on crop production under diverse climate change scenarios for China's food security, there are still research demands of incorporation of the bio-physical impact into the socio-economic system.

The most important change in Chinese society is the extensive urbanization in recent decades, which has induced an increase in food demand, especially the demand for "good quality" food (high-protein and healthier food), such as meat and dairy products. Nowadays, China's economy is characterised by the interwoven influences of the powerful centralized policy and the increasing market economic forces after the 1978 reforms. Therefore the food economy in China is not only controlled by the normal market mechanics, but also strongly affected by agricultural policy and government investments in agricultural sectors. Such characteristics of food economy need to be carefully considered in a food economic model.

Huang & Li (1999) suggested a model, CAPSiM, which simulates the actual market of food products with consideration of the influences of economic and policy factors on the agricultural sector. The food market in their model is described as an equilibrium process including the prices of food commodities, policy factors (e.g. investment in agriculture and technology stock), environmental influences, land and labour prices, urbanization, and market development. Based on the CAPSiM model, Huang & Chen (1999) studied the influences of trade liberalization on China's agriculture and grain self-sufficiency after joining the WTO, including the effects of specific macro-economic policies on the agricultural sector, farmer's welfare, and food self-sufficiency. The model is built on the price mechanics by which the variables of food supply and demand, including changes in crop yield, are mainly determined by prices of food commodities and agricultural inputs (i.e. fertilizer, labour and land) in addition to the non-price factors such as government investment, subsidy, and income.

However, in reality, only the sown area of a certain crop is determined by the prices of commodities, labour, and land. The crop yield actually depends on the bio-physical productivity of a specific cultivar, agricultural technology (e.g. cropping management), and environmental factors (e.g. soil and climate conditions), not those prices used in the CAPSiM model.

Therefore, an improved model was developed for the thesis study by constructing the function of crop yield with only those non-price factors, e.g. investment in agricultural research, investment in irrigation facilities and environmental stresses. Investment in agricultural technology represents the effects of upgrading cultivars for yield and development of cropping management, and investment in constructing irrigation systems representing the growth of irrigation efficiency and the increase in high-potential croplands, being the most crucial variables to guarantee stable crop production.

In order to incorporate the climate change impacts into the food economic model, the changes in yield of a certain crop simulated by the improved DSSAT model were firstly aggregated from grids up to national level as described in Section 5.1. This was then added into the improved yield function of the food economic model as the environmental stress. For coupling of the improved DSSAT into one package, this food economic model was developed using Fortran90. Details of the model integration are discussed in this chapter.

6.2 Module structure

Following the modelling approach of Huang & Li (1999), the food economic model in this research describes an economic system including the production, consumption, international trade of 11 crops and 7 livestock products. It has two major components, food supply and demand. The supply component simulates the response of crop and livestock production to the producer-side prices, internal input, and external shocks. The demand component calculates food consumption for rural and urban communities given income and consumer-side prices, the demand for feed, seed, industry, and waste.

Crop and livestock supply and production are determined by the producer price, the prices of other competing commodities (e.g. wheat, maize and other grains are the competing commodities for rice), the prices of internal inputs (i.e. fertilizer and labour), empirical input (i.e. investment in agricultural technology and irrigation systems), and the external shocks (i.e. natural disasters, impacts of climate change, and agricultural policy). The internal inputs are determined by the economic system, while the empirical inputs and external shocks are exogenous non-market factors, added by external drivers, e.g. government and environment.

The consumption of crop and livestock were simulated separately for urban and rural communities using different elasticities. It is a function of income, its consumer prices, the prices of other substitute commodities, and the market development. The market system in urban communities is assumed to be well developed, and the effects of market development were only considered in the rural community.

In general, the production and consumption equations are assumed to be modelled by the Cobb-Douglas function,

$$Q = \alpha \cdot \prod_i X_i^{\beta_i} \quad (\text{Eq. 6-1})$$

where X_i is the quantity of input factors, e.g. capital and labour; Q is the quantity of output; and α and β_i are the empirical parameters. The parameter α is a scale factor to evaluate the long-term level of output productivity, which is usually taken as the productivity measuring the long-term improvement in technology; and the parameter β_i is usually called economic elasticity, indicating the percentage change of Q with per unit change of X_i .

The logarithmic form of the Cobb-Douglas function is:

$$\log Q = \log \alpha + \sum_i \beta_i \cdot \log X_i \quad (\text{Eq. 6-2})$$

Its differential form with respect to time:

$$\frac{1}{Q} \cdot \frac{dQ}{dt} = \sum_i \frac{\beta_i}{X_i} \cdot \frac{dX_i}{dt} \quad (\text{Eq. 6-3})$$

Thus the percentage change in Q between the year t and $t+1$ can be easily calculated by

$$\frac{Q_{t+1}}{Q_t} = \sum_i \beta_i \cdot \frac{X_{i,t+1}}{X_{i,t}} \quad (\text{Eq. 6-4})$$

where $\frac{\Delta Q_t}{Q_t}$ (or $\frac{\Delta X_{i,t}}{X_{i,t}}$) is the percentage change of Q (or X_i) between the year t and $t+1$, $\Delta Q_t = Q_{t+1} - Q_t$ and $\Delta X_{i,t} = X_{i,t+1} - X_{i,t}$. If the variable X_i is the input factor represented in index numbers, $\frac{\Delta X_{i,t}}{X_{i,t}}$ is namely the relative change of X_i in the $t+1$ year to its base value in the year t .

For index numbers, it is usually taken as the index value of 100 in the base year, and the index values in the other years are expressed as the percentage of the base year. The index value is obtained by

$$\mathbf{Index\% = 100\% + (X_{t+1} - X_t)/X_t} \quad (\text{Eq. 6-5})$$

where X_t is the price in this case.

Obviously, the time variation of the Cobb-Douglas function is greatly simplified into a simple and clear linear equation by introducing the index number. Therefore, all the input factors that are in the similar form of the Cobb-Douglas function can be transformed into index numbers in model simulations. Resorting to the logarithmic form of the Cobb-Douglas function, the annual increase in any economic variable is easily described and calculated.

6.2.1 Food production

The production equations for crop and livestock products are introduced in this section.

6.2.1.1 Crop production

A crop's production is determined by its sown area multiplied by the yield, as well as the external shocks, such as the natural disasters, the investment in agriculture and government subsidy.

The sown area of a crop is assumed to react to its own price, the other crops' prices and input factors' prices, as well as subsidy.

The crop yield is not just determined by the physical environmental factors, e.g. the impacts of climate change, but also by the investments in agriculture and cropping management systems, e.g. investment in improving agricultural techniques, and the effective irrigation area.

The equations of area, yield and production are assumed to follow the Cobb-Douglas function, as in:

Area:

$$A_{ic,t} = A_0^{\beta A_{ic,0}} \cdot \prod_{jc=1}^{ncrop} (PC_{jc,t}^S)^{\beta A_{ic,jc}} \cdot \prod_{jc=1}^3 (PI_{jc,t})^{\beta A_{ic,ncrop+jc}} \cdot \prod_{jc=1}^2 (ZA_{jc,t})^{\beta A_{ic,ncrop+3+jc}}$$

(Eq. 6-6)

Yield:

$$Y_{ic,t} = Y_0^{\beta Y_{ic,0}} \cdot \prod_{jc=1}^2 (ZY_{jc,t})^{\beta Y_{ic,jc}} \cdot (CIm_{ic,t})^{\beta Y_{ic,3}}$$

(Eq. 6-7)

Production:

$$Qc_{ic,t}^S = A_{ic,t} \cdot Y_{ic,t} \cdot \prod_{jc=1}^3 (ZQc_{jc,t})^{\beta Qc_{ic,t}^S}$$

(Eq. 6-8)

Thus, we can get their variant forms:

$$\begin{aligned} \Delta A_{ic,t}/A_{ic,t} = & \sum_{jc=1}^{ncrop} (\beta A_{ic,t} \cdot \Delta PC_{jc,t}^S / PC_{jc,t}^S) + \sum_{jc=1}^3 (\beta A_{ic,ncrop+jc} \cdot \Delta PI_{jc,t} / PI_{jc,t}) + \\ & \sum_{jc=1}^2 (\beta A_{ic,ncrop+3+jc} \cdot \Delta ZA_{jc,t} / ZA_{jc,t}) \end{aligned} \quad (\text{Eq. 6-9})$$

$$\Delta Y_{ic,t}/Y_{ic,t} = \sum_{jc=1}^2 (\beta Y_{ic,t} \cdot \Delta ZY_{jc,t} / ZY_{jc,t}) + \beta Y_{ic,3} \cdot \Delta Clm_{ic,t} / Clm_{ic,t} \quad (\text{Eq. 6-10})$$

$$\Delta Qc_{ic,t}^S / Qc_{ic,t}^S = \Delta A_{ic,t} / A_{ic,t} + \Delta Y_{ic,t} / Y_{ic,t} + \sum_{jc=1}^4 (\beta Qc_{ic,jc}^S \cdot \Delta ZQc_{jc,t} / ZQc_{jc,t}) \quad (\text{Eq. 6-11})$$

where

$A_{ic,t}$, $Y_{ic,t}$, and $Qc_{ic,t}^S$ are the sown area, yield, and production of the ic -th crop at the t -th time slice,

$PC_{jc,t}^S$ is the producer-side price of the jc -th crop at the t -th time slice,

$PI_{jc,t}$ is the price of input factors (i.e. labour, land, fertilizer, when $jc=1, 2, 3$) at the t -th time slice,

$ZA_{jc,t}$ is the exogenous shock on sown area change, i.e. the price subsidy for planting a crop ($jc=1$), and the agriculture tax (which was cancelled after 2005, $jc=2$),

$ZY_{jc,t}$ is the exogenous shock on crop yield, including the investments in agricultural research ($jc=1$) and the area of effective irrigation ($jc=2$),

$Clm_{ic,t}$ is the yield corruption of the ic -th crop due to climate change, in this study, only maize reduction induced by climate change was used,

$ZQc_{j,c,t}$, is the exogenous shock on total production of the jc -th crop at the t -th time slice, i.e. the investments in support services of agriculture ($jc=1$), in farm facilities ($jc=2$), and in rural relief fund ($jc=3$),

$\beta A_{ic,jc}$, $\beta Y_{ic,jc}$, $\beta Qc_{ic,jc}^S$, are the elasticities of the produce prices of crops, the input prices and the external shocks to per unit change in sown area, yield and production.

A total of 11 crops ($ic=1,\dots, 11$) were considered: 1) rice (the milled ratio of paddy to rice is 1:0.7), 2) wheat, 3) maize, 4) tubers (sweet potato and potato), 5) coarse grains, 6) soybean, 7) oil crops (in raw seeds), 8) sugar crop (in raw products), 9) vegetables, 10) cotton (in raw products) and 11) fruits.

The yield change due to climate change ($Clm_{ic,t}$) is summarized from the projections in 2020 and 2050 given in Chapter 5. The average status of food security under climate change impact of the coming decades could be measured by the insufficient supply to the total demand, which is produced by the climate-driven changes in crop yield.

6.2.1.2 Livestock production

The livestock production is a function of the prices of meat products, input prices such as fodder and labour, and shocks such as support policies and diseases. Depending on the feed efficiencies and fodder resources, the livestock production in China has three modes, i.e. backyard mode, specialized household mode and commercial mode (Tian & Chudleigh, 1999). Generally, the backyard mode is thought to be a fully-feed-use but low-efficiency-in-output feeding system, while the commercial mode is highly efficient in output but not efficient in feed use. The specialized household feeding is a combination of the two modes.

It is assumed that the livestock production has a similar function formula to the crop production, but the grain-meat ratios and the grains' shares are different (Zhao et al., 2006). As the livestock sectors are becoming specialized and concentrated in recent decades, the proportion of share of the three modes in meat output has changed and will continue to change in future. Therefore the livestock production component in this model requires inputs of the growth rate, grain-meat-conversion ratios and grains' shares in fodder of each mode. Three feeding modes were applied in swine production, while only the specialized household and commercial mode were applied in other livestock productions. A fixed development rate for specialized and commercial modes was used, based on a national planning for livestock sectors (MOA, 2001). It is a moderate estimation of meat production growth, with only pork products produced under backyard mode.

Livestock production in variation form:

$$\Delta Qm_{im,t}^S / Qm_{im,t}^S = \sum_{jm=1}^{nmeat} (\beta Qm_{im,jm}^S \cdot \Delta PM_{jm,t}^S / PM_{jm,t}^S) + \sum_{jm=1}^2 (\beta Qm_{im,nmeat+jm}^S \cdot \Delta PI_{jm,t} / PI_{jm,t}) + \sum_{jm=1}^2 (\beta Qm_{im,nmeat+2+jm}^S \cdot \Delta ZQm_{jm,t}^S / ZQm_{jm,t}^S)$$

(Eq. 6-12)

where

$Qm_{im,t}^S$ is the production of the im -th livestock at the t -th time slice,

$PM_{jm,t}^S$ is the producer-side price of the jm -th livestock product at the t -th time slice,

$PI_{jm,t}$ is the input price (i.e. $jm=1$ for labour, $jm=2$ for fodder) at the t -th time slice.

Since the main feeding resource is maize and its products in China, the forage price is assumed to equal to the maize price,

$ZQm_{jm,t}^S$ is the external shock on livestock production, i.e. the government subsidy in livestock sectors ($jm=1$), and the disease damage ($jm=2$),

$\beta Qm_{im,jm}^S$ is the elasticity of livestock product' prices, input prices and the external shocks to per unit change in livestock production,

7 livestock products ($nmeat=7$) were considered, i.e. 1) pork, 2) beef, 3) mutton, 4) poultry, 5) egg, 6) dairy products (all the dairy products were converted to the equivalent of liquid fresh milk), and 7) aquatic products.

The ratio of feed mode was calculated by

$$Rmode_{imode,im,t} = Rmode_{imode,im,t-1} \cdot (1 + RateRmode_{imode,im,t}) \quad (\text{Eq. 6-13})$$

with the condition

$$\sum_{imode=1}^3 Rmode_{imode,im,t} = 1 \quad (\text{Eq. 6-14})$$

where $Rmode_{imode,im,t}$ is the ratio of the $imode$ -th feeding mode in the im -th livestock production at the t -th time slice, and $RateRmode_{imode,im,t}$ is the growth rate of the $imode$ -th feeding mode in the im -th livestock production at the t -th time slice. $imode$ denotes the three feeding modes: 1) backyard, 2) specialized household, and 3) commercial.

6.2.2 Food demand

Food demand is determined by the food consumption, feed, seed, industry use, and waste.

6.2.2.1 Food

The per capita food consumption is assumed to be a function of consumer prices, per capita income, and market development with respect to urban or rural consumers.

Since the economic reform in the early 1980s, the grain circulation system of China has gradually transformed from the strong planning-domination, where state controls purchasing and distribution to the current overall open market after 2004. The current dietaries in urban and rural areas are quite different. The rural market of food economy is not yet fully developed in China. A large number of farmers have only small arable land areas under traditional intensive cultivation, and decentralization management with considerably low levels of mechanization. The outputs of their own farm are still their main food source, and just partial amounts of products are sold and purchased. The high quality food, like dairy and aquatic products, is hardly accessible in remote rural areas due to under-developed transport systems and retail businesses (see Eq. 6-15 and Eq. 6-16). Therefore an index on market development was introduced into the consumption equation for rural consumers.

Food consumption equations were developed separately for urban and rural markets with different elasticities. The average per capita demand was calculated, weighted by the rural and urban population. The food consumption equations are shown as follows:

$$\text{Urban: } Q_{ic,t}^{DU} = Q_0^{DU} \cdot \prod_{jc=1}^{ncrop+nmeat} (P_{jc,t}^{DU})^{\beta Q_{ic,jc}^{DU}} \cdot (IM_t^U)^{\beta IM_{ic}^U} \quad (\text{Eq. 6-15})$$

$$\text{Rural: } Q_{ic,t}^{DR} = Q_0^{DR} \cdot \prod_{jc=1}^{ncrop+nmeat} (P_{jc,t}^{DR})^{\beta Q_{ic,jc}^{DR}} \cdot (IM_t^R)^{\beta IM_{ic}^R} \cdot (MKT_t^R)^{\beta MKT_{ic}^R} \quad (\text{Eq. 6-16})$$

Then, we can get a uniform equation of urban and rural communities in the variation form:

$$\frac{\Delta Q_{ic,t}^D}{Q_{ic,t}^D} = \sum_{jc=1}^{ncrop+nmeat} (\beta Q_{ic,jc}^D \cdot \Delta P_{jc,t}^D / P_{jc,t}^D) + \beta IM_{ic} \cdot \Delta IM_t / IM_t + \lambda \cdot \beta MKT_{ic} \cdot \Delta MKT_t / MKT_t \quad (\text{Eq. 6-17})$$

where

$Q_{ic,t}^D$, is the population-weighted per capita consumption of the ic -th food commodity at the t -th time slice,

$Q_{ic,t}^{DR}$, and $Q_{ic,t}^{DU}$, are the per capita consumptions of the ic -th food commodity at the t -th time slice for rural and urban communities, respectively,

$P_{jc,t}^{DR}$, and $P_{jc,t}^{DU}$, are the consumer-side prices of the ic -th food commodity at the t -th time slice for rural and urban,

IM_t^R , and IM_t^U , are the per capita incomes at the t -th time slice for rural and urban communities,

MKT_t^R , is the rural food market development index at the t -th time slice,

$\beta Q_{ic,jc}^{DR}$, and $\beta Q_{ic,jc}^{DU}$, are the price elasticities of the jc -th food commodity to per unit change in demand of the ic -th food product for rural and urban areas,

βIM_{ic}^R and βIM_{ic}^D , are the income elasticities to the demand of the ic -th crop in rural and urban areas,

λ , the sign of rural or urban areas, $\lambda = 0$ when it is the urban equation, $\lambda = 1$, when it is rural,

ic and jc ($=1, \dots, ncrop+nmeat$), is the index of food commodities concerned in the model, including rice, wheat, maize, tubers, coarse grain, soybean, oil, sugar, vegetables, other food products (i.e. fruits), non-food products (i.e. cotton), pork, beef, mutton, poultry, egg, dairy, and aquatic products.

And then the total food consumption was calculated by

$$Q_{ic,t}^D = POP_t^R \cdot Q_{ic,t}^{DR} + POP_t^U \cdot Q_{ic,t}^{DU} \quad (\text{Eq. 6-18})$$

$$Q_{ic,t}^{Dtot} = Q_{ic,t}^D \cdot POP_t \quad (\text{Eq. 6-19})$$

where

$Q_{ic,t}^{Dtot}$, is the total demand of the ic -th food commodity at the t -th time slice,

POP_t , is the total population at the t -th time slice,

POP_t^R and POP_t^U , are the shares of rural and urban population at the t -th time slice.

6.2.2.2 Feed

In this model, grains used as feed sources included rice, wheat, maize, tubers, and coarse grains. Given the livestock production in each feeding mode, feed demand was computed by the grain-meat conversion ratios and the grain shares of feeding,

$$Feed_{imode,ic,t}^G = \sum_{im=1}^{nmeat} Qm_{im,t}^S \cdot Rmode_{imode,im,t} \cdot Rfm_{imode,im,t} \cdot FGshare_{imode,ic,im} \quad (\text{Eq. 6-20})$$

$$Feed_{ic,t} = \sum_{imode=1}^3 Feed_{imode,ic,t}^M \quad (\text{Eq. 6-21})$$

where

$Feed_{ic,t}$ is the total feed demand in the ic -th grain at the t -th time slice,

$Feed_{imode,ic,t}^G$ is the feed demand in the ic -th grain under the $imode$ -th mode at the t -th time slice,

$Qm_{im,t}^S$ is the im -th livestock production at the t -th time slice,

$Rmode_{imode,im,t}$ is the $imode$ -th mode share of the im -th live production at the t -th time slice,

$Rfm_{imode,im,t}$ is the feed meat conversion ratio of the im -th meat under the $imode$ -th mode at the t -th time slice,

$FGshare_{imode,ic,im}$ is the ic -th grain share of the total feed use in the im -th meat production under the $imode$ -th mode,

$imode$ denotes the index of feeding modes, 1) the backyard feeding mode, 2) the specialized household feeding mode, 3) the commercial feeding mode,

ic is the index of feed grains (i.e. rice, wheat, maize, tubers, and coarse grain). The soybean and its by-products are not included in feed demand, since the primary use of soybean in China is edible oil and is not consumed directly in feeding livestock,

im is the index of livestock products, i.e. pork, beef, mutton, poultry, egg, dairy product, aquatic product.

6.2.2.3 Seed, industry use and waste

Seed demand is determined by the crop sown area and the seed used per hectare. The latter was estimated to be the same for all of China. The annual industry demand was determined by the demand of the previous year and an assumed growth rate was estimated from the historical census data. The grain waste, which is the loss after harvest, during processing and transporting, was assigned a ratio of the total production for a certain crop. The estimations of grain loss are from 10% to about 3% of total grain production (State Council of China, 1996). The moderately low estimation, i.e. 5%, is taken as the initial waste share of total grain production, and is assumed to be reduced by about 1% per year in the future because of the improvements in crop processing and transferring.

$$\text{Seed:} \quad \text{Seed}_{ic,t} = \text{Des}_{ic,t}^{\text{Seed}} \cdot A_{ic,t} \quad (\text{Eq. 6-22})$$

$$\text{Des}_{ic,t}^{\text{Seed}} = (1 + \text{inc}_{ic,t}^{\text{Seed}}) \cdot \text{Des}_{ic,t-1}^{\text{Seed}} \quad (\text{Eq. 6-23})$$

$$\text{Industry:} \quad \text{Industry}_{ic,t} = (1 + \text{inc}_{ic,t}^{\text{Industry}}) \cdot \text{Industry}_{ic,t-1} \quad (\text{Eq. 6-24})$$

$$\text{Waste:} \quad \text{Waste}_{ic,t} = \text{Des}_{ic,t}^{\text{Waste}} \cdot \text{Qc}_{ic,t}^{\text{S}} \quad (\text{Eq. 6-25})$$

$$\text{Des}_{ic,t}^{\text{Waste}} = (1 + \text{inc}_{ic,t}^{\text{Waste}}) \cdot \text{Des}_{ic,t-1}^{\text{Waste}} \quad (\text{Eq. 6-26})$$

where

$\text{Seed}_{ic,t}$, is the seed demand of the ic -th crop at the t -th time slice,

$\text{Industry}_{ic,t}$, is the industry demand of the ic -th crop at the t -th time slice,

$\text{Waste}_{ic,t}$, is the ic -th crop's loss at the t -th time slice,

$\text{Des}_{ic,t}^{\text{Seed}}$, is the seed demand per ha of the ic -th crop at the t -th time slice,

$\text{Des}_{ic,t}^{\text{Waste}}$, is the loss share of the ic -th crop's total production at the t -th time slice,

$\text{inc}_{ic,t}^{\text{Seed}}$, is the growth rate of $\text{Des}_{ic,t}^{\text{Seed}}$,

$\text{inc}_{ic,t}^{\text{Industry}}$, is the annual growth rate of industry demand of the ic -th crop at the t -th time slice,

$\text{inc}_{ic,t}^{\text{Waste}}$, is the growth rate of $\text{Des}_{ic,t}^{\text{Waste}}$,

$A_{ic,t}$, is the sown area of the ic -th crop at the t -th time slice,

$\text{Qc}_{ic,t}^{\text{S}}$, is the ic -th crop's production at the t -th time slice.

6.2.2.4 Total grain demand

When food consumption, feed, seed, and industry demand, and waste were obtained, the total demand for grain was calculated,

$$Qc_{ic,t}^D = Q_{ic,t}^D + Feed_{ic,t} + Seed_{ic,t} + Industry_{ic,t} + Waste_{ic,t} \quad (\text{Eq. 6-27})$$

where

$Qc_{ic,t}^D$, is the total demand of the ic -th crop at the t -th slice,

$ic = 1, \dots, 11$, is the crop index: 1) rice, 2) wheat, 3) maize, 4) tubers, 5) coarse grains, 6) soybean, 7) oil crops, 8) sugar crops, 9) vegetable, 10) cotton, 11) fruits.

6.2.3 Stock and trade

Besides the aspects of supply and demand introduced above, stock and trade are also necessary components in the food market. Only grain stock and trade were considered in the model.

6.2.3.1 Grain stock

The grain stock is a function of the growth of grain demand, the stock of the previous year, and the domestic prices of grain products. In the long-term planning, the increase in grain stock is a linear function of grain consumer price, but the short-term storage strategy is a little different: it is the stock ratio of total production that is a linear function of consumer price. Moreover, the realistic stock strategy at the national scale is to keep a storage which is about 5% to 30% of the production of each grain. Therefore, if the calculated stock exceeds the upper limit (in which case the domestic price of that crop is likely to decrease), the exceeding part will be forced to export in order to maintain stock within a reasonable range of production. In contrast, if it is less than 5% of the production, the deficient amount will be filled from the import.

$$Stock_{ic,t} = Stock_{ic,t-1} \cdot (1 + \varphi \cdot Qc_{ic,t}^D / Qc_{ic,t-1}^D) - \varphi \cdot Stock_{ic,t-1} + \beta St_{ic} \cdot \Delta P_{ic,t}^D / P_{ic,t}^D \quad (\text{Eq. 6-28})$$

where

$Stock_{ic,t}$, is the ic -th grain's stock at the t -th time slice,

$Qc_{ic,t}^D$, is the ic -th grain's total consumption at the t -th time slice,

βSt_{ic} , is the price elasticity of the change in the ic -th grain stock at the t -th time slice,

βSt_{ic} , is always given a negative value, since it requires selling an amount of storage as consumer price increases in order to raise domestic supply,

$P_{ic,t}^D$, is the ic -th grain's consumer price at the t -th time slice,

$\varphi = 0, \text{ or } 1$), is the switch of long or short term stock strategy. In the long term (when $\varphi = 0$), the change in grain stock follows $Stock_{ic,t} - Stock_{ic,t-1} = \beta St_{ic} \cdot P_{ic,t}^D$, while in the short term (when $\varphi = 1$), it will be $Stock_{ic,t}/Qc_{ic,t}^D - Stock_{ic,t-1}/Qc_{ic,t-1}^D = \beta St_{ic} \cdot P_{ic,t}^D$. The short term strategy is applied in the projection of less than five years.

ic ($= 1, \dots, 6$) denotes the grains' index, and includes 1) rice, 2) wheat, 3) maize, 4) tubers, 5) coarse grains, 6) soybean. The stocks of other crops and food items were not considered in this model.

6.2.3.2 International trade

The import and export of grains between domestic and international markets were computed after completing the simulation of production and all demands for the food products. In the trade component, the annual change in import and export are determined by the difference between world price and domestic price and the change in total demand, as shown in Eq. 3 and Eq. 4. The world price is firstly transformed to the domestic currency with the agricultural subsidy deducted. The total demand, $Qtot_{ic,t}^D$ in Eq. 5 is the demand after deducting (or adding) the import and export quantity from (or into) the $Qc_{ic,t}^D$ obtained in Section 6.2.2.4.

Import

$$\Delta X_{ic,t}^{import} / X_{ic,t}^{import} = \beta X \cdot (\Delta P_{ic,t}^D / P_{ic,t}^D - \Delta P_{ic,t}^{import} / P_{ic,t}^{import}) + \Delta Q_{tot_{ic,t}}^D / Q_{tot_{ic,t}}^D \quad (\text{Eq. 6-28}),$$

Export

$$\Delta X_{ic,t}^{export} / X_{ic,t}^{export} = \beta X \cdot (\Delta P_{ic,t}^D / P_{ic,t}^D - \Delta P_{ic,t}^{export} / P_{ic,t}^{export}) + \Delta Q_{tot_{ic,t}}^D / Q_{tot_{ic,t}}^D \quad (\text{Eq. 6-29}),$$

Total demand

$$Q_{tot_{ic,t}}^D = Qc_{ic,t}^D - X_{ic,t}^{import} + X_{ic,t}^{export} \quad (\text{Eq. 6-30}),$$

where $X_{ic,t}^{import}$ (or $X_{ic,t}^{export}$) is the import (or export) amount of the ic -th grain in the t -th year, $P_{ic,t}^{import}$ (or $P_{ic,t}^{export}$) is the import (or export) price and $P_{ic,t}^D$ is the domestic price. To solve this problem, two more equations of $\Delta X_{ic,t}^{import} / X_{ic,t}^{import}$ and $\Delta X_{ic,t}^{export} / X_{ic,t}^{export}$ are required.

Based on Eq. 6-30, we can get

$$\Delta Q_{tot_{ic,t}}^D / Q_{tot_{ic,t}}^D = \Delta Qc_{ic,t}^D / Q_{tot_{ic,t}}^D - \Delta X_{ic,t}^{import} / Q_{tot_{ic,t}}^D + \Delta X_{ic,t}^{export} / Q_{tot_{ic,t}}^D \quad (\text{Eq. 6-31})$$

and after introducing $Qc_{ic,t}^D$, it is transformed into

$$\begin{aligned} \Delta Q_{tot_{ic,t}}^D / Q_{tot_{ic,t}}^D &= (\Delta Qc_{ic,t}^D / Qc_{ic,t}^D) \cdot (Qc_{ic,t}^D / Q_{tot_{ic,t}}^D) - (\Delta X_{ic,t}^{import} / X_{ic,t}^{import}) \cdot \\ & (X_{ic,t}^{import} / Q_{tot_{ic,t}}^D) + (\Delta X_{ic,t}^{export} / X_{ic,t}^{export}) \cdot (X_{ic,t}^{export} / Q_{tot_{ic,t}}^D). \end{aligned} \quad (\text{Eq. 6-32})$$

If $w_d = Qc_{ic,t}^D / Qtot_{ic,t}^D$ (Eq. 6-33)

$$w_{import} = X_{ic,t}^{import} / Qtot_{ic,t}^D \quad (\text{Eq. 6-34})$$

and $w_{export} = X_{ic,t}^{export} / Qtot_{ic,t}^D$ (Eq. 6-35)

Eq. 6-28 and Eq. 6-29 will become a set of two equations with two unknown variables, i.e. $\Delta X_{ic,t}^{import} / X_{ic,t}^{import}$ and $\Delta X_{ic,t}^{export} / X_{ic,t}^{export}$,

$$\begin{aligned} (1 + w_{import}) \cdot \Delta X_{ic,t}^{import} / X_{ic,t}^{import} - w_{export} \cdot \Delta X_{ic,t}^{export} / X_{ic,t}^{export} \\ = \beta X \cdot (\Delta P_{ic,t}^D / P_{ic,t}^D - \Delta P_{ic,t}^{export} / P_{ic,t}^{export}) + w_d \cdot \Delta Qtot_{ic,t}^D / Qtot_{ic,t}^D \end{aligned} \quad (\text{Eq. 6-36})$$

$$\begin{aligned} -w_{import} \cdot \Delta X_{ic,t}^{import} / X_{ic,t}^{import} + (1 + w_{export}) \cdot \Delta X_{ic,t}^{export} / X_{ic,t}^{export} \\ = -1 \cdot \beta X \cdot (\Delta P_{ic,t}^D / P_{ic,t}^D - \Delta P_{ic,t}^{export} / P_{ic,t}^{export}) - w_d \cdot \Delta Qtot_{ic,t}^D / Qtot_{ic,t}^D \end{aligned} \quad (\text{Eq. 6-37})$$

So its solution is obtained

$$\begin{aligned} \Delta X_{ic,t}^{import} / X_{ic,t}^{import} \\ = [\beta X \cdot (\Delta P_{ic,t}^D / P_{ic,t}^D - \Delta P_{ic,t}^{import} / P_{ic,t}^{import}) + w_d \cdot \Delta Qtot_{ic,t}^D / Qtot_{ic,t}^D \\ + w_{export} \cdot \beta X \cdot (\Delta P_{ic,t}^{export} / P_{ic,t}^{export} - \Delta P_{ic,t}^{import} / P_{ic,t}^{import})] / (1 + w_{import} \\ + w_{export}) \end{aligned} \quad (\text{Eq. 6-38})$$

$$\begin{aligned} \Delta X_{ic,t}^{export} / X_{ic,t}^{export} \\ = [-1 \cdot \beta X \cdot (\Delta P_{ic,t}^D / P_{ic,t}^D - \Delta P_{ic,t}^{export} / P_{ic,t}^{export}) - w_d \cdot \Delta Qtot_{ic,t}^D / Qtot_{ic,t}^D \\ + w_{import} \cdot \beta X \cdot (\Delta P_{ic,t}^{export} / P_{ic,t}^{export} - \Delta P_{ic,t}^{import} / P_{ic,t}^{import})] / (1 + w_{import} \\ + w_{export}) \end{aligned} \quad (\text{Eq. 6-39})$$

The import and export prices ($P_{ic,t}^{import}$ and $P_{ic,t}^{export}$) were computed by the following formulae:

$$P_{ic,t}^{import} = P_{ic,t}^{cif} \cdot XR_t \cdot (1 + \text{Subsidy}_{ic,t}^{import}) \quad (\text{Eq. 6-40})$$

$$P_{ic,t}^{export} = P_{ic,t}^{fob} \cdot XR_t \cdot (1 + \text{Subsidy}_{ic,t}^{export}) \quad (\text{Eq. 6-41})$$

where

$P_{ic,t}^{cif}$ is the CIF price, the price of the products at ports, which includes transportation price and insurance cost;

$P_{ic,t}^{fob}$ is the FOB price, the price of departing products without shipping freight and insurance charges;

XR_t , is the exchange rate at the t -th time slice;

$\text{Subsidy}_{ic,t}^{import}$ and $\text{Subsidy}_{ic,t}^{export}$ are the producer subsidy of the ic -th food commodity at the t -th time slice;

$X_{ic,t}^{import}$ (or $X_{ic,t}^{export}$) is the import (or export) of the ic -th food commodity at the t -th time slice;

βX , is the elasticity of substitution, which indicates the percentage change in import or export when the changes in domestic consumer prices are faster or slower than the changes in world market prices.

6.2.4 Running model

This food economic model is designed to run yearly. It has two running modes: 1) calibration mode, in which the key variables, i.e. production, sown area, food consumption, and demand in other usages, would be computed separately on supply and demand sides using exogenous producer's and consumer's prices, and these

calculations are only carried out one time in a year without running the market clearing mechanics; and 2) market clearing mode, in which the price reaction within the economic system to those changes in exogenous inputs is considered, and the price of food commodities will be adjusted until the entire system reaches an “equilibrium” status, in which the total supply would be roughly equal to the total demand. In the market clearing mode, the supply and demand were calculated by the endogenous prices of food commodities, i.e. the equilibrium price. In practice, the equilibrium prices in a certain year would be found after many times of iteration.

6.2.4.1 Market clearance

At the market clearing status, the total supply of a food commodity needs to satisfy (or quasi equals to) its total demand, as shown in the following equation:

$$Qc_{ic,t}^S + (X_{ic,t}^{import} - X_{ic,t}^{export}) =$$

$$Qc_{ic,t}^D + Feed_{ic,t} + Seed_{ic,t} + Industry_{ic,t} + Waste_{ic,t} + (Stock_{ic,t} - Stock_{ic,t-1})$$

(Eq. 6-42)

The equilibrium prices of food commodities each year can be obtained under that market clearing status. In other words, the procedure to reach a market clearance is a process to search a proper group of food prices under which the supply of each food commodity quasi-equals its demand separately. Mathematically, it requires solving a set of 11 equations with 18 variables (including the prices of 11 crops and 7 livestock products). Theoretically, the change in equilibrium price for one food commodity can be calculated by solving its own supply-demand equation, when other variables are kept as constant.

Figure 6-1 shows how to obtain that theoretical solution of equilibrium status can be obtained in the case where the supply and demand of only one commodity change in the food market from time slice (t) to slice (t+1). The point A at which the

supply curve (S_t) and demand curve (D_t) cross, shows the status where supply and demand both have the value of Q^*_0 which ideally is equal to each other at the price of P^*_0 in the year t . However, in the year $(t+1)$ when the supply and demand curves move on due to the change in inputs, the equilibrium price P^*_0 in the year t cannot be kept at the new equilibrium point B. Now, we do not know the new equilibrium price P^*_1 , but it can be calculated by the following method.

Firstly, the interim supply (point C) and demand (point D) under the P^*_0 can be obtained by (an example of a grain product) equations of **Area** and **Yield** in Section 6.2.1.1. If $\Delta X_{ic,t} = X_{ic,t+1} - X_{ic,t}$ for all the variables, then

$$\begin{aligned} \frac{\Delta S_{ic,t}}{S_{ic,t}^S} = & \sum_{jc}^{ncrop} \beta A_{ic,jc} \frac{\Delta PC_{jc,t}^S}{PC_{jc,t}^S} + \sum_{jc}^3 \beta A_{ic,jc} \frac{\Delta PI_{jc,t}}{\Delta PI_{jc,t}} + \sum_{jc}^2 \beta A_{ic,jc} \frac{\Delta ZA_{jc,t}}{ZA_{jc,t}} \\ & + \sum_{jc}^2 \beta Y_{ic,jc} \frac{\Delta ZY_t}{ZY_t} + \beta Y_{ic,3} \frac{\Delta Clm_{ic,t}}{Clm_{ic,t}} + \sum_{jc}^3 \beta Q_{ic,jc} \frac{\Delta ZQ_{jc,t}}{ZQ_{jc,t}} \end{aligned} \quad (\text{Eq. 6-43})$$

and,

$$\frac{\Delta D_{ic,t}}{D_{ic,t}} = \beta IM_{ic} \cdot \frac{\Delta IM_t}{IM_t} + \sum_{jc}^{ncrop+nmeat} \beta Q_{ic,jc}^D \frac{\Delta P_{jc,t}^D}{P_{jc,t}^D} + \lambda \cdot \beta MKT_{ic} \frac{\Delta MKT_t}{MKT_t} \quad (\text{Eq. 6-44})$$

Thus, when $P^*_0=0$, the interim supply and demand are

$$\begin{aligned}
\frac{S_{ic,t+1} - S_{ic,t}^*}{S_{ic,t}^*} &= \frac{\Delta S_{ic,t} | \Delta PC_{ic,t}^S = 0}{S_{ic,t}^*} \\
&= \sum_{jc \neq ic}^{ncrop} \beta A_{ic,jc} \frac{\Delta PC_{jc,t}^S}{PC_{jc,t}^{S^*}} + \sum_{jc}^3 \beta A_{ic,jc} \frac{\Delta PI_{jc,t}}{\Delta PI_{jc,t}} + \sum_{jc}^2 \beta A_{ic,jc} \frac{\Delta ZA_{jc,t}}{ZA_{jc,t}} \\
&+ \sum_{jc}^2 \beta Y_{ic,jc} \frac{\Delta ZY_t}{ZY_t} + \beta Y_{ic,3} \frac{\Delta Clm_{ic,t}}{Clm_{ic,t}} + \sum_{jc}^3 \beta Q_{c_{ic,jc}} \frac{\Delta ZQ_{c_{jc,t}}}{ZQ_{c_{jc,t}}}
\end{aligned}
\tag{Eq. 6-45}$$

$$\begin{aligned}
\frac{D_{ic,t+1} - D_{ic,t}^*}{D_{ic,t}^*} &= \frac{\Delta D_{ic,t} | \Delta P_{ic,t}^D = 0}{D_{ic,t}^*} \\
&= \beta IM_{ic} \cdot \frac{\Delta IM_t}{IM_t} + \sum_{jc \neq ic}^{ncrop+nmeat} \beta Q_{ic,jc}^D \frac{\Delta P_{jc,t}^D}{P_{jc,t}^{D^*}} + \lambda \cdot \beta MKT_{ic} \frac{\Delta MKT_t}{MKT_t}
\end{aligned}
\tag{Eq. 6-46}$$

where $Q_{c_{ic,t}}^{S^*}$ and $Q_{c_{ic,t}}^{D^*}$ are the supply and demand of the ic -th grain product at the equilibrium status of the t -th year, and so $S_{ic,t}^* = D_{ic,t}^* = Q_{c_{ic,t}}^*$. The $PC_{jc,t}^{S^*}$ and $P_{jc,t}^{D^*}$ are corresponding equilibrium prices of the grain products except the ic -th grain, and $PC_{jc,t}^{S^*} = P_{jc,t}^{D^*} = P_{jc,t}^*$.

Letting

$$\begin{aligned}
\Delta EFF_t^S &= \sum_{jc}^3 \beta A_{ic,jc} \frac{\Delta PI_{jc,t}}{\Delta PI_{jc,t}} + \sum_{jc}^2 \beta A_{ic,jc} \frac{\Delta ZA_{jc,t}}{ZA_{jc,t}} + \sum_{jc}^2 \beta Y_{ic,jc} \frac{\Delta ZY_t}{ZY_t} + \beta Y_{ic,3} \frac{\Delta Clm_{ic,t}}{Clm_{ic,t}} + \\
&\sum_{jc}^3 \beta Q_{c_{ic,jc}} \frac{\Delta ZQ_{c_{jc,t}}}{ZQ_{c_{jc,t}}}
\end{aligned}
\tag{Eq. 6-47}$$

and

$$\Delta EFF_t^D = \beta IM_{ic} \cdot \frac{\Delta IM_t}{IM_t} + \lambda \cdot \beta MKT_{ic} \frac{\Delta MKT_t}{MKT_t}
\tag{Eq. 6-48}$$

then Eq. 6-45 and Eq. 6-46 become

$$\frac{S_{ic,t+1} - Qc_{ic,t}^*}{Qc_{ic,t}^*} = \sum_{jc \neq ic} \beta A_{ic,jc} \frac{\Delta PC_{jc,t}^S}{P_{jc,t}^*} + \Delta EFF_t^S \quad (\text{Eq. 6-49})$$

$$\frac{D_{ic,t+1} - Qc_{ic,t}^*}{Qc_{ic,t}^*} = \sum_{jc \neq ic} \beta Q_{ic,jc}^D \frac{\Delta P_{jc,t}^D}{P_{jc,t}^*} + \Delta EFF_t^D \quad (\text{Eq. 6-50})$$

That is

$$S_{ic,t+1} = Qc_{ic,t}^* \left(1 + \sum_{jc \neq ic} \beta A_{ic,jc} \frac{\Delta PC_{jc,t}^S}{P_{jc,t}^*} + \Delta EFF_t^S \right) \quad (\text{Eq. 6-51})$$

$$D_{ic,t+1} = Qc_{ic,t}^* \left(1 + \sum_{jc \neq ic} \beta Q_{ic,jc}^D \frac{\Delta P_{jc,t}^D}{P_{jc,t}^*} + \Delta EFF_t^D \right) \quad (\text{Eq. 6-52})$$

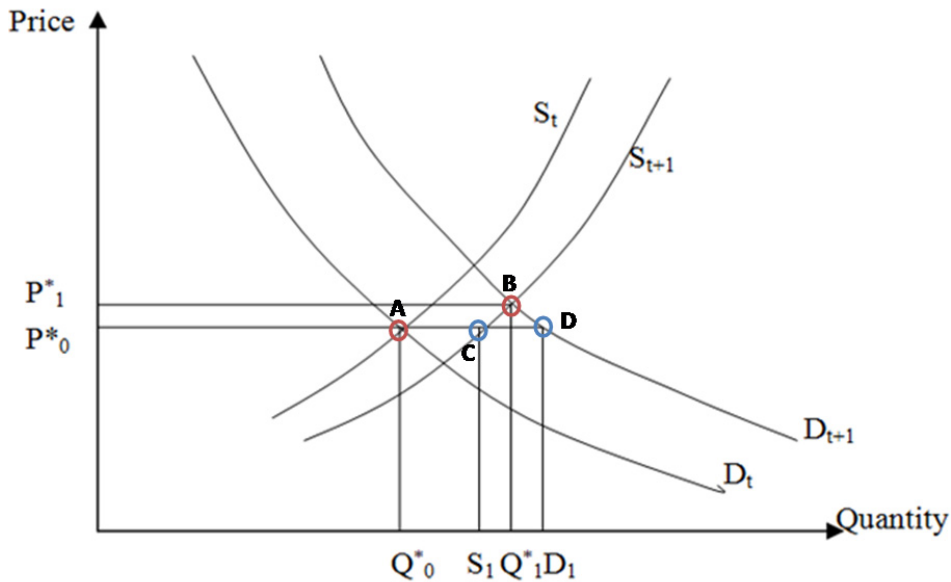


Figure 6-1 The equilibrium of supply and demand functions.
Source: Huang & Li (1999).

The equilibrium price would increase in the $(t+1)$ -th year from P_0^* to P_1^* as the supply and demand curves move, and the new equilibrium amount $Qc_{ic,t+1}^*$ (i.e. Q_1^* in Figure 6-1), obviously is computed by the known $S_{ic,t+1}$ and $D_{ic,t+1}$, and the unknown $\Delta P_{ic,it}^* = P_{ic,it+1}^* - P_{ic,it}^*$ (i.e. $P_1^* - P_0^*$ in Figure 6-1) based on the S_{t+1} and D_{t+1} curves, the slope of which at point C and D are known as $\beta A_{ic,ic}$ and $\beta Q_{ic,ic}^D$,

$$Qc_{ic,t+1}^* = S_{ic,t+1} \left(1 + \beta A_{ic,ic} \cdot \frac{\Delta P_{ic,t}^*}{P_{ic,t}^*} \right) = D_{ic,t+1} (1 + \beta Q_{ic,ic}^D \cdot \frac{\Delta P_{ic,t}^*}{P_{ic,t}^*}) \quad (\text{Eq. 6-53})$$

Thus the unknown $\Delta P_{ic,t}^*$ can be solved as

$$\Delta P_{ic,t}^* = \frac{P_{ic,t}^* (D_{ic,t+1} - S_{ic,t+1})}{(S_{ic,t+1} \cdot \beta A_{ic,ic} - D_{ic,t+1} \cdot \beta Q_{ic,ic}^D)} \quad (\text{Eq. 6-54})$$

and then $Qc_{ic,t+1}^*$ can be calculated by Eq. 8.

Eq. 8 and Eq. 9 give the theoretical solution of the equilibrium in a new supply-demand status only if the price of a product changes and the other prices are kept at the previous equilibrium status. Therefore, in the case where supply-demand relations of all products change, repeated calculating of Eq. 8 and Eq. 9 is required for thousands of iterations until a group of prices that can satisfy the market clearing condition for all the products at the same time was found. In actual numerical computation, the new supply-demand balance is supposed to be reached when the difference between the calculated supply and demand is less than 99% of demand, which is the quasi-equal status or balance (i.e. quasi-equilibrium in this thesis).

6.2.4.2 Limitation on area

As mentioned in Chapters 1 and 2, the arable land of China was declining in the past, and still faces the challenge from competition of land used for industry and housing construction even after strict government policy on non-agricultural land use. Thus it was necessary to include an environmental limitation on total sown area into the model, apart from the economic factors. The upper limit of the total sown area of all crops was set by the total arable land in history (about 120 million ha, derived from NBS yearbooks).

6.2.4.3 Limitation on food consumption

As the economy is growing, the dietary intake will change due to increasing income and rapid urbanization and modernization. This means that the elasticities of demand may be different from the current situation. It therefore requires a mechanic added into the food consumption component of the model in order to capture the pattern change in diet. Details of the mechanic will be discussed in Section 7.2.4.

6.3 Assumption and data

Some of the data required by the food economic model cannot be derived directly from the NBS census or the statistical yearbooks of MOA and there are also many missing records for existing data. Since a complete input data set was required by the model, it was necessary to construct the input data based on those available from the NBS census with the assumptions below that used in constructing the input data.

6.3.1 Assumptions

6.3.1.1 Inflation and CPI

Inflation is a crucial factor in preparing the datasets of prices and income. Usually, the CPI (consumer price index) is taken as an indicator of inflation rate in economic statistics. CPI reflects the changes in the cost of a fixed group of products and services, i.e.

$$CPI_t = \frac{t \text{ e cost on a fixed group of products at period } t}{t \text{ e cost on a fixed group of products at base period } t_0} \times 100 \quad (\text{Eq. 6-55})$$

The detailed calculation method of CPI in the National Bureau of Statistics of China is given at http://www.stats.gov.cn/tjzs/CPI/t20090219_402557357.htm

The real growth of all variables, i.e. price index, income, and investment, can be calculated by their nominal growth from the statistic yearbooks and its corresponding CPI,

$$Value^{real} = Value^{nominal} / CPI \quad (\text{Eq. 6-56})$$

Thus the index number of the variable's real value in year t+1 is,

$$\begin{aligned} Index_{t+1}^{real} &= \frac{Value_{t+1}^{real}}{Value_t^{real}} \\ &= \frac{Value_{t+1}^{nominal} / CPI_{t+1}}{Value_t^{nominal} / CPI_t} \\ &= \frac{Value_{t+1}^{nominal}}{Value_t^{nominal}} \cdot \frac{1}{CPI_{t+1} / CPI_t} \\ &= \frac{Index_{t+1}^{nominal}}{CPI_{t+1} / CPI_t} \end{aligned}$$

(Eq. 6-57)

The variables in monetary form, i.e. prices, income, and investment, were pre-processed by the CPI indices using the index equation above.

6.3.1.2 Price inputs in production function

The historic labour price for both crop and animal husbandry is measured by the average wage of agricultural labours (RMB/year) from Chinese statistic yearbooks. In future projections, the rural income is used as a surrogate of the labour price based on the strong relationship between the indices of rural income and agricultural wage in the historical census. Figure 6-2 gives the labour price indices

and rural income indices from 1980 to 2007, the changes in two indices match up to each other very well after 1986 with a Pearson correlation coefficient of 0.86.

The price of chemical fertilizer for projections is partially determined by the GDP growth, which historically has a weak correlation with the fertilizer price index (see Figure 6-3).

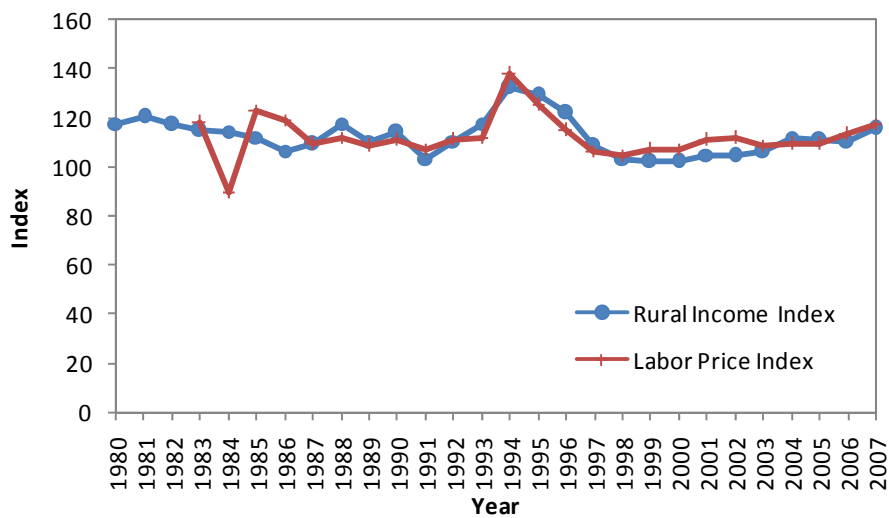


Figure 6-2 The labour price index and rural income index historically (1980-2007, preceding year =100). The Pearson correlation coefficient of two variables is 0.61. Source: Statistics NBS, 2007.

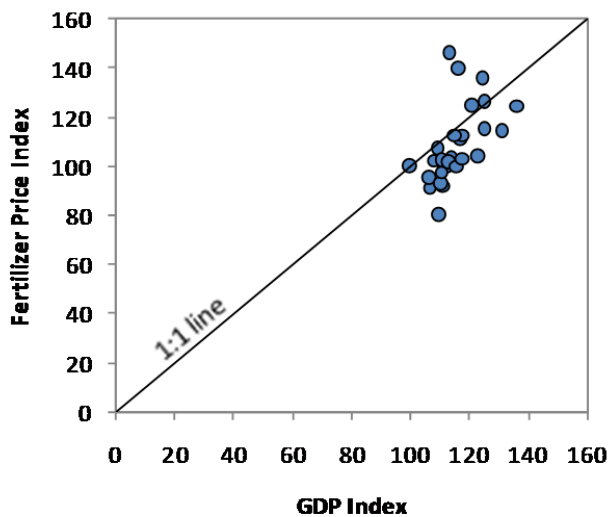


Figure 6-3 The relationship of historical fertilizer price index and GDP index (1978-2007, preceding year =100). The Pearson correlation coefficient of these two variables is 0.55. The original data are derived from statistical yearbooks of China (Statistics NBS, 2007).

6.3.1.3 Income

The annual growth rate of per capita income (urban and rural) in the future is supposed to be determined by the per capita GDP growth rate. The historical census (in Figure 6-4) indicates a strong relationship between the indexes of GDP and income (urban and rural). Details of this relationship are discussed in Ch7.

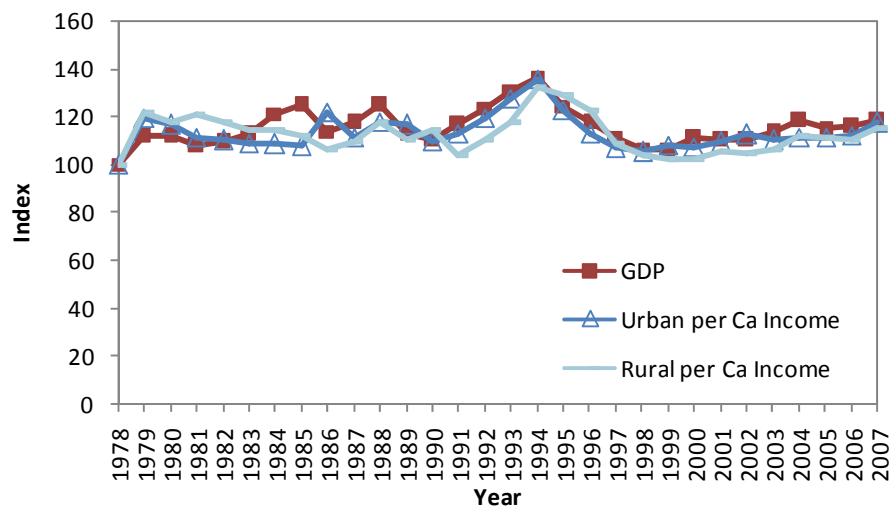


Figure 6-4 The historical census of urban and rural per capita income growth index, and GDP index (1978-2007). Urban income is the urban disposable income and rural income is the rural net income in Chinese yearbooks.

6.3.2 Historical data

This section discusses the calibration of the elasticities used in the food model and the validation of the model performance in simulating crop supply and demand of the historical census data from 1983 to 2007.

6.3.2.1 Price index

Some prices index data, i.e. chemical fertilizer and forage prices, are recorded in Statistical yearbooks (Statistics NBS, 1990-2007). The producer price of agricultural commodities is taken as the purchasing price indexes of farm products. The consumer price of urban and rural residents in yearbooks is not detailed enough for 11 crops and 7 livestock commodities. Thus average consumer price indexes are firstly reconstructed from the market price based on the Development Report of Chinese Agriculture (MOA, 2007) and Statistics NBS (2007). The consumer prices in urban and rural markets are then derived by using the corresponding CPI deflators obtained from Statistics NBS (2007). The producer or consumer price index of crops and livestock products was adjusted by the CPIs to remove the effect of inflation. The average wage of agricultural staff in NBS yearbooks was used as the indicator of labour price.

6.3.2.2 Shocks

The “shocks” on crop and livestock production are exogenous inputs, except for the agricultural subsidy, which is the policy employed only if the projected production of crops is lower than a threshold. Currently, agricultural subsidy is available for farmers who grow grain products or oil crops, to help maintain the national 95% self-sufficient ratio of grain production in the medium term and an improving domestic supply of edible oil. In this study, the subsidy on the prices of grain-cotton-oil products was considered as a measure of the “yellow” box subsidy policy under the WTO frame (definition of “yellow” box by WTO: <http://www.wto.org/>). The agricultural subsidy supporting a reasonable total cropping area, is derived from the annual subsidy cost on grain-cotton-oil products (Financial yearbooks of China, 2010); the stimulators of yield improvement, which includes the investment in agricultural technology from the national account (namely the “Nong-ye-ke-ji-san-xiang” fee in Financial yearbooks of China) and the growth in effective irrigation

area which is supposed to represent the capability to maintain normal yield levels in droughts; the factors contributing to the total crop production, i.e. the investments in the agriculture support sector (such as the meteorology service), the investments in reserved cropping land infrastructure, and investments in the financial support to rural residents, were also obtained from Financial yearbooks of China.

6.3.2.3 Crop yield (t/ha), sown area (ha), and production (t)/livestock production (t)

At the national scale, the average historical crop yield is calculated by the total sown area and production records from Statistics NBS (2007). Among the 11 crops considered in this model, the total production and sown area of starch crops were considered as the summary of potato and sweet potato in yearbooks. The NBS yearbooks only provide the sum statistics of all kinds of beans, so the soybean data are obtained from the crop database provided by MOA (available at <http://www.zzys.gov.cn/nongqing.aspx>). The bean crops except soybean are considered as part of the coarse grains. The meat productions of pork, beef, mutton and poultry are the slaughtered weight outputs without head, feet and offal in NBS' survey. The aquatic products include fish and shellfish (converted as the equivalent amount in fish).

6.3.2.4 Per capita consumption (kg/capita/year)

NBS yearbooks include the per capita consumption of the total grain consumption but not food products for each food category. However, the consumption of some individual grain can be found at province level in several years. A per capita consumption of grain data was therefore constructed based on the average food consumption per reference man per day in a nation-wide food intake survey (Zhai et al., 2005), the household food demand in Fan's studies (1994a, 1994b), the survey on grain demand (Gao, 2004) and the data from the China Rural Household Survey

Statistical Yearbooks. The starch and tubers are classified as one statistical category in the NBS yearbook, but this research only considered the consumption of tubers, because the consumption of processed starch products is small. In NBS yearbooks, the total soybean demand includes direct food consumption, soybean product and soybean oil demands in statistical data. The soybean oil is also included in the vegetable oil category, and in this study the ratio of soybean oil consumption to the total vegetable oil consumption remains at the historical level. The beef and mutton consumptions are classified in one category for some years in the NBS yearbook, and they were separated into two parts based on their proportions derived from the census available from provincial yearbooks.

All the grains were measured in raw grain terms to be coincident with the units of production statistics (the conversion factors are shown in Appendix A.9). The vegetable oil was converted into raw oil crop weight with an average conversion ratio of 0.43 (see details in Appendix A.1). The sugar output productivity was assumed as 0.1225 (see details in Appendix A.1). Dairy products were calculated into equivalent milk. All the food item consumption was measured in weight (kg/capita/year).

Some factors may affect the accuracy of food per capita consumption: 1) for urban residents, all those statistics reflect the purchasing quantity, without consumption in restaurants (eating-out consumption), while food consumption of rural residents is likely to be more accurate, since it covers all the actual consumption of both purchasing or self-output of food; 2) the statistics of meat consumption are thought to be over-reported during the 1980s and 1990s (Fuller et al., 2000), so it may not match to the surveyed production and the actual feed demand; 3) uncertainty in the reproduced soybean consumption results from the lack of the survey on soybean oil consumption.

6.3.2.5 Per capita income (RMB/capita/year)

Urban income used in this study is the per capita disposable income in NSB yearbooks, and the income of rural residents is per capita annual net income of rural households. Income data in yearbooks are the nominal values, so all the income was then transformed to their real values by taking into account of the CPI deflator for this study.

6.3.2.6 Population (million)

The urban population in the NSB dataset denotes the normal resident in cities and towns, and the rural population refers to the population other than urban population. Thus the population seasonally shifting between urban and rural is regarded as the rural population. Uncertainty in estimating food demand is caused by this inaccurate population classification, since rural workers who may live in cities and towns are not included in the urban population.

6.3.2.7 Feed factors

The proportion of the three feed modes in the feed industry, the proportion of the grain share in feed and the meat conversion ratio were obtained from the meat production survey and previous studies (China Animal Agriculture Association, 2001; Zhao, 2006; Fuller, 1997). Estimations of these three factors were collected in 1996, 2004 and 2006, and it was assumed that there was no significant difference in the feeding mode and efficiency before and after 1996. All the feed factors are given in Appendix A.7 and A.8.

6.3.2.8 CIF and FOB price

In this study, the import price was obtained from FAPRI (2009) and FAO-OECD outlooks (2008, 2009). The consumer price in the rural market was taken as the export price. The trade subsidy in agricultural products is simply set to zero for simplification.

6.4 Model performance

The elasticities used in the model were collected from the literature (Huang et al., 1996; Huang & Li 1999; Huang 2004), and were estimated based on the data in the 1980s and 1990s. Slight adjustments were done to these elasticities on the grounds of the longer data series from the 1980s to 2007 compared to those of previous studies (usually before 2000). Details are given in Appendix A.

Simulations from the economic model were validated by comparing with the adjusted census described in Section 6.3. Simulations in comparison included the simulated supply and demand of 4 main staples (i.e. rice, wheat, maize, tubers) and 7 livestock products (pork, beef, mutton, poultry, egg, dairy, and aquatic food), the simulated area and yield with the census data from 1984 to 2007. The simulations were calculated in the calibration mode of the model, and the inputs in equations, e.g. the prices of producer and consumer, prices of inputs, income, CPI, and policy items, were derived from real census data.

6.4.1 Historical supply-demand balance

The history of food supply and demand is given as a reference (4 main staples in Figure 6-5, and 7 livestock products in Figure 6-6).

In general, the historical supply of 4 staples can successfully satisfy the total demand. The average self-satisfy ratio was 101% for rice, 97% for wheat, 104% for maize, and 110% for tubers during 1984 to 2007. Only wheat had to be imported from overseas, but the large volume of import (more than 10% of supply) in the 1980s shrank to an acceptable small level (less than 1% of supply) in the late 1990s. Food consumption and feed demand of grains are two important parts of total demand. The ratio of food consumption to total demand was decreasing slowly, as feed demand in all grain staples were growing quickly after the late 1990s.

Because there is a lack of statistics for food demand, the food demand data are approximately derived from national census in NBS yearbooks. The derived total demand has a systematic bias to the supply. An unknown component calculated from the average of the biases, was added to demand (see Figure 6-5).

As to livestock, the availability of all meat products was optimistic in the past. Pork, poultry and eggs were the main protein resources for Chinese, and their growth was steady despite the increasing rate becoming lower from the late 1990s. The demand for other meat accelerated after the 1990s, especially the explosive growth in dairy demand starting from the year 2000 (see Figure 6-6).

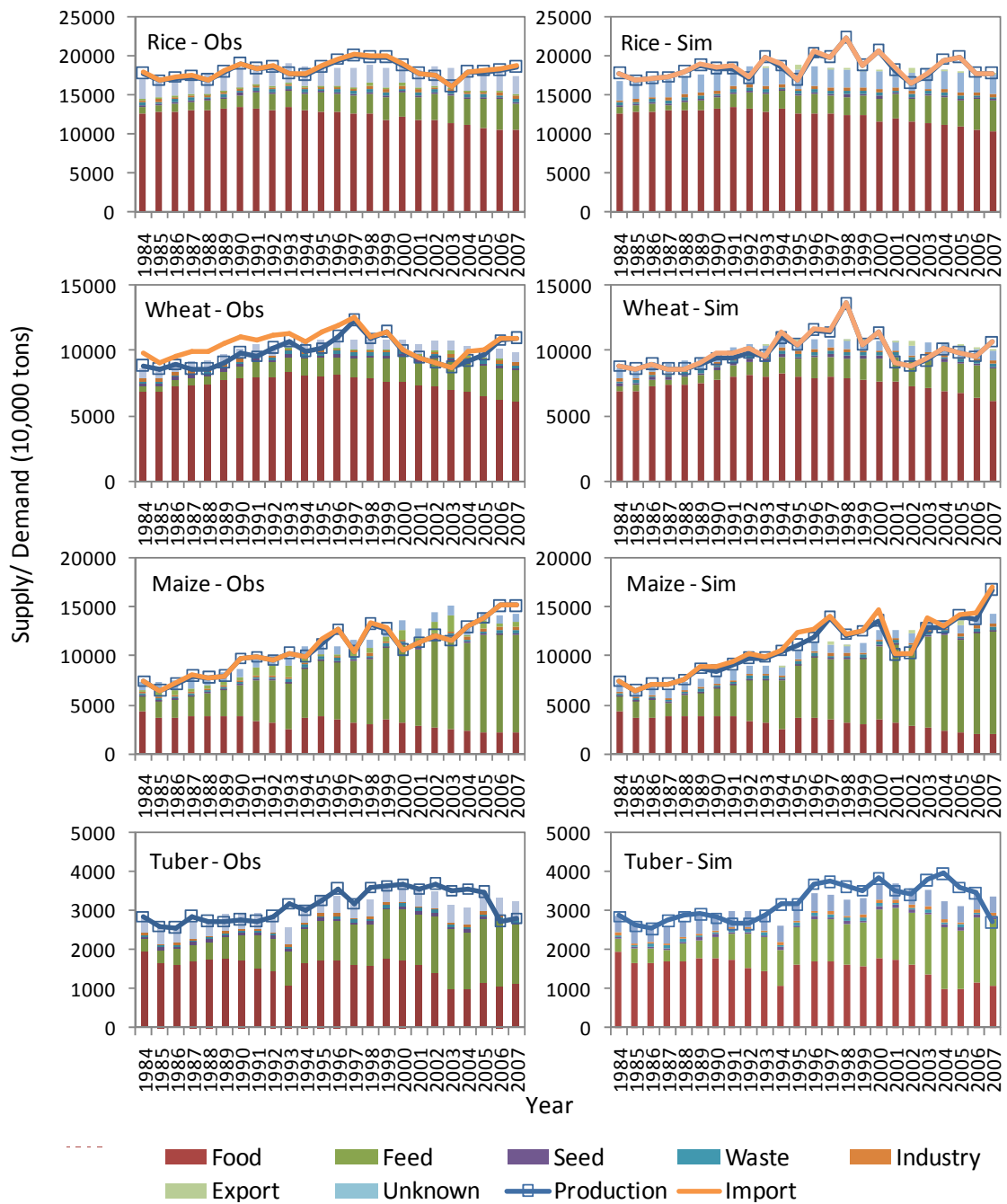


Figure 6-5 The supply and demand of 4 main staples: census vs simulation (from 1983 to 2007).

The unknown item is the average bias between the census supply (= census production + census import) and the adjusted census demand. Unit ton is the metric tonne (1000 kg).

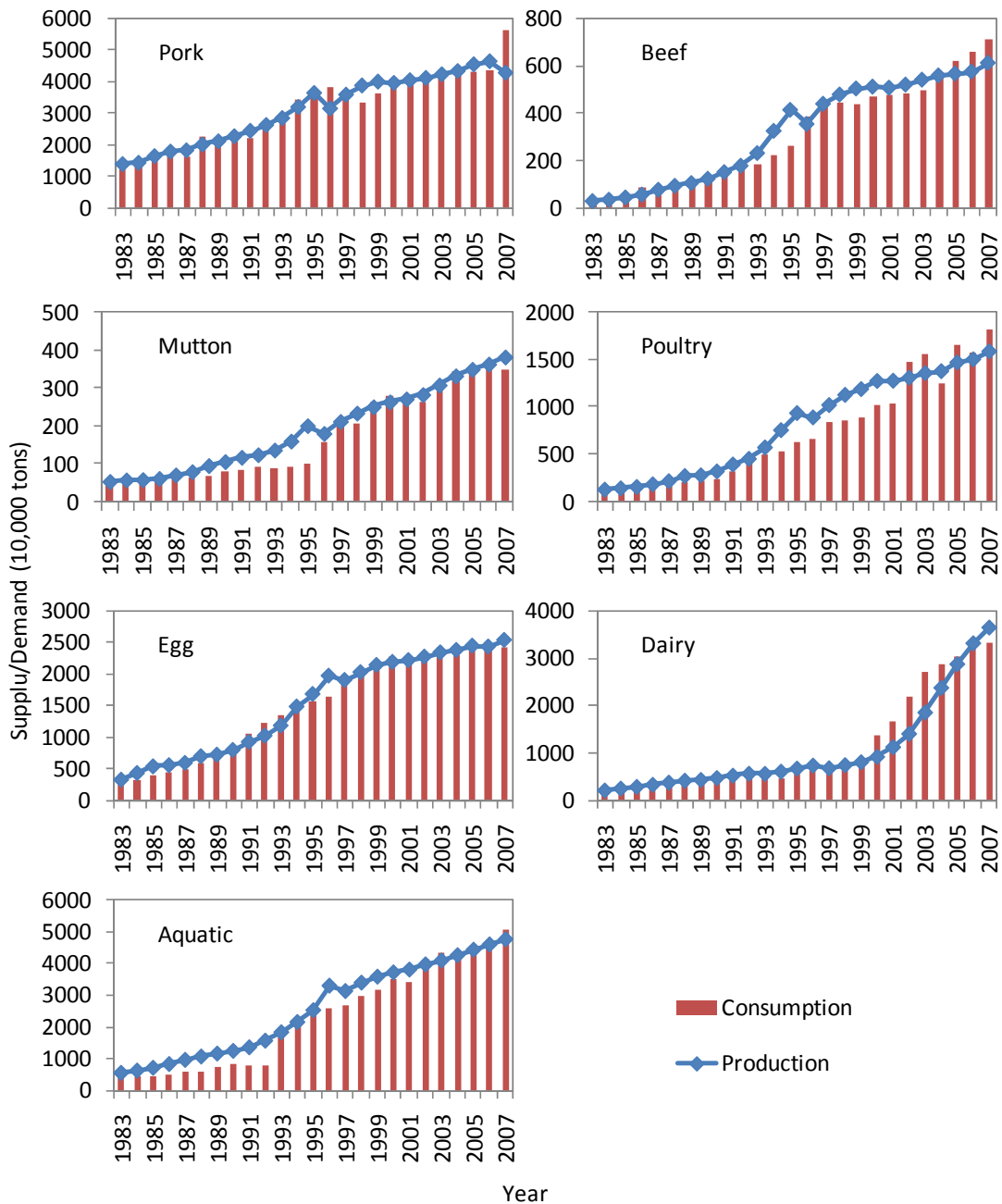


Figure 6-6 Historical production and consumption of livestock products (from 1983 to 2007). Unit ton is the metric tonne (1000 kg).

6.4.2 Model performance

The performance of this food economic model was measured by comparing the model results to the historical sown area, yield, production, and food consumption by urban and rural communities. The comparison of census and simulations of production and per capita consumption of 4 main grains (i.e. rice, wheat, maize and tuber) are given in this section. The rest of the results are shown in Appendix B.

The model simulation in this chapter is operated in calibration mode, which means that the production and consumption were calculated separately based on census producer and consumer prices. In general, the improved food economic model works well in the simulation of both supply and demand (Figure 6-7, 6-8). In the simulation of grain production, the average bias to census data is 1% for rice, 0.8% for wheat, 0.3% for maize, and 5% for tubers. With respect to variability, the model results had a larger variance than the census. In the simulation of consumption, the model has good performance for rice and wheat. For maize, rural consumption is slightly overestimated by the model with the major underestimations occurring in 1994 and 2000 (Figure 6-8). For tubers, the consumption is overestimated in the year 2003, which is likely due to the discontinuous census.

Good performance provides some confidence for the model to be used for future work. More importantly, the model includes sufficient information of price, income and other policies for simulation, which is critical for climate change impact assessment on food security.

In Fig. 6-8, compared with rice and wheat, the relationship between simulated and observed data for maize is weaker. The observed consumption data was obtained from the Chinese Statistical Bureau. The statistics about rice and wheat food consumption are much more accurate and smoothing than maize, because some

part of the real maize consumption is for the processed food, and the other part of maize consumption is eaten directly. So the maize observation data is not smoothing in some years, and thus it shows some outliers from the 1:1 Line in Fig. 6-8.

In this section, the model was run in the calibration mode, because 1) we have the real prices from census data for use in calculating supply and demand, and 2) those census prices can be considered as the equilibrium prices historically.

In Chapter 7, the model will run in the market clearance mode, in which the production and consumption are calculated by the endogenous equilibrium price to investigate the climate change impact on national scale food security in the terms of availability and prices.

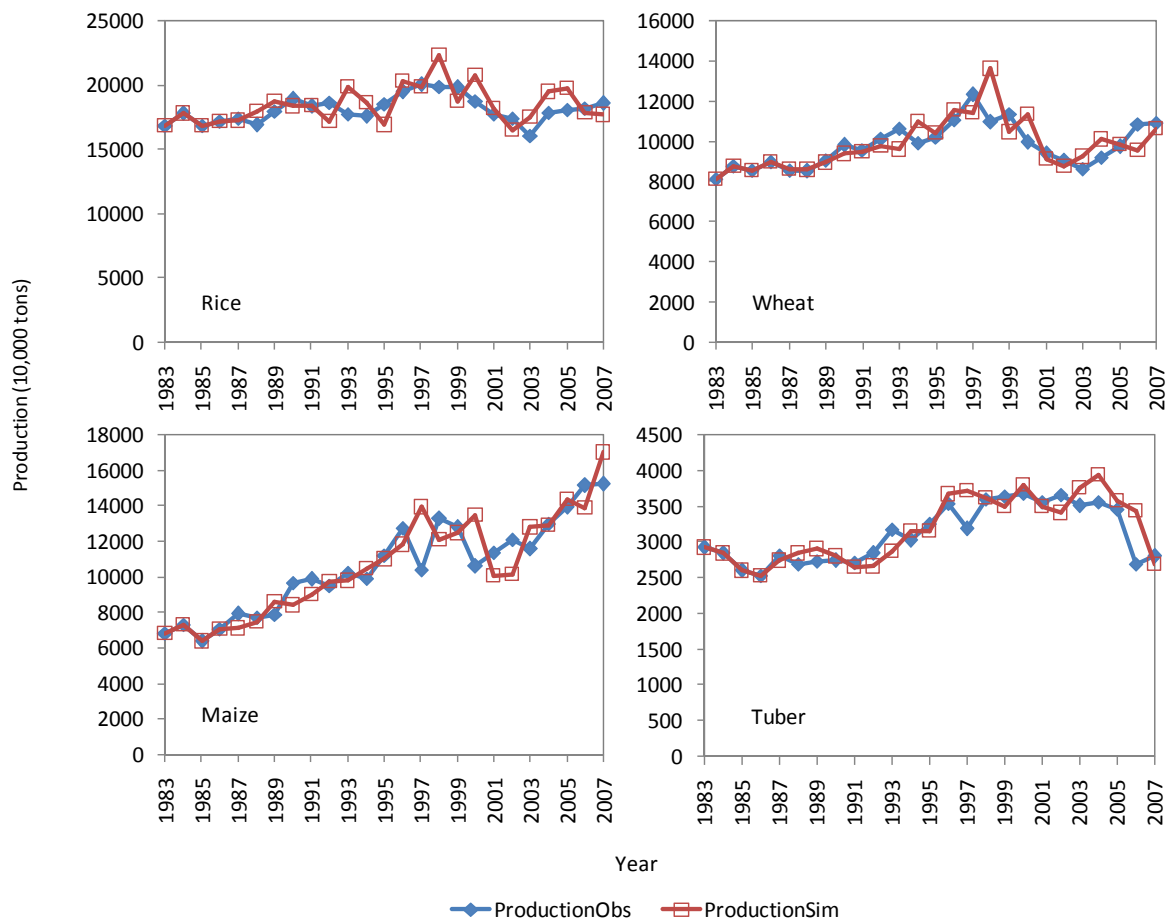


Figure 6-7 Historical (ProductionObs) and simulated (ProductionSim) production of 4 main staples (i.e. rice, wheat, maize, tubers). Unit ton is the metric tonne (1000 kg).

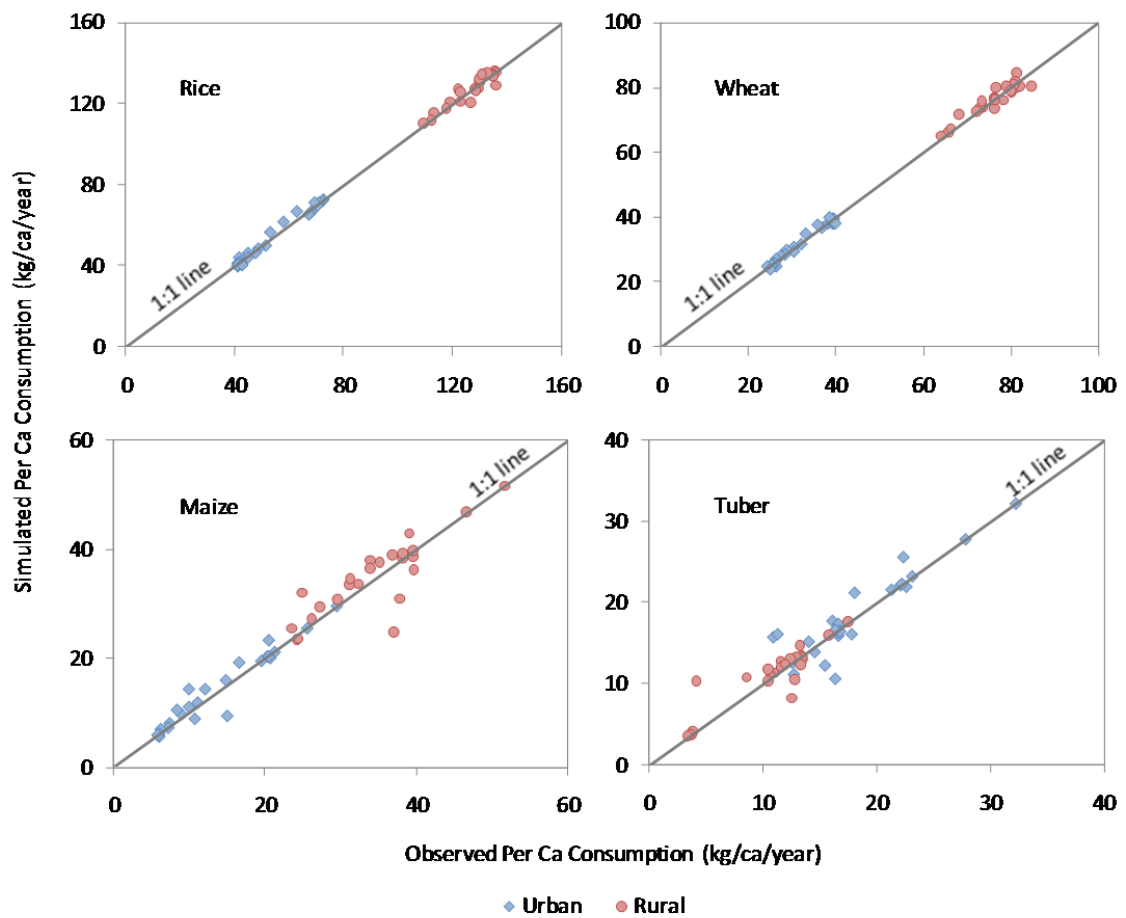


Figure 6-8 Historical and simulated per capita (ca) consumption of 4 main staples (i.e. rice, wheat, maize, tubers). The urban and rural data are shown in blue and red. The grey line in the figure is the 1:1 line of the historical and simulated data.

Chapter 7 Impacts of Climate Change on Food Security: a Case Study of China

7.1 Introduction

China's food security was analysed in this chapter for the next few decades. Projections of food production, consumption and prices under multiple climate change and socio-economic scenarios were generated by the food economic model described in Chapter 6. In the projections, the food economic model runs in market clearing mode, in which the prices of food commodities are calculated by the model and the supply and demand in the future are then computed based on these endogenous prices.

The climate change impact on food security was assessed in terms of food availability, accessibility and stability, with food utilization being further discussed in Chapter 8. The chapter is organised as follows: Section 7.2 introduces socio-economic and climate change scenarios used in generating the projections. Results of projections and food security are analysed in Section 7.3. In Section 7.4, two adaptation options are assessed at the national scale for coping with climate change. Section 7.5 discusses uncertainties and several extreme cases within projections. Finally, the future food security of China with respect to climate change is summarized in section 7.6.

7.2 Scenarios

In order to construct macro-economic and policy scenarios, a few projections of macro-economic indicators in the coming decades were collected from a wide range of literature, including OECD-FAO agricultural outlooks (OECD-FAO 2007, 2008, 2009), USDA agricultural projections (USDA 2009), USDAERS International Macro-economic Dataset (USDA ERS 2009), FAPRI world agricultural outlooks (FAPRI 2007, 2008, 2009), World Bank global economic prospects (World Bank 2009), World Bank China research papers, IMF world economic outlook (IMF 2009) as well as from Chinese research, and the national government's perspective. All the scenarios were compiled from 2005 to 2050.

7.2.1 GDP and income scenarios

No direct projection of China's income was found from the literature. However, historically there is a strong relationship between GDP and income and it is relatively easy to collect reliable predictions of GDP. Therefore the future income was estimated based on that relationship (see Section 7.2.1.2).

Furthermore, changes in per capita income and input prices (i.e. fertilizer and labour prices) were assumed to be dependent on GDP variation, making it very important to construct proper GDP scenarios. The predictions of GDP growth rate from previous research, as the reference, are given in Figure 7-1. Based on these projections, four growth scenarios of Chinese real GDP before the middle of the 21st century (see Figure 7-2) were reconstructed.

7.2.1.1 GDP growth scenarios

The projections of GDP were sourced in the short and long terms from the literature. Of the ten predictions that were used there was a similar moderate down trend of GDP growth rate before 2020, except for the projection from the USDA International Macroeconomic dataset which predicts a slight increase in GDP growth rate after 2015. Different projections gave different rates of GCP increase.

Three GDP growth scenarios (high, mid, and low) were constructed for this research. The high scenario is the most optimistic projection, of which the annual growth rate of GDP remains about 7% in 2050. Under the low scenario, GDP growth rate will decline rapidly until 2030 and remain only at 4%. Under the mid scenario, GDP growth rate will remain at a steady level before 2030 and then decrease, smoothing to 5.5% in 2050.

In addition, a "Best guess" scenario was constructed from the World Bank projection (2009). It has a downdrift from a higher growth level in the initial years to the lowest growth level of all those scenarios in the final year 2050. It is the so-called "soft landing" that the Chinese government is expecting during the economic transfer period. This was taken as the best projection of GDP for this study.

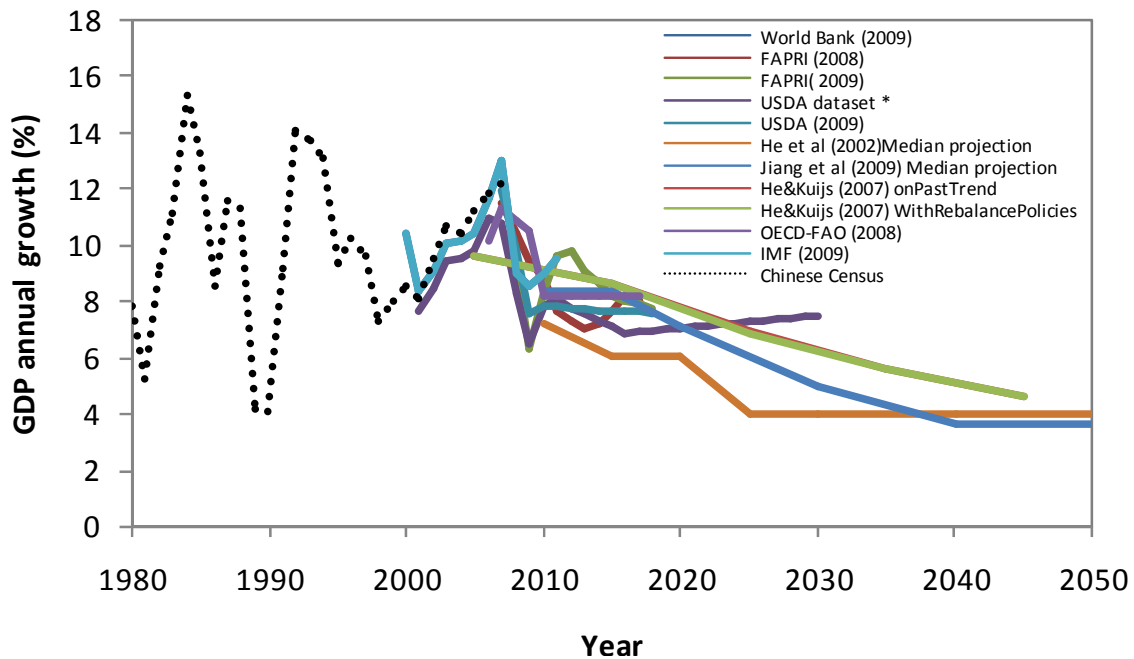


Figure 7-1 Projections of real GDP growth from the literature. The dotted line is the census data (from 1980 to 2007) from Statistics NBS.* USDA dataset is the USDA International Macroeconomic Dataset (<http://www.ers.usda.gov/data-products/international-macroeconomic-dataset.aspx>).

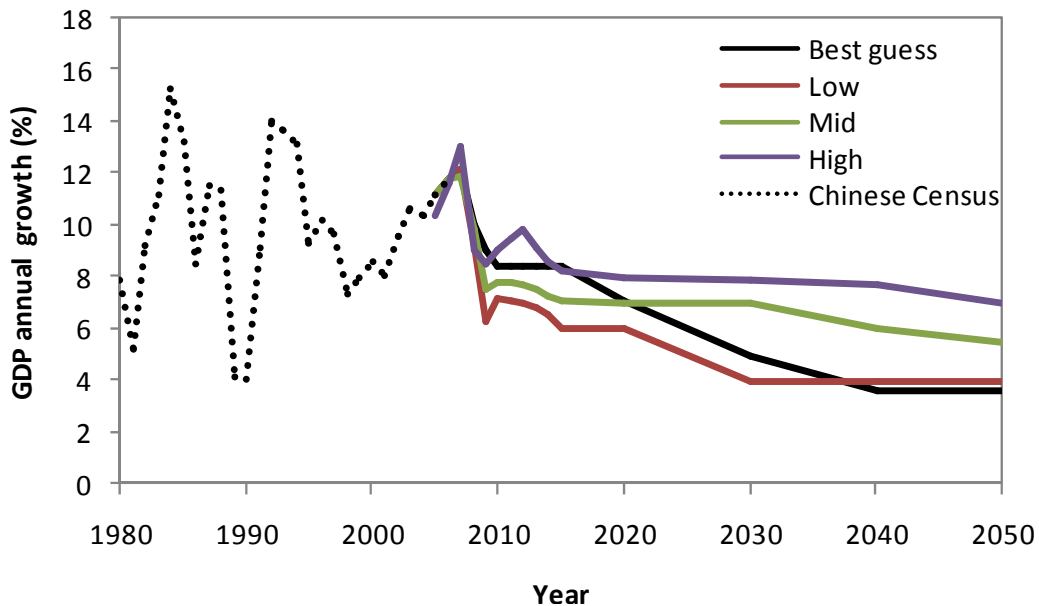


Figure 7-2 The historical and projected GDP annual growth. The dotted line is the historical line from 1980 to 2007. The coloured lines show five scenarios of GDP growth estimated from the sources given above: the low prediction is made up from FAPRI (2008) and the median projection of He et al. (2002), the mid is from USDA (2018) and USDA International Macroeconomic Dataset, and the high is from FAPRI (2009) and World Bank (2009).

7.2.1.2 Income scenarios

Historically, the per capita income has a strong relationship with per capita GDP (Figure 7-3). The coefficient of determination (R^2) for the urban (or rural) income to GDP regression is 0.99 (or 0.97). Future income growth was projected based on scenarios of GDP and its relationship with GDP as shown in Figure 7-4.

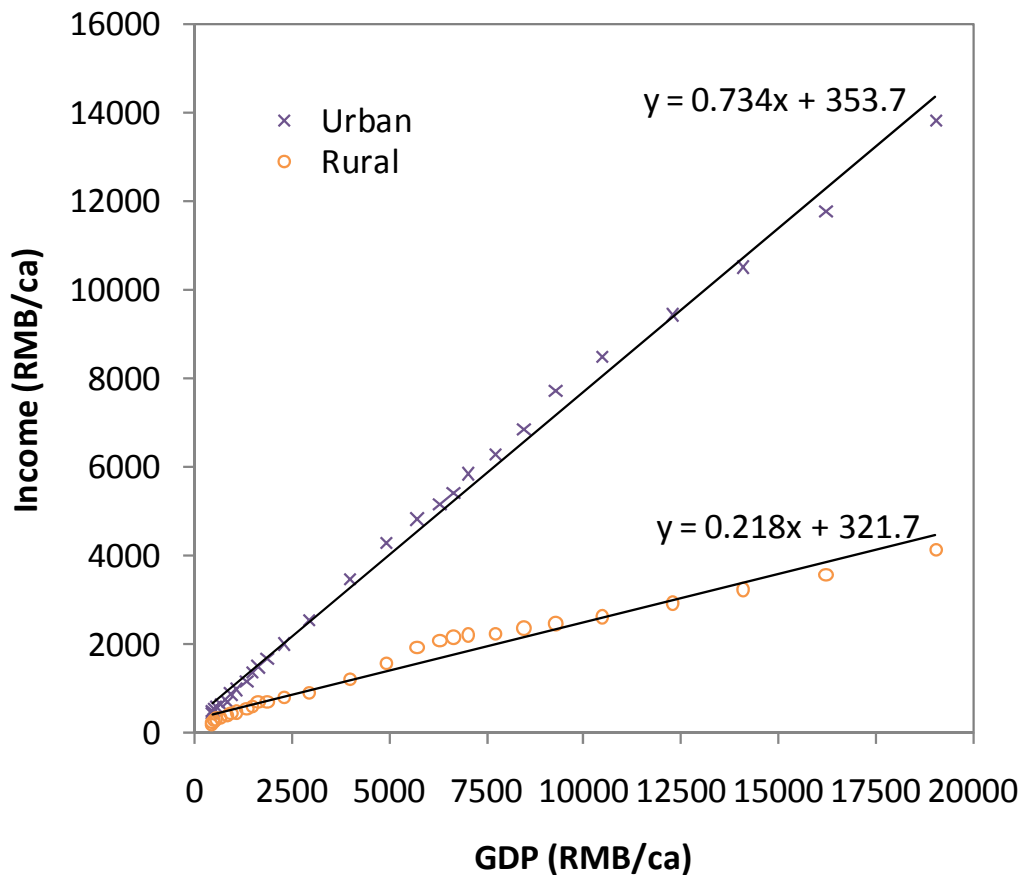


Figure 7-3 Relationship of per capita GDP and income (1978 - 2007). The solid line shows the linear regression of per capita GDP and urban (or rural) income. The future per capita income was calculated by $Income_{Rural} = 0.218 \cdot GDP + 321.7$ and $Income_{Urban} = 0.734 \cdot GDP + 353.7$.

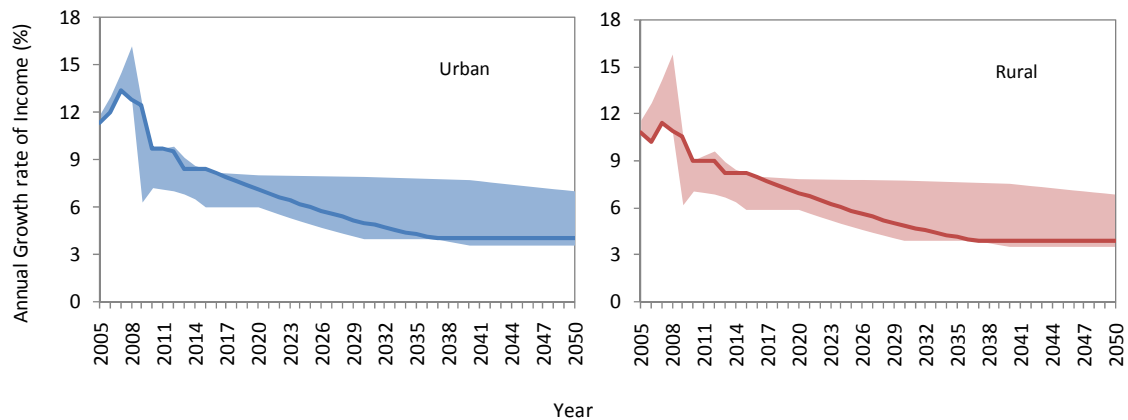


Figure 7-4 Scenarios of income annual growth. The solid line is the best guess scenario, and the shaded areas show the range of possible income growth.

7.2.2 Policy scenarios

As mentioned in Chapter 1, the main challenge of climate change for food security is the potential decline in yield due to changes in bio-physical processes and water usage in a warming environment. Responding to these negative impacts, the feasible adaptation is switching to new breeds, introducing new plants or improving the cropping management, such as irrigation facilities.

On a national scale, two agricultural policies were considered as adaptation options in projections. Investment in agricultural research (P1) reflects the optimal potential increase of a crop's yield, and effective irrigation area (P2) represents the effect of irrigation facilities on food production.

Based on the suggestions by Huang (2004) and Mei (2008), three scenarios were given for each policy (Table 7-1): the mid scenario has a similar growth level as that in the year 2007, and the low (or high) scenario is the pessimistic (or optimistic) estimation of growth of P1 and P2. The P2 high scenario has a relative small change

compared to the mid, because historically, the initial growth of effective irrigation area was relatively small.

Table 7-1 Policy scenarios used in projections. Only two policy scenarios were considered in the thesis. The annual growth rates of policy scenario are applied in Eq. 6-47 in projection.

Annual growth rate (%)	Low	Mid	High
Investment in Agricultural Research (PL1)	3	5	10
Effective Irrigation Area (PL2)	0.4	1.5	2.0

7.2.3 Population and urbanization scenarios

Considering the population control policy in China, the change in its population is usually projected to follow the same pattern, peaking at some point before the 2050s (see the previous projections in Figure 7-5). However, the time point when the population summit occurs and the peak value are quite different in the existing studies. The projections from the Chinese State Family Planning Commission (SFPC) and United Nations (UN) were used in this study (Figure 7-7). The best guess scenario of the total population was the estimation from SFPC; the low, mid, and high scenario were obtained from the UN projection.

Since the rapid urbanization is likely to result in reduced birth rates, the urbanized process is a factor affecting the total population growth pattern. It was assumed that the total population and urbanization were not independent in this study. The urbanization may be indirectly affected by the GDP growth rate. However, policy forcing is assumed as the main driver of urbanization in China. Therefore the high (or low) growth scenario of population was assumed to match the low (or high) urbanization scenarios.

Projections of China urbanization in the literature are shown in Figure 7-6. The scenarios of urban population share used in the thesis (Figure 7-8) are: 1) The best guess and low scenarios are derived from China's 12th 5-year Plan (National People's Congress, 2002), and 2) the median and high scenarios are from Huang (1999).

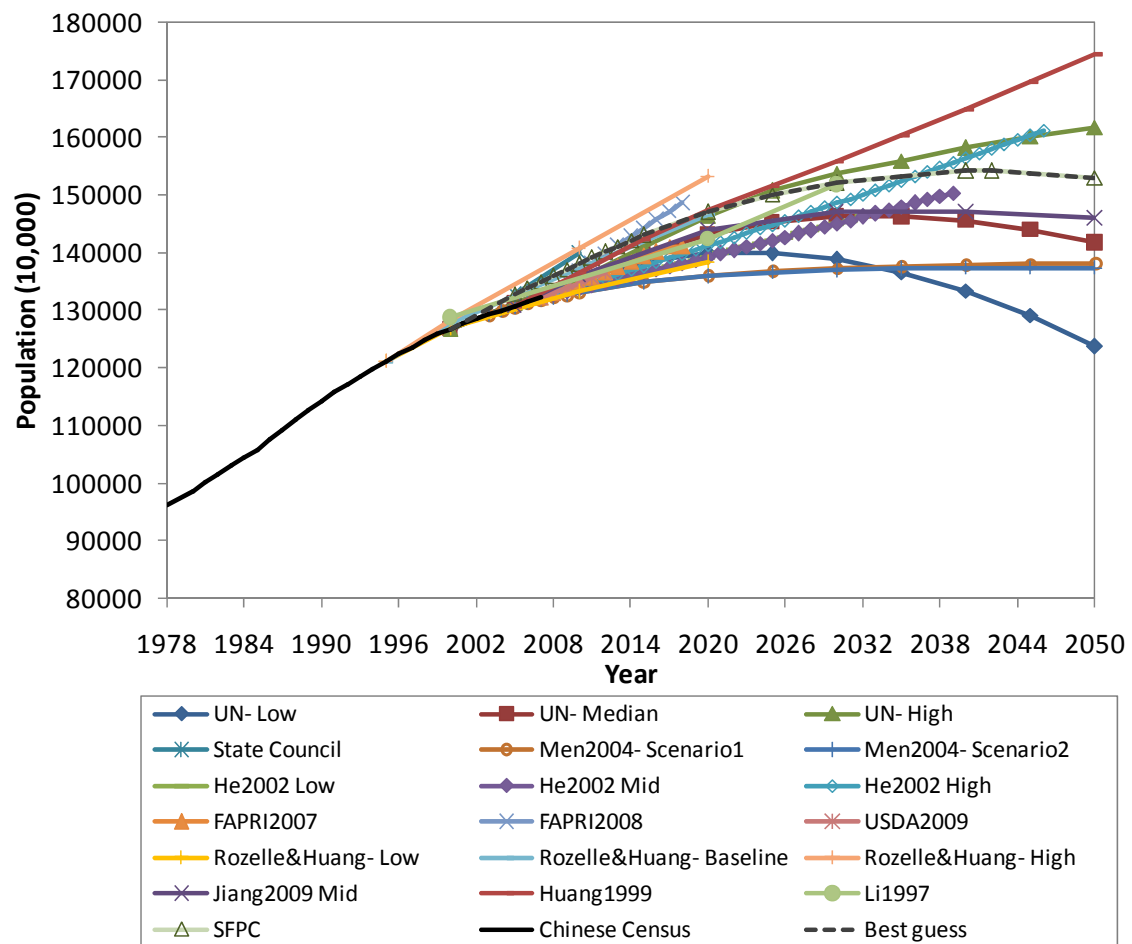


Figure 7-5 Projections from the literature of the Chinese population before the middle of the 21st century.

The dotted line is the best guess scenario of population used in the thesis. The sources for other projections are: UN (-Low, Median, and High) from World population prospect - 2008 revision population database (<http://esa.un.org/unpp/p2k0data.asp>); State Council's Program of Action for Sustainable Development in China in the Early 21st Century (State Council of China, 2003); Men & Zeng (2004); He et al. (2002); FAPRI (2007); FAPRI (2008); USDA (2009); Rozelle & Huang (1999); Jiang et al. (2009); Huang (1999); Li (1997); SFPC (State Family Planning Commission, <http://www.sfpc.gov.cn>); Chinese census (NBS yearbooks).

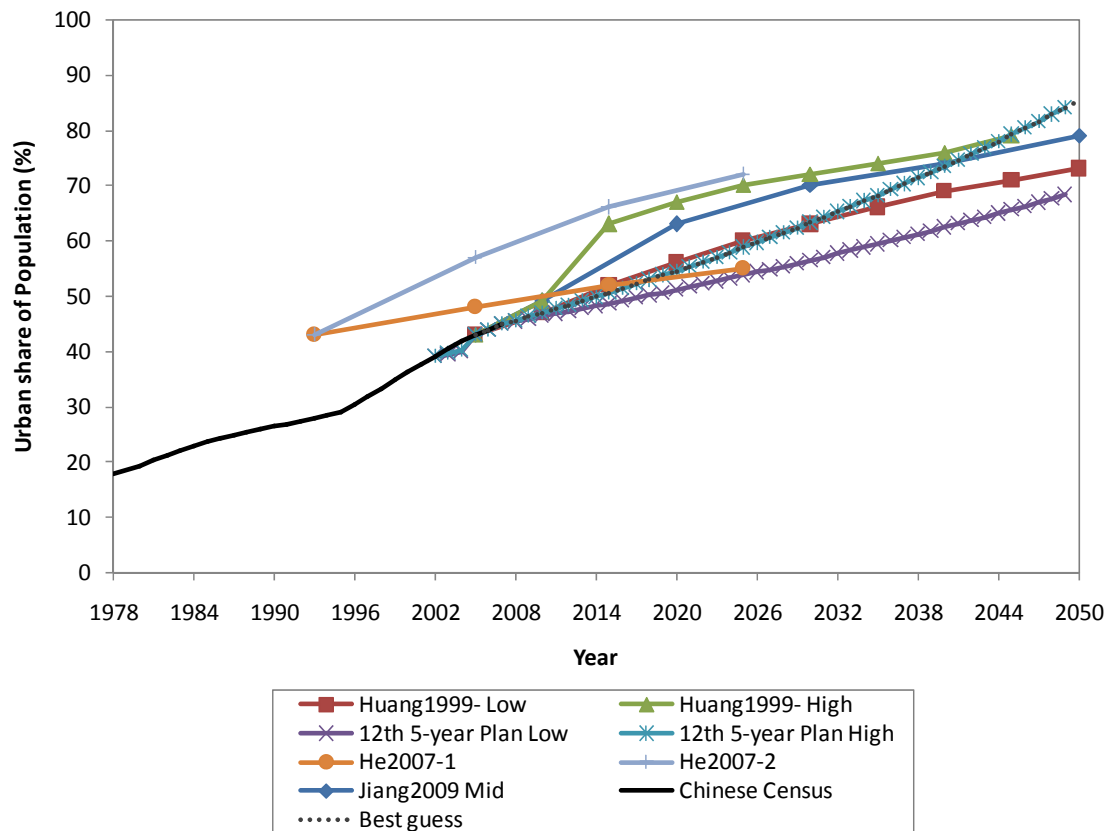


Figure 7-6 Projections from the literature of urban share of population before the middle of the 21st century.

The dotted line is the Best guess scenario used in the thesis. The other lines are the predictions derived from different sources: Huang (1999); the 12th 5-year Plan (2002); He et al. (2007); Jiang et al. (2009); Chinese census (NBS yearbooks).

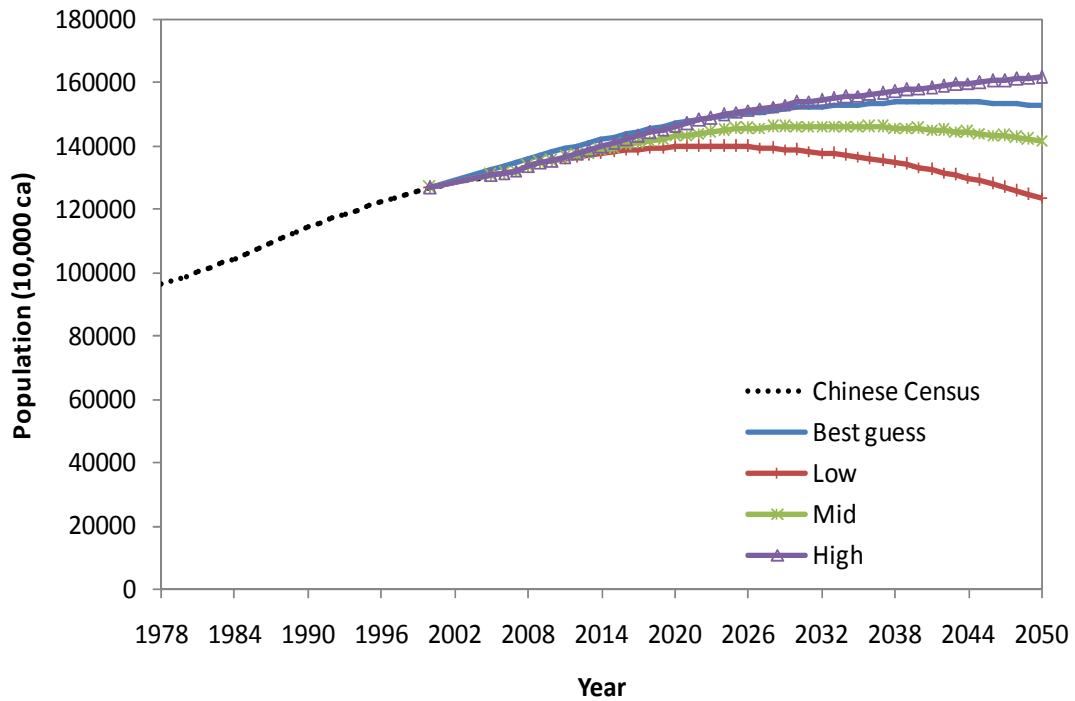


Figure 7-7 The population scenarios used in the thesis. The Best guess scenario is the estimation from SFPC, and the low, mid, and high scenarios were obtained from the UN population projection.

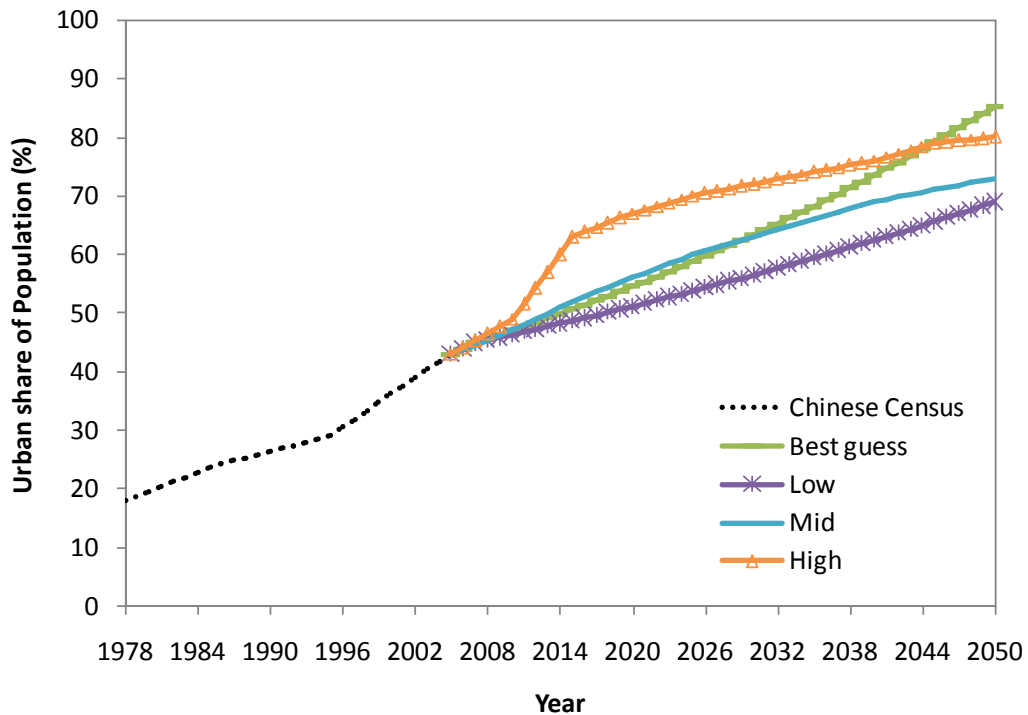


Figure 7-8 The scenarios of urban population share used in the thesis. The Best guess and low scenarios are derived from 12th 5-year Plan (2002), and median and high scenarios are from Huang (1999).

7.2.4 Nutrition standard

In the original CAPSiM model, the change in per capita food consumption is calculated from the changes in income and consumer prices of food commodities with the fixed elasticities ($\beta_{ic,jc}^D$, $\beta Q_{ic,jc}^R$, βIM_{ic}^U , and βIM_{ic}^R , in Eq. 1 and Eq. 2, see Section 6.2.2.1), which may lead to unreasonable projection in both the short and long run.

For future projections the elasticities are kept the same as calibrated against the observation in CAPSiM. For a fully developed food market economy, it may be appropriate to use fixed elasticities in the long-term projection. However, for an economy where marketization is still under development, the elasticities will obviously not remain the same in the long run. Also, in the short term, the huge variation in price caused by a sudden shock does not alter consumers' dietary pattern, and the demand for food is relatively rigid compared with demands for other commodities, which may also lead to unreasonable simulations using fixed elasticities.

For example, with a sudden shock such as the economic crisis of 2007, a large variation of price may produce a simulated rapid reduction in food demand using the fixed elasticities. However, the actual response of food demand to the sudden rise in prices is very limited.

In the long-term projection, for developing countries like China, the elasticities in the middle 21st Century obviously would not be the same as for the 1990s. As per capita income of both urban and rural residents continues to increase, the Engel's coefficient (see definition in Appendix B.1) is likely to decrease more rapidly and food preference will also change. If using the current elasticities, a dramatic

alteration in food demand will occur: a very fast reduction in grain demand and a rapid rise in consumption of livestock products which even may unrealistically exceed the current nutrition standard of developed countries.

Against this background a modification was introduced to the CAPSiM by adjusting the elasticities dynamically to scale for the per capita consumption in a proper range for the both short and long term:

- To estimate the reasonable range of food consumption, a "nutrition standard" was constructed as the ideal food consumption in the future based on the income scenario and the food consumption pattern of China, which is described in Section 7.2.4.1.
- To adjust the elasticities in the demand side equation, a series of rules and thresholds of food consumption were built into the market clearing mode of the food economic model. At each step when a new simulation of consumption was obtained, it was compared to the nutrition standard. If the simulation of grain demand was much smaller than the standard, the income elasticities of grain demand (here it refers to rice, wheat and maize) was adjusted to keep the declining rate of the computed grain consumption not larger than the standard rate; if the simulated demand in livestock product was much larger than the nutrition standard, the elasticities were adjusted to a smaller value. The iteration of adjustment was repeated until the simulated consumption fell within the range of 10% less or more than the "nutrition standard".

7.2.4.1 Development of the nutrition standard

Food consumption is not only dependent on economic factors, e.g. per capita income and commodity prices, but is also controlled by the diet preference associated with

culture and geographic location. A cross-country study (Ikegami, 2005) suggested that the past trend in food consumption could be divided into three patterns: the western style of EU and NAFTA countries, the Japanese style of Japan and Korea, and the Chinese styles of Mainland China, Hong Kong and Taiwan. It was therefore reasonable to predict the future China food consumption from the current consumption patterns of the Chinese-inhabited regions but with higher GDP and income levels than China. There are three options to be considered, i.e. Taiwan, Hong Kong, and Macau. Following Ikegami's suggestion, in this thesis, the historical dietary pattern of income-food-consumption in Taiwan was used to estimate the future trend of food preference in China, because Taiwan's pattern is more similar to China than Hong Kong or Macau.

Firstly, this assumption was examined using the historical census of Taiwan and China, and then a nutrition standard of China in the future was developed.

The historical income and per capita food consumption of Taiwan (1952, 1965, 1975, 1985, and 1989–2009) were collected from the Taiwan Statistic Data Books and Husbandry census (from the online resource:

<http://www.cepd.gov.tw/encontent/m1.aspx?sNo=0001453> and

<http://www.coa.gov.tw/view.php?catid=207>). The historical data of China (1983–2007) was obtained from the Chinese Statistic Yearbooks. All the income data were converted to US dollars (USD) using the annual average exchange rate.

It was assumed that the per capita consumption of food commodities may vary with the disposable income following the Cobb-Douglas function,

$$QN_{ic,t}^D = \alpha \cdot Income_t^\beta \quad (\text{Eq. 7-1}),$$

where $QN_{ic,t}^D$ is the per capita consumption of the *ic-th* food commodity in the *t-th* year, and $Income_t$ is the per capita disposable income (in USD) in the *t-th* year, the parameter α is a scale to represent the effects of the factors besides income, and β is the income elasticity of food demand, which is the measurement of the percentage change in the demand of a food commodity responding to the change in income.

The proper parameters, α and β , of the consumption pattern of Chinese were estimated by the historical Chinese and Taiwanese data (the blue diamond and red asterisk, respectively, shown in Figure 7-9). The solid line is the regression of per capita income and food consumption in the form of Eq. 10, showing how much the consumption demand for a certain food commodity will change as the disposable income increases on average.

Figure 7-10 gives the per capita urban and rural income of Taiwan and China in the past and the future incomes of China under the best guess growth scenario. The growth of Chinese per capita income seems to follow the historical trend of Taiwan, but will not surpass the current income level of Taiwan for the study period of this research. Thus it is acceptable to use this scenario to project values of per capita food consumption in the future.

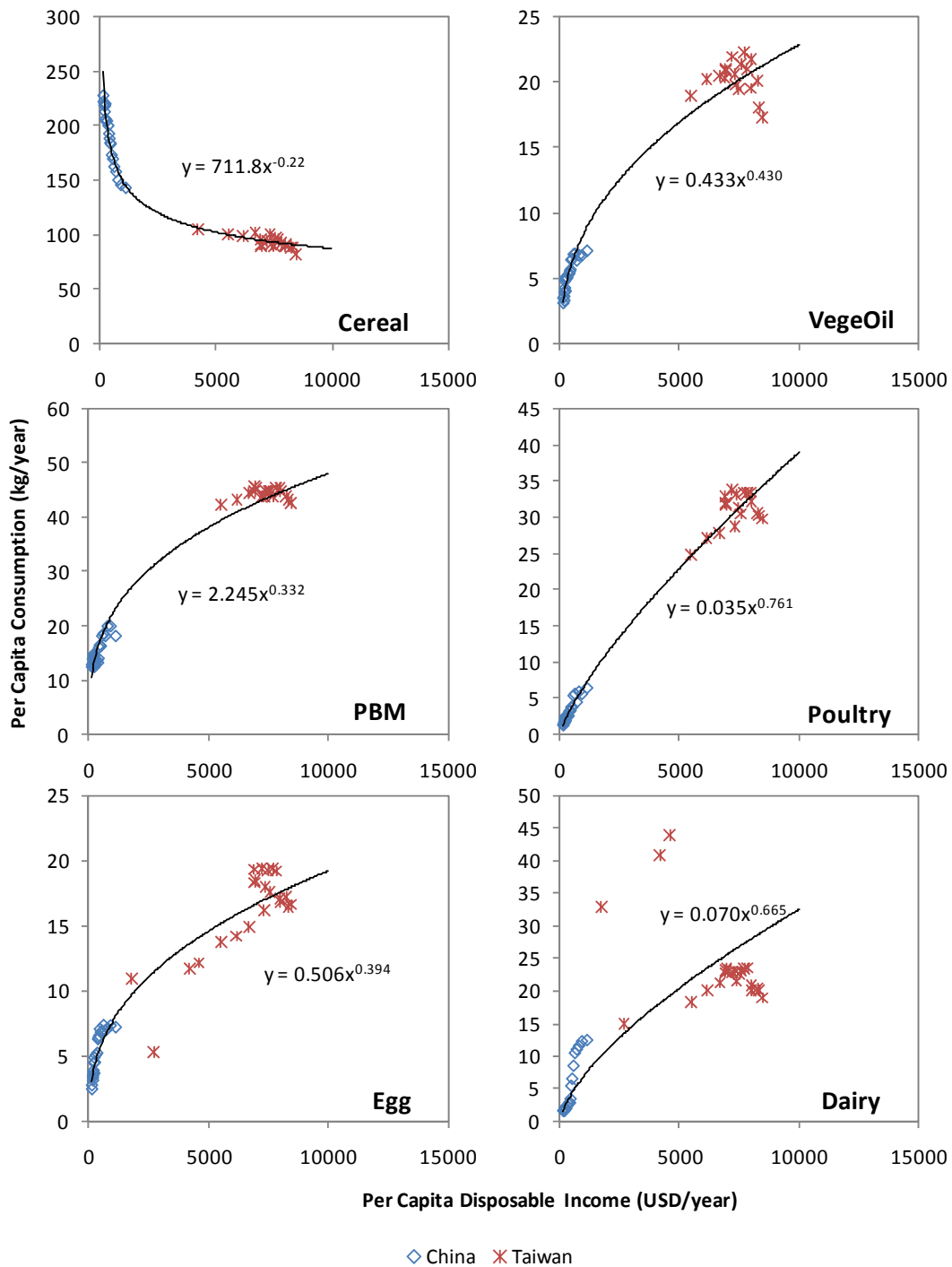


Figure 7-9 The historical relationship of per capita disposable income and food consumption of China and Taiwan. The historical data are from the Chinese statistics yearbooks (1983 to 2007) and from the online database of the Taiwan census (1952, 1965, 1975, 1985, and 1989–2009). The solid line shows the relationship of food consumption and income in the Chinese style of food consumption.

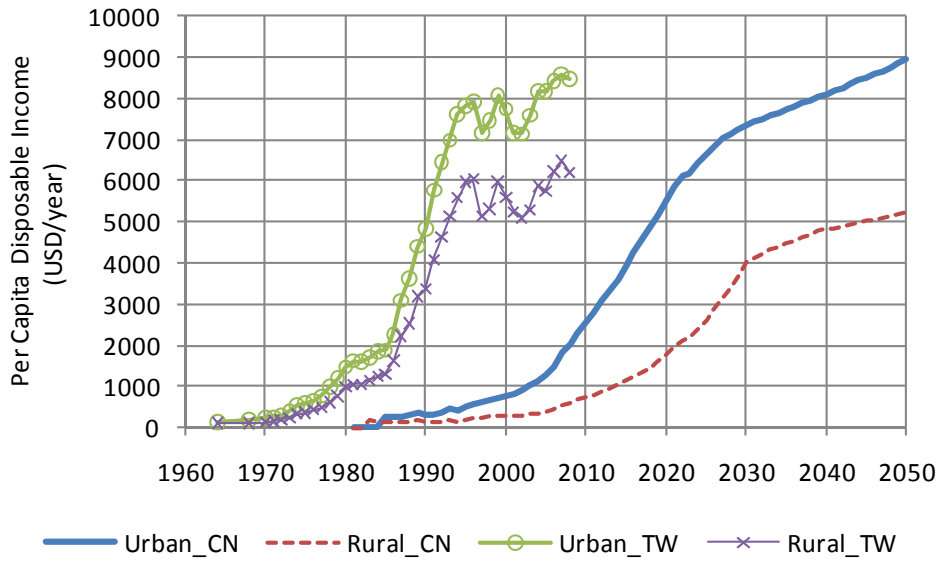


Figure 7-10 The per capita disposable income of China (CN) and Taiwan (TW) for both urban and rural regions. The Chinese data before 2007 are the historical statistics, and from 2008 to 2050 is the best guess projection of future income. The data of Taiwan are all the statistics.

Now, the ideal food consumption in the future then can be calculated by the given income scenarios in Eq. 11.

$$\frac{\Delta QN_{ic,t}^D}{QN_{ic,t}^D} = \beta \cdot \frac{\Delta Income_t}{Income_t} \quad (\text{Eq. 7-2}),$$

where $\frac{\Delta QN_{ic,t}^D}{QN_{ic,t}^D}$ is the percentage change in food consumption of the *ic-th* commodity in the *t-th* year, $\frac{\Delta Income_t}{Income_t}$, the percentage change in disposable income of the *ic-th* commodity in the *t-th* year, is obtained from the income scenarios. The income elasticity of food demand, β , has been already estimated by the historical data.

7.2.4.2 Scenarios of impact on maize yield

From results in Chapter 5, the physical reduction of maize yield due to climate change is summarized over the whole of China by 6 SRES emission scenarios (see

Table 7-2). Based on this table, a continuous time series of reduction of yield was produced on the assumption that the reduction of yield is linear between two time slices.

Table 7-2 Yield reduction of maize in China under different climate change scenarios. The reduction scenarios were obtained from the results in Chapter 5.

Scenario	% Reduction in yield		
	2020	2050	2070
Median	-2.98%	-9.23%	-14.32%
A1B	-2.64%	-9.89%	-15.35%
A1FI	-2.84%	-11.19%	-20.57%
A1T	-3.75%	-10.88%	-14.86%
A2	-2.58%	-8.4%	-15.1%
B1	-2.91%	-7.3%	-10.63%
B2	-3.49%	-8.7%	-12.49%

7.3 Future food security of China with and without climate change

Given the scenarios of income, population, and agricultural policy and the per capita food demand limitation, projections of supply and demand of 4 main staples (i.e. rice, wheat, maize, and tuber) were made using the model described in Chapter 6. In the projection, the food economic model ran in market clearing mode, in which the prices of food commodity were calculated by the model, and the supply and demand in the future were then computed based on these endogenous prices. The market clearance was applied to 4 main staples and 7 livestock products in this research.

To examine the response of the economic system to the bio-physical impact on maize caused by climate change, all the projections were investigated by running the economic model for two cases: 1) without the impacts of climate change; 2) with the impacts of climate change on maize added as one shock in the economic model.

Ideally, a comprehensive assessment of the food security under climate change requires taking the impacts of climate change on all main staples into consideration. However, given the enormity of the task this was not done for the current thesis. Instead, one representative staple was chosen to give an example of such an assessment. Maize was chosen for this study for two reasons: firstly, the fundamental studies on modelling the bio-physical growth of maize is extensive, affording the possibility of model simulation with a reliable precision level; secondly, the feed demand, most of which is produced from maize, will likely increase rapidly with the economic and population growth of China in the next decades, with maize production becoming the most important emerging issue threatening food security in China. The interpretation of results did not consider the climate change impact on other food commodities.

In this thesis, food security is assessed from three aspects:

- the balance of supply and demand, to assess the overall food availability with considered the impacts on a single crop, maize
- the change in price of staples, to assess one dimension of the food access
- the impact duration of a single-year disaster, to assess the resilience of food supply.

In addition, the impacts of climate change on a single crop might transfer to the supply/demand and price of other crops and such ripple effects were also analysed.

As mentioned in Chapter 1, the reasonable socio-economic projections for decision-makers are about twenty to fifty years. Thus the analysis was focused on the period

from current to the middle of this century. All the projections start from 2008 to 2050.

In order to reflect the uncertainties in projections, several groups of socio-economic scenarios were used to drive the model. The "Best guess" scenario was based on the best guess scenarios of income, population, the mid scenario of agricultural policy, the future input prices (i.e. fertilizer and labour prices) and the assumed import and export prices calculated by the method (see Section 6.3.1), and other settings, which were the same as those in simulations from 1983 to 2007 as discussed in Chapter 6. The remaining groups of scenarios were:

- " + P1high (or low)" means using " Best guess " settings except the high (or low) scenario of investment in agricultural research (P1);
- " + P2high (or low)" means using " Best guess " settings except the high (or low) scenario of growth of effective irrigation area (P2);
- " + IMhigh (or low)" means using " Best guess " settings except the high (or low) growth scenario of income;
- " + POPhigh (or low)" means using " Best guess " settings except the high (or low) growth scenario of population;
- " + Disaster2019 (/2029/2039/2049)" means using " Best guess " settings and adding a disaster on maize production in the year 2019 (/2029/2039/2049);
- " + Disaster2019onAll (/2029/2039/2049)" means using "Best guess" settings and adding a disaster on all 4 main staples' production in the year 2019 (/2029/2039/2049).

Similarly, the impacts under different climate change scenarios were labelled as:

- " + CC0", using the impact of climate change under the median scenario of six SRES;
- " + CCAB (AF/AT/A2/B1/B2)", using the impacts under the A1B (A1FI/A1T/A2 /B1/B2) emission scenario.

7.3.1 Food supply-demand balance

The supply-demand balance reflects the overall availability of a food commodity. The simulated balance results of 4 main staples (rice, wheat, maize, and tuber) and 7 livestock products (pork, beef, mutton, poultry, egg, dairy and aquatic) are discussed in this section.

7.3.1.1 Without climate change

Without considering climate change and using the best guess scenario, the total supply of 4 main staples can satisfy the total demand in general (Figure 7-11). The overall food availability of China in the next few decades is moderately optimistic. The production of rice, wheat, and tubers can fulfil the demand in most years of the projection period. The supply and demand of maize will be in a so-called "tight" balance with the self-sufficiency ratio remaining between 95% and 100% in the long term.

Results indicate that rice and wheat demand is going to decrease in future, but the demand for maize and tubers will rise. The demand for rice, wheat, and maize as food will decrease, while the consumption of livestock products as food will grow steadily (Figure 7-13). Tuber consumption as food remains at the same level as before 2007. The demand for all grains as feed increases, especially the demand for maize will increase very quickly with an astonishing absolute quantity. The demands for seed, industry, and waste, only play a very small part, and the international trade volume (including export and import) is small. Only maize requires importing thousands of tonnes, on average about 1% of the total supply.

Increasing feed demand for grains throughout the projection period is caused by the growth of livestock consumption. In Figure 7-13, it is obvious that the production and consumption of all livestock products have steady growth before 2050 along with income growth and changing diet. The peak of meat demand occurs later than the total population summit around 2032. Besides pork and poultry, which are traditionally the main protein resource, demand for the rest of the meat products has even kept rising in years close to 2050. This is because income growth and urbanization play the primary role in dietary transfer. That means, without climate change, food availability in China in the next decades would mostly be decided by the demand side factors, e.g. income and urbanization.

7.3.1.2 With climate change

In the cases where impacts of climate change are considered, the supply-demand balance is disrupted for maize. Figure 7-12 gives the projections of supply and demand for the main staples with addition of impacts on maize in the economic model. There is no significant change for the balance of rice, wheat and tubers from the ripple effects of climate change impact on maize. This indicates that little impact on maize has transferred to the other staples with respect to the supply-demand balance. The production of maize shows steady drawdown for the reduction of yield due to climate change. The gap between total supply and demand grows even larger quickly after 2030s. The self-satisfy ratio of maize is reduced from 99% in 2008 to about 92% in 2050.

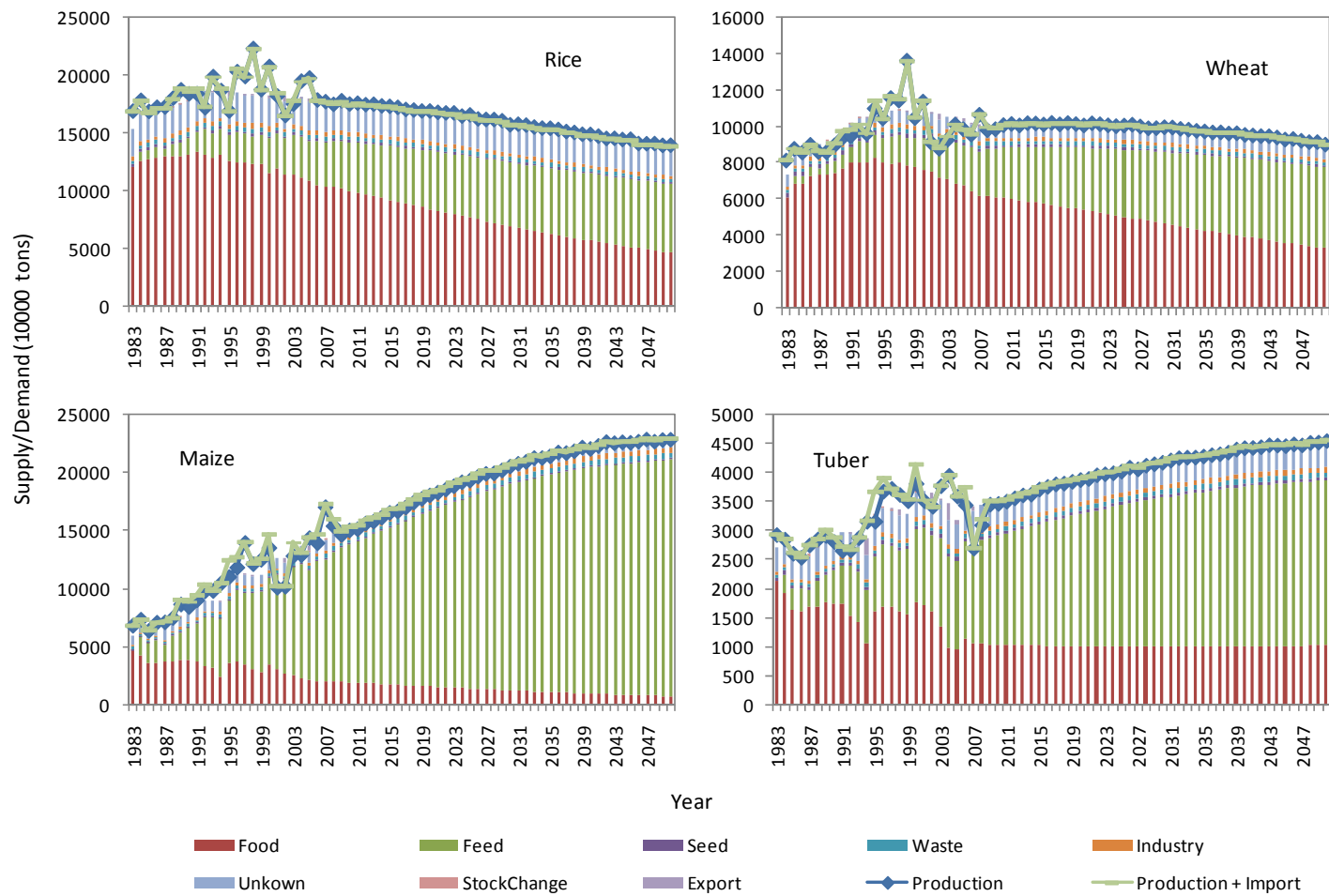


Figure 7-11 Simulated supply-demand balance of 4 main staples under the "Best guess" scenario. Simulation is from 1984 to 2007, and the projection is from 2008 to 2050. Unit ton is the metric tonne (1000 kg).

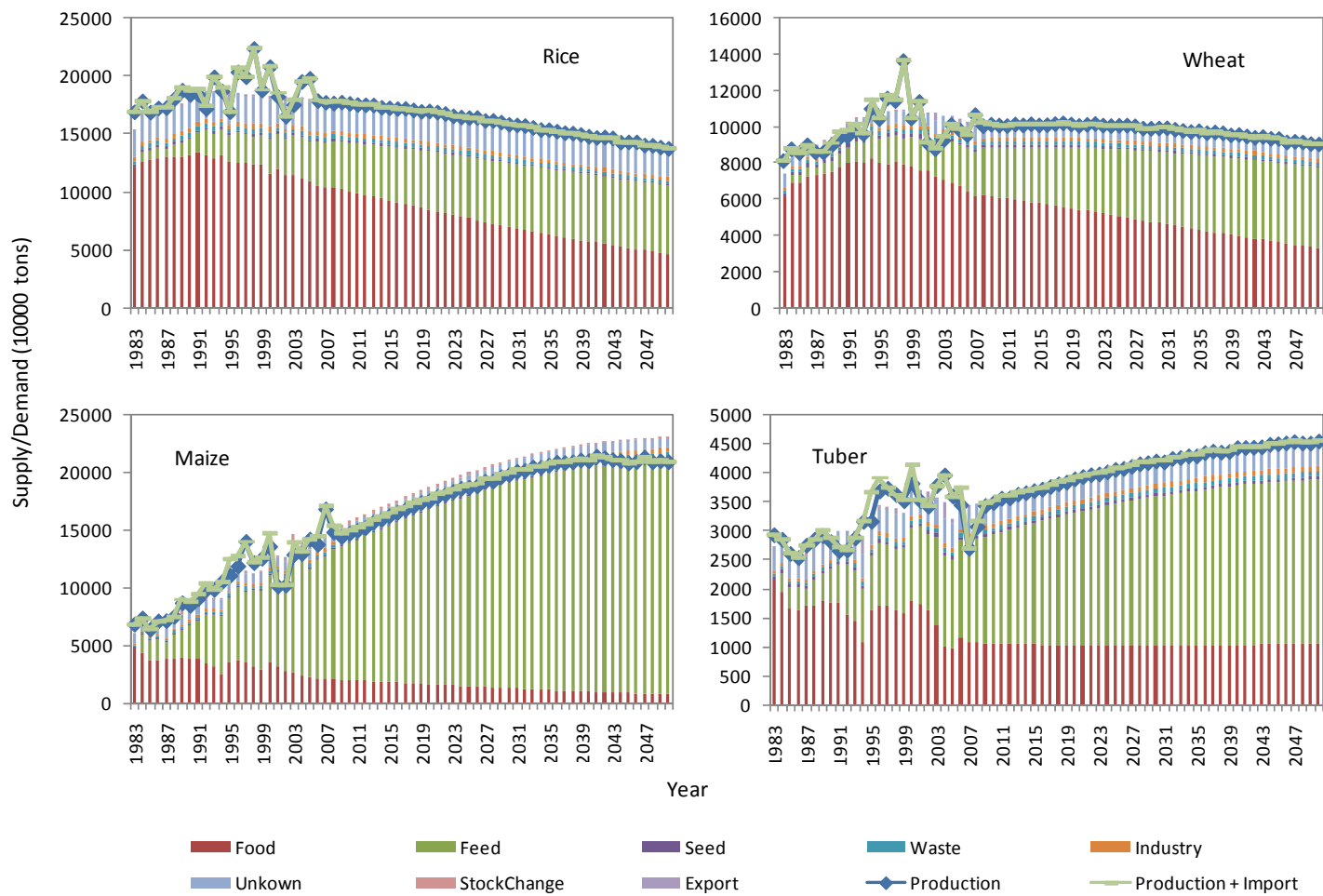


Figure 7-12 Simulated supply-demand balance of 4 main staples under the "Best guess" scenario and the median scenario of climate change. Simulation is from 1984 to 2007, and the projection is from 2008 to 2050. Unit ton is the metric tonne (1000 kg).

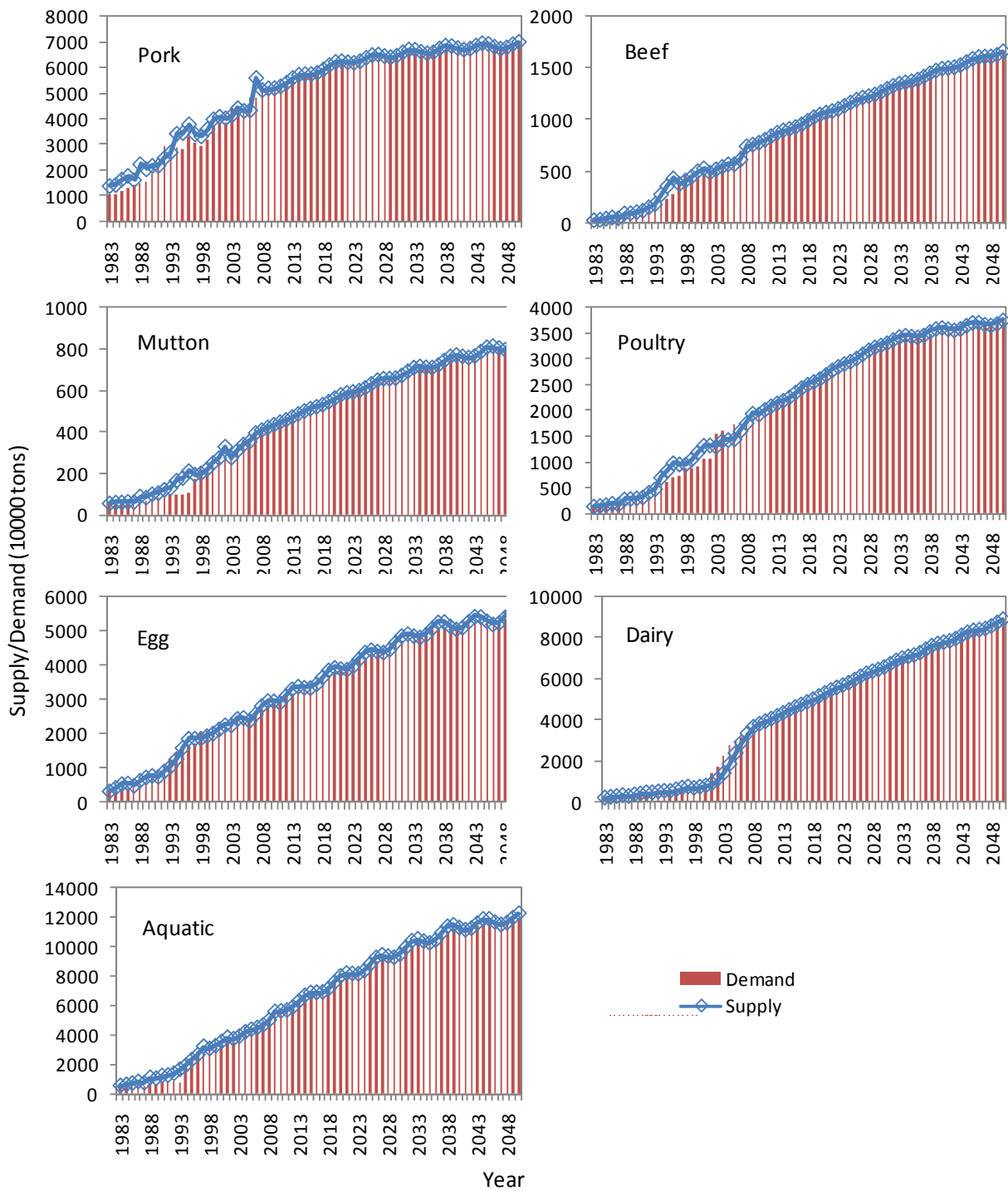


Figure 7-13 Projections of supply-demand balance of livestock products under the Best guess scenario.

Simulation is from 1983 to 2007, and the projection is from 2008 to 2050. Unit ton is the metric tonne (1000 kg).

Table 7-3 Projections of supply and demand (Mt) for the main food commodities.

		2000	2020	2050	
		(census)	(without CC)	(without CC)	
Rice	Production	188	169	139	
	Food	122	85	47	
	Feed	30	50	59	
	Other demand	9.4	8.4	6.7	
	Net import	-2.7			
Wheat	Production	99.6	101	90	
	Food	77	54	33	
	Feed	18.7	34	45	
	Other demand	5.8	5.4	4.6	
	Net import	0.7			
Maize	Production	106	180	228	
	Food	32	17	8.2	
	Feed	79.4	151	203	
	Other demand	5.2	8.3	9.9	
	Net import	-10.4	2.7	0.6	
Self-sufficiency ratio (%)	2000s (census)	2020s (projected)		2040s (projected)	
		Without CC	With CC	Without CC	With CC
Rice	99%	100%	100%	100%	100%
Wheat	94%	99%	99%	100%	100%
Maize	104%	98%	95%	98%	90%

It is interesting to note that in economic systems, the reduction in production of maize due to climate change after price adjustment is a little smaller than the simulation from the bio-physical model. The projected reduction from the economic model is about 1.65% and 8.84% for 2008 and 2050, respectively, in contrast to the bio-physical model which gave 3.39% in 2008 and 9.23% in 2050.

Within the economic system the reduction due to climate change simulated by the bio-physical process is traded-off slightly through the internal price adjustment in the market clearance process. When production is likely to decline to less than the total demand, the price will be adjusted to rise, reacting to stimulate production (e.g. increase the sown area) and suppress consumption. The increase in maize price leads to an increase in sown area of maize and the small decline in both food and feed demand. The demand will be relatively rigid in the future, and the influences of the rising price are mainly reflected in changes in sown area (see Figure 7-14).

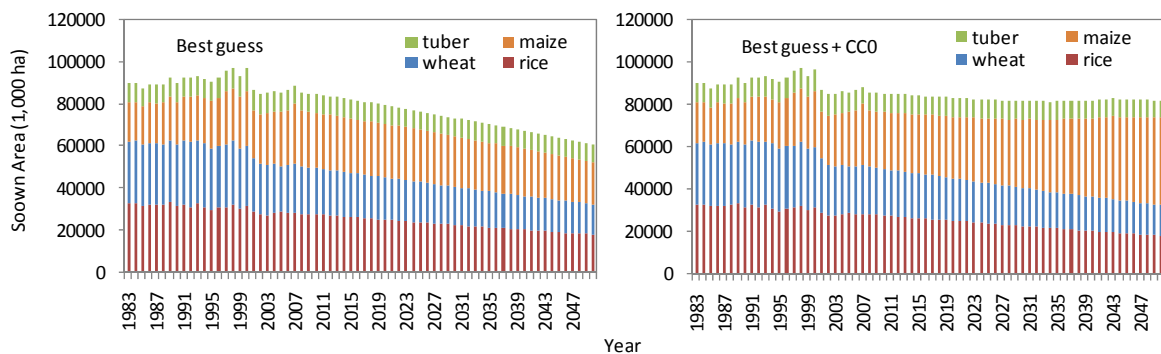


Figure 7-14 Changes in sown area of 4 main staples with and without climate change. Simulation is from 1983 to 2007, and projection is from 2008 to 2050.

This section only discusses the demand and supply balance by adding the impacts of climate change on a single crop in the system as an indicator of climate change impact on the overall food availability. It was found that the impact of climate change on a single crop just affected its own availability and that impact effect is reduced by market. But could the impacts transfer to other crops in other ways? Will climate change impact on food access? To answer these questions, the changes in price with and without climate change are examined in the next section.

7.3.2 Change in price

In this section, changes in price of the main staples with and without climate change impacts are discussed.

The price used is the equilibrium price calculated by the economic model in its market clearing mode. Theoretically, the equilibrium price is found by the model when the supply of a commodity equals its demand (this status is called equilibrium). Practically, when the error between supply and demand is less than 99% of demand, the equilibrium (also known as the quasi equilibrium) is reached.

The model process that looks for the equilibrium price is described in Chapter 6. However, there are some issues in the searching process. Firstly, a reasonable searching range of price was introduced to overcome unreasonable extremely high or low prices; secondly, the searching for optimal solutions is stopped, if the so-called quasi-equilibrium cannot be reached using the prices within the searching range, in which case, the prices are taken as the equilibrium solution if the difference between the simulated supply and demand no longer decreases.

It may be noted that the total supply of maize does not satisfy the demand due to climate change impact (Figure 7-12). Theoretically, supply and demand should be in

balance if no constraints are imposed on the economic model. However, in the model, there are some limitations: 1) the adjustment in price is limited to certain ranges in the historical census as mentioned in the paragraph above; 2) the future demand is highly dependent on income level (controlled by the large income elasticity and the nutrition standards described in Section 7.2.4). It also does not react very sensitively to price (controlled by the small price elasticities), and these elasticities are also based on their historical value. A thorough examination was made to investigate which limitation was the primary source leading to the balance gap. To test the first limitation, the searching range of prices in the model was enlarged, without changing the model performance. To test the second limitation, the nutrition standards in the model were disabled. The gap disappeared but the projections of grain demand soared to an unreasonably high level. Thus the nutrition standards projection was the main reason the model did not balance in realistic socio-economic settings. In reality, improvement of nutrition would be slowed down as the food price increases become too high. In modelling, it means there must be a process added to adjust the nutrition standards by altering both income and price elasticities properly. However, it is currently difficult to model this process, because no existing research has been conducted on altering those elasticities in other developing countries. In addition, the alteration could not be accomplished by using the Chinese historical data. On one hand, one would argue that the economic consequence of climate change impact on maize is so severe that it could make the model deficient for periods close to the middle of the century. On the other hand, it implies that climate change will likely have significant impact on future food utilization in China, which may lead to a significant alteration of nutrition standards.

Nevertheless, the economic model was designed from the current China economic system and ran with the most reasonable economic settings that could be projected so far. Its results, to a large degree, indicate the direction of climate change impact on China's food security in the future, as discussed below (Figure 7-15).

The price index is a measure of relative change in price from the base year. In this case, the previous year is set as the base year. Thus, if the price index in year t equals 100, it means the price in year t does not change compared to the previous year ($t-1$); if the price index is larger than 100, the absolute price rises, and *vice versa*.

On average, the price indexes of rice and wheat are smaller than 100, decreasing slowly for both crops with and without climate change, but then they start to increase slightly in the last few years before 2050, influenced by the ripple effects. In contrast, for maize the price index is likely to increase under climate change, soaring unprecedentedly after 2040 to a value of 116 in the year 2050, whereas the price will keep falling towards a value of 94 in 2050 in the same period when climate change is not taken into account. The tuber price index was less than 100 and decreasing similarly to rice and wheat under the scenario without climate change. However, it keeps on a stable level close to 100.

Thus if climate change is not considered in the projections, the absolute price of 4 staples will fall at an accelerating rate. In scenarios with climate change, the absolute price of rice and wheat decreases with a slightly slow rate until 2045, and then the decreasing trend remains at the low level. The absolute price of maize will keep rising, and soar after 2040. The tuber price will likely stay at a stable level even with climate change

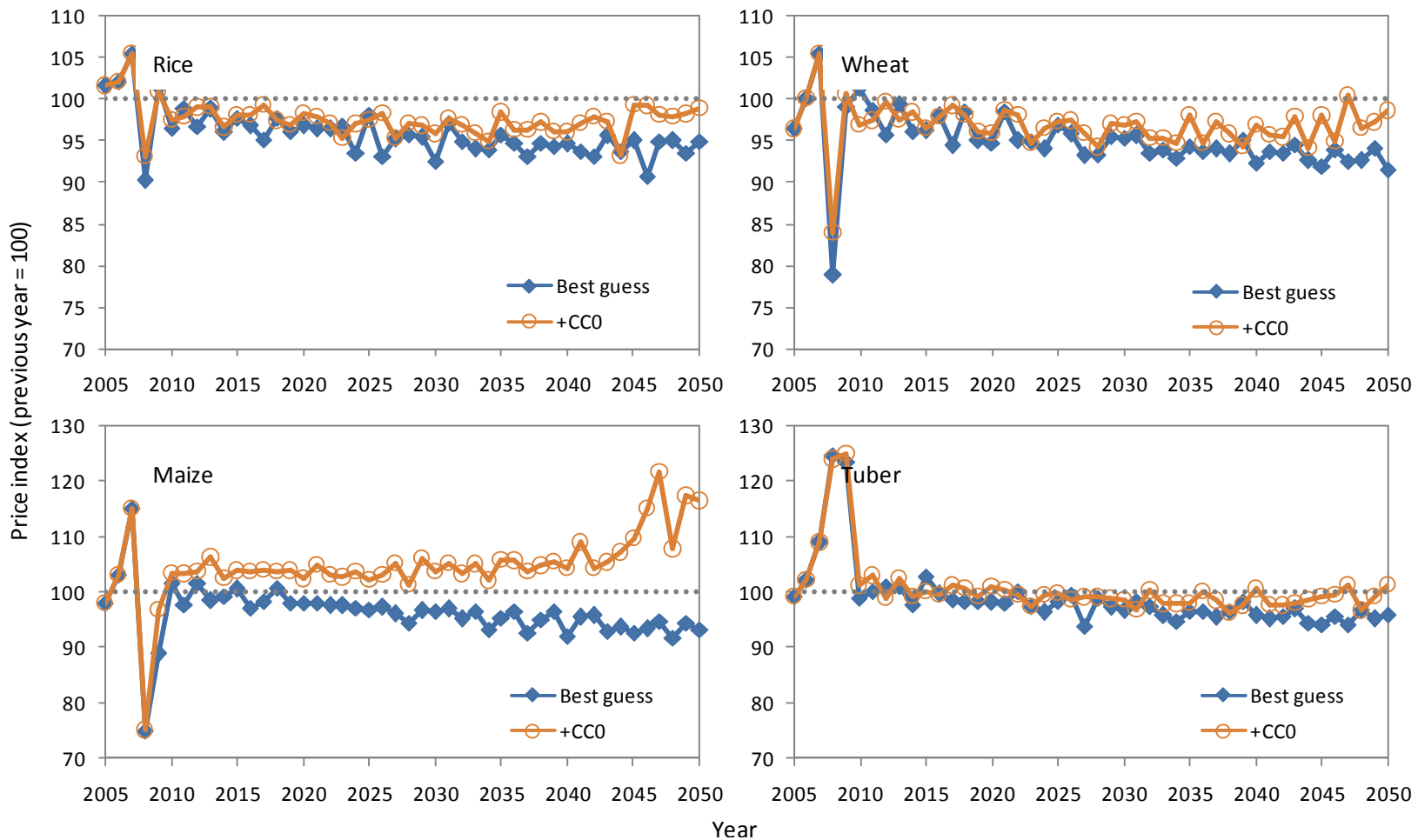


Figure 7-15 Projections of the price index for 4 main staples to the year 2050 (time series).

The price index in year 2005, 2006, and 2007 is the value in the NBS census, and the remainder of the series is the projected equilibrium price index. The value larger than 100 means that the price increases, and less than 100 means the price declines compared to the previous year.

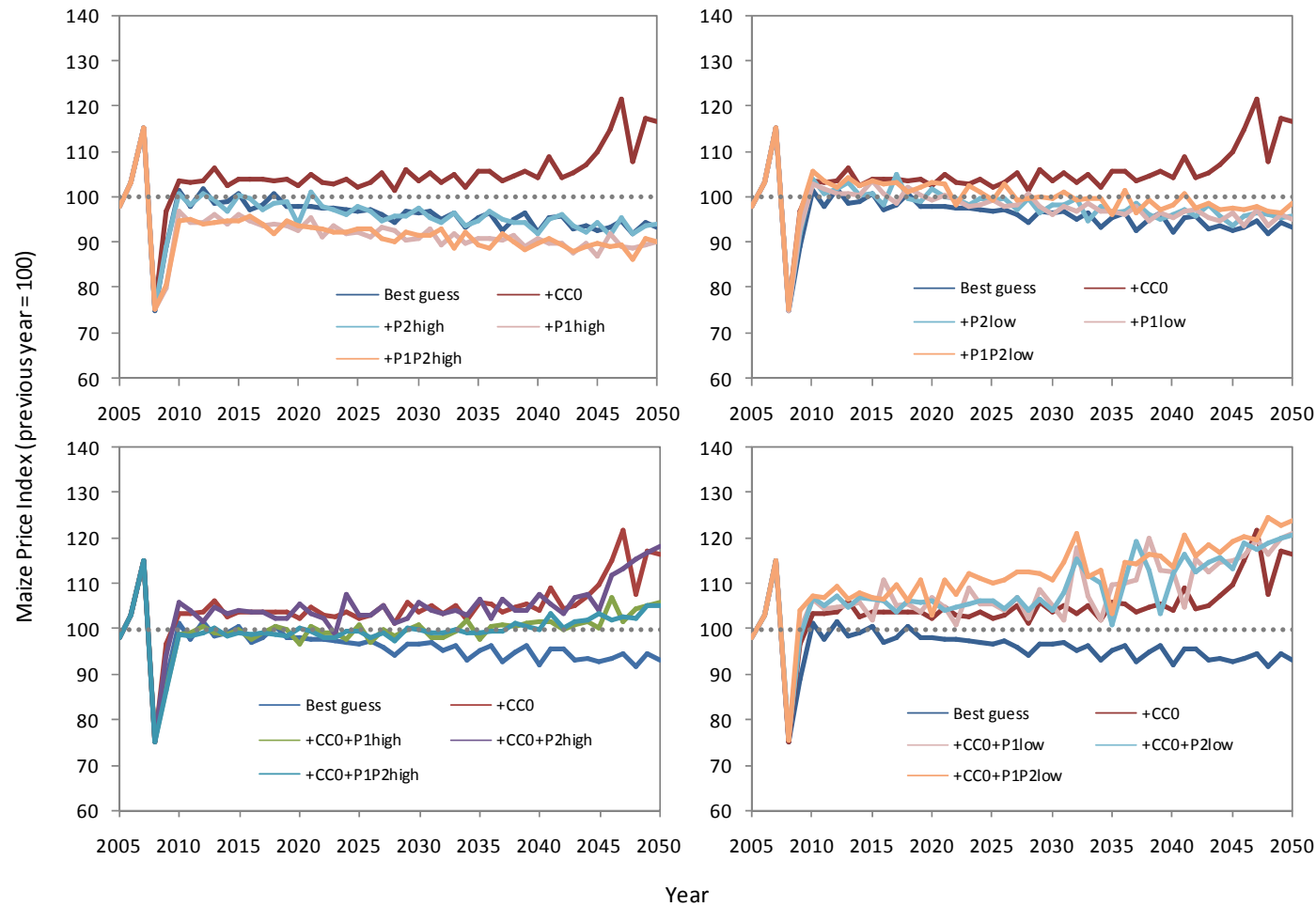


Figure 7-16 Projections of the price index for maize to the year 2050 under different scenarios. The price index in year 2005, 2006, and 2007 is the value in the NBS census, and the remainder of the series is the projected equilibrium price index. The dotted line is the index value of 100, which means no change in price.

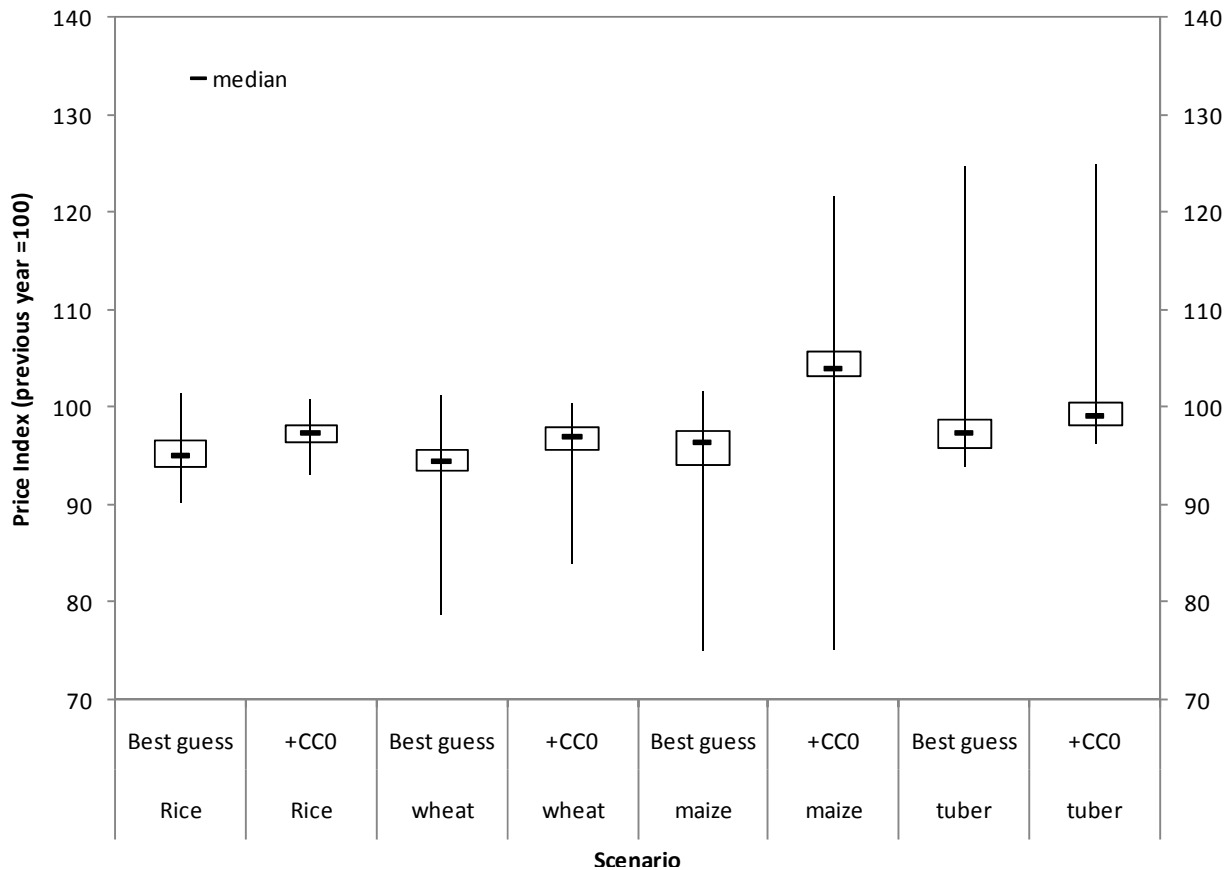


Figure 7-17 Projections of the price index of 4 main staples from 2008 to 2050 (box plot). The top and bottom of the box is the 75% and 25% percentiles, respectively. The dashed line through the box gives the maximum and minimum values.

The variance of the price index for wheat and maize after 2045 becomes much larger in scenarios with climate change compared to that without climate change. The instability of price change may bring consumers more financial risks apart from the rise in prices.

From the box plot (Figure 7-17), the median values with climate change are marginally larger than those under best guess scenario and the whole population of prices moves to a larger level. It is suggested that the level of the declining trend in price will be reduced with climate change. In other words, although the prices are still decreasing under climate

change, rice and wheat are at a higher price level than that under the Best guess scenario without climate change.

In contrast to the food availability, it appears that it will be a challenge to maintain the food access as usual for all the main staples by adding climate change impact on price. The challenge is reflected in two respects: one is that food prices, in general, are likely to be at a higher level for all projections with climate change than without climate change, and secondly, the larger fluctuations in price time series may burden consumers with financial problems.

7.3.3 Impact of disaster

Resilience is an important dimension of food security. The concept of "resilience" is originally introduced by the ecologist Buzz Holling (1973). It is defined by the capability of a natural system return to balance status from damage. In ecology, the resilience is related to but different from the concept of "stability" and "the ability to maintain a steady state" (Adger, 2000). It describes the system function being able to absorb the turbulence before system status change (Holling et al., 1995) or the recovery rate of a system from turbulence. Besides resilience, the stability of a system also includes the resistance process (Peterson et al., 1998).

In this thesis, it is measured by the duration the food system takes to return to a balanced status after suffering a sudden shock (for example, a drought or flood disaster damaging grain production). In this section, three questions are addressed in order to probe this situation further:

1. In the Chinese food system, how much and how long would a sudden shock on the supply-side affect food availability and food prices?

2. Considering climate change, how would the duration of the impact of disaster change?
3. In the extreme case where all main staples are damaged by disasters, what would the main impacts be?

7.3.3.1 Disasters in history

Firstly, it was assumed that disasters in future would have the same scale as those in the past. All disaster information was sourced from the historical census of the Chinese grain production. Disaster was measured by the variability of grain production. In this section, only rice, wheat and maize were considered because the production of tubers does not vary much historically.

The variability was calculated by the ratio of census data of production to trend of production, i.e. $(census - trend) / trend$. The trend of production was produced by the linear moving average method suggested by Xue et al. (2003). The census data from 1949 to 2005 was derived from NBS yearbooks. The production trend of three staples historically is given in Figure 7-18 and the variability is summarized in Table 7-3. Historically, the largest disasters caused 8.9%, 10% and 11.7% reduction in the production of rice, wheat, and maize, respectively.

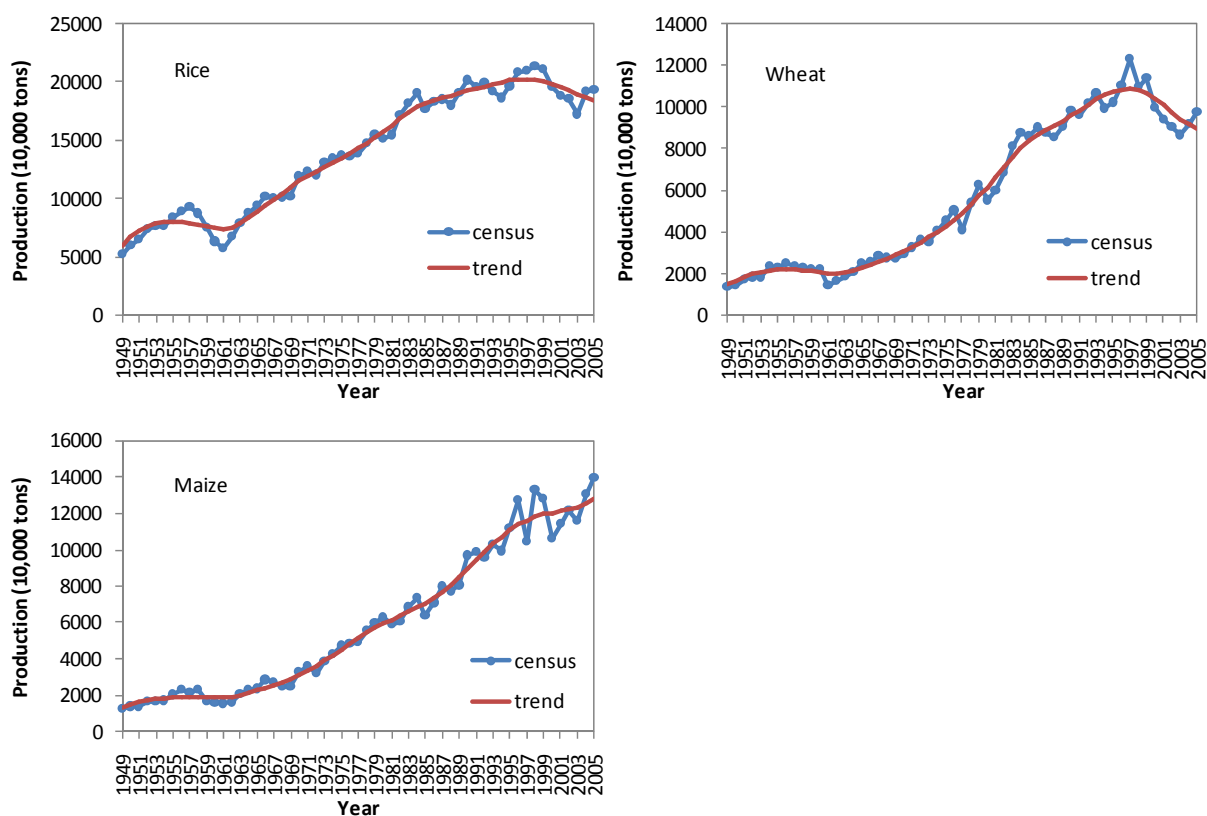


Figure 7-18 The historical census of production of 3 main staples from 1949 to 2007. The trend was calculated by the linear moving average method given by Xue et al. (2003). Unit ton is the metric tonne (1000kg).

Table 7-4 Historical variability of production of 3 main staples from 1949 to 2005.

	Variability (% of production)
Rice	-8.9 ~ 6.8
Wheat	-10 ~ 13.4
Maize	-11.7 ~ 12.3

7.3.3.2 Impacts of disaster on food security

The impact durations were then tested when adding a one-year disaster only to maize and adding a one-year disaster to all three staples (i.e. rice, wheat and maize). The projections

were carried out under the scenarios with and without climate change. To capture the temporary differences as climate change develops, disaster was considered in respective years: 2019, 2029, 2039 and 2049.

Disaster only applied to maize

From the supply-demand charts (Figure 7-19), disasters on maize do not result in any significant negative effects on rice, wheat, and maize, but only lead to a large loss of maize supply in that year. The unbalanced status of maize only occurs in the disaster year without climate change, but is likely to last at least for one year after the disaster when considering impacts of climate change. If a disaster happens in 2039, the unbalanced status (with the self-sufficiency ratio less than 95%) would likely last for three years. Thus a sudden shock on a specific staple has very limited impacts on food availability, and the supply-demand balance could be recovered very quickly in one or two years in general. However, as impacts of climate change become more intensive towards the middle of this century, the resilience of Chinese food systems to recover from a disaster will be weakened.

With regard to price, the disaster signal appears on the price index of all staples as shown in Figures 7-21, 7-22, 7-23, and 7-24. Firstly, the variance of price index becomes slightly larger after the disaster year, but the disaster does not alter its trend for any of the staples. This means that the impact duration of disaster lasts longer on price variability but does not change the basic trend of price. Secondly, when climate change is considered, a disaster may not only lead to an increased trend in price index of maize, but also result in intensive variation of that index in the following decades. Thirdly, when disaster occurs with climate change, the longer its impacts will last and the larger will be the fluctuations of price index. If disaster were added in year 2039, the variation in maize price index would last for about five years on a high level (i.e. the annual growth of price index from 2039 to 2043 would remain at the value of 120 in Figure 7-23), meaning that the real price would keep increasing with an accelerating rate for years after 2039.

Disaster applied to three staples

This section examines the enhancement of the disaster scale by adding the largest disasters in history of the three staples at one time.

For rice and wheat, the basic trend of price will likely decline in the future, but would shift to rise for years by the reinforced disaster shock. For example, in the case for 2039, the price index of rice keeps above the 100 level for 4 years with climate change. A similar phenomenon happens to tubers. With regard to maize, the price increase responding to disaster damage from climate change becomes worse. Its price index in impact duration of disaster has a significantly high value, twice that even when climate change is considered.

In conclusion, a sudden shock on food supply will affect both food availability and access. The impact on food availability is milder and shorter than on food access, and it will transfer among all the staples in the market by price mechanisms. The duration of that impact on food access could last for a number of years. The impact will likely deteriorate due to climate change and last even longer. Even for those staples that have an optimistic prospect for food security, the price may keep rising for long periods.

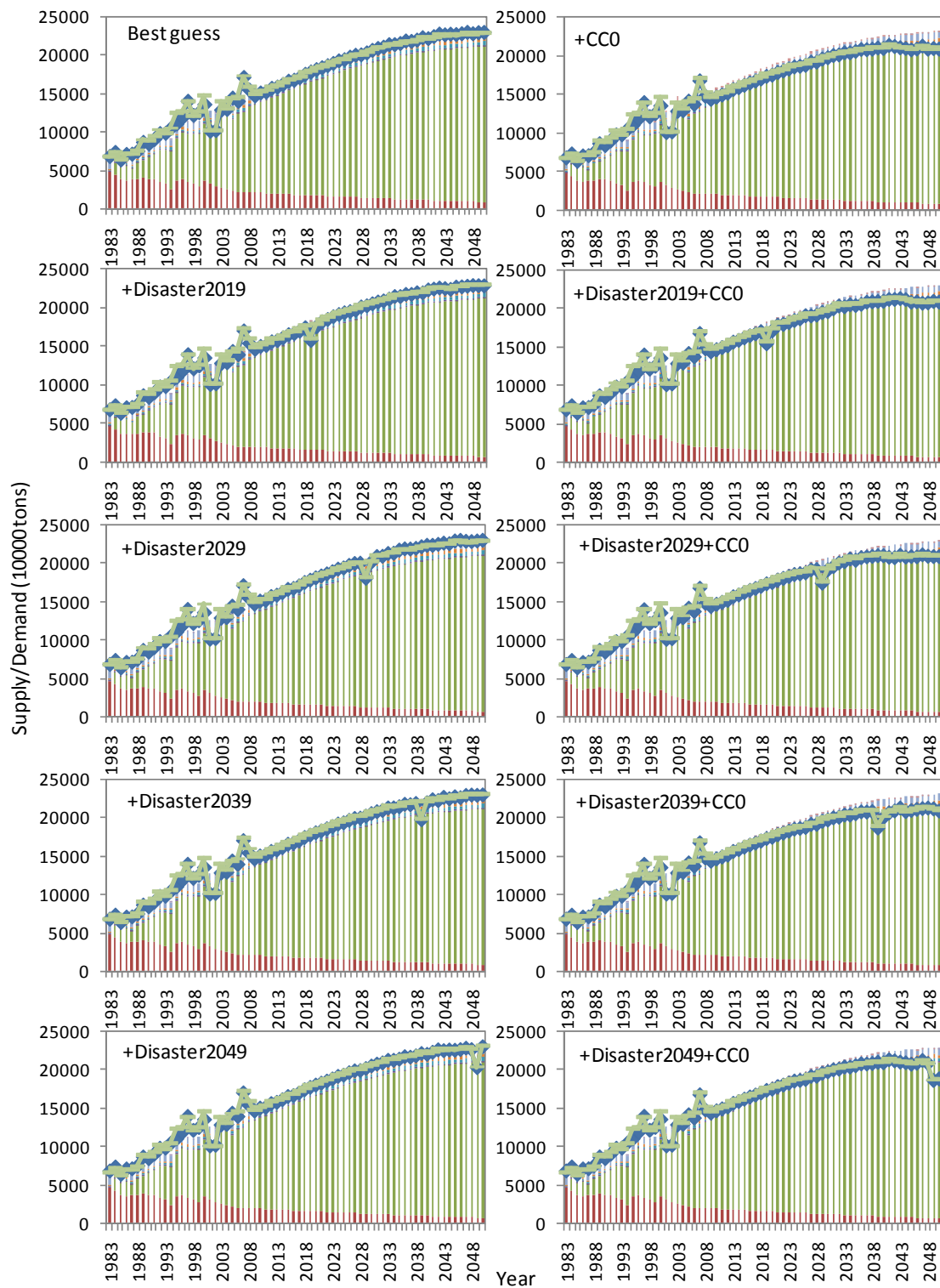


Figure 7-19 Projected supply-demand balance of maize with disaster on maize in the years 2019, 2029, 2039, and 2049. Simulation is from 1984 to 2007, and the projection is from 2008 to 2050. Unit ton is the metric tonne (1000kg).

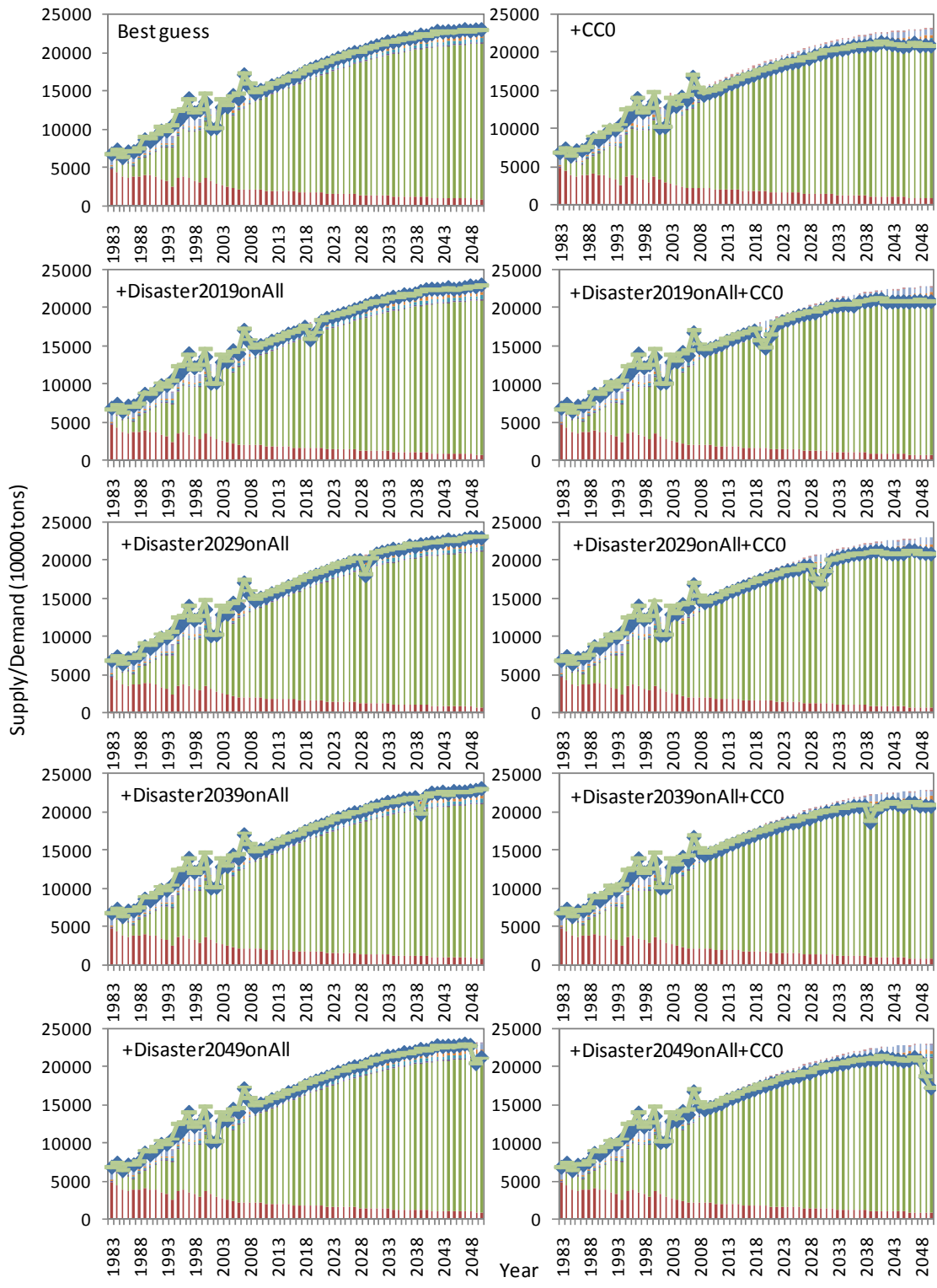


Figure 7-20 Projected supply-demand balance of maize with disaster on all 4 main staples in the years 2019, 2029, 2039, and 2049. Simulation is from 1984 to 2007, and the projection is from 2008 to 2050. Unit ton is the metric tonne (1000kg).

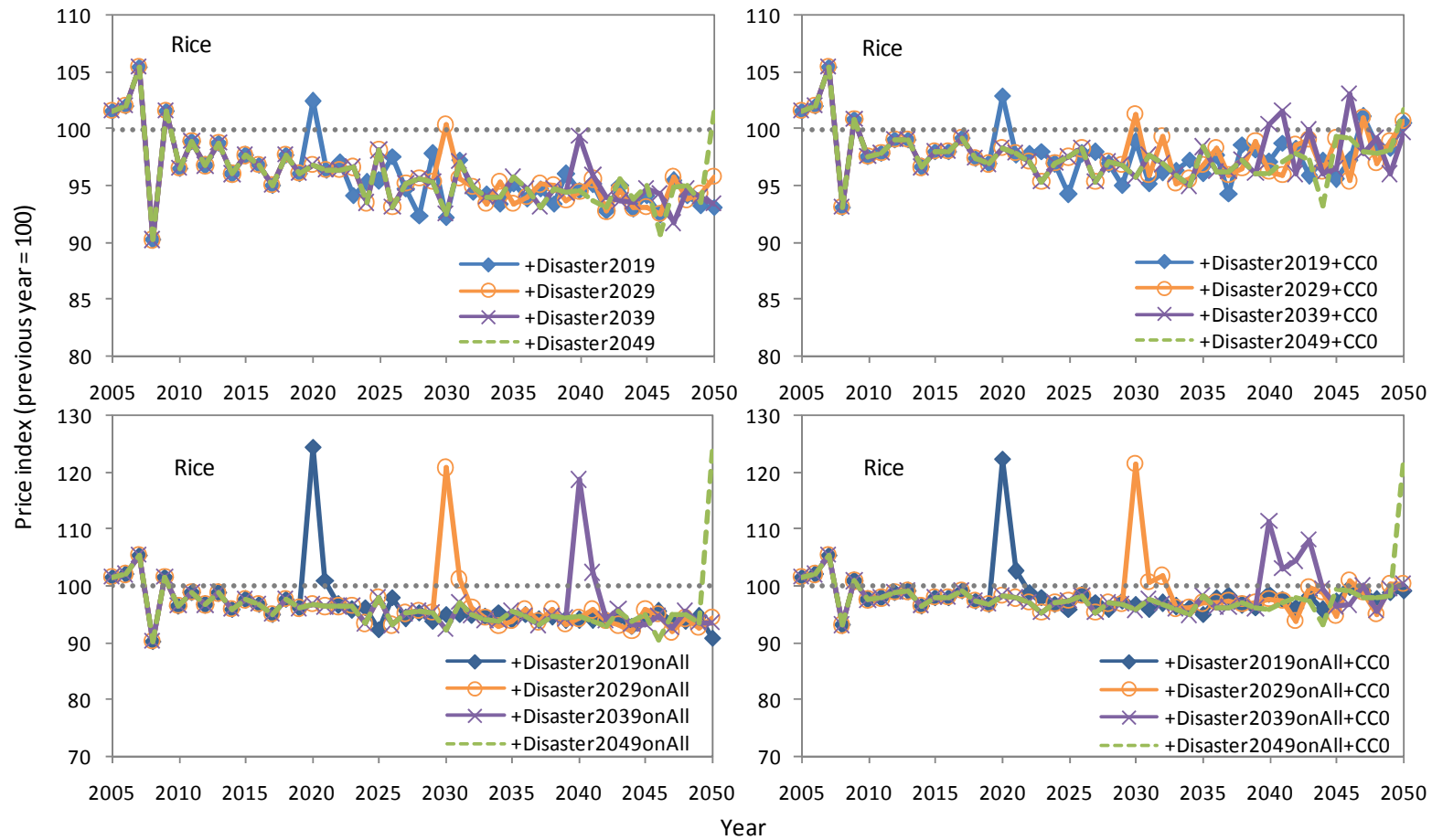


Figure 7-21 Projections of the indexed rice price with disaster in the years 2019, 2029, 2039, and 2049. The projections are from 2008 to 2050, and price indexes in 2005, 2006, and 2007 are from the NBS census.

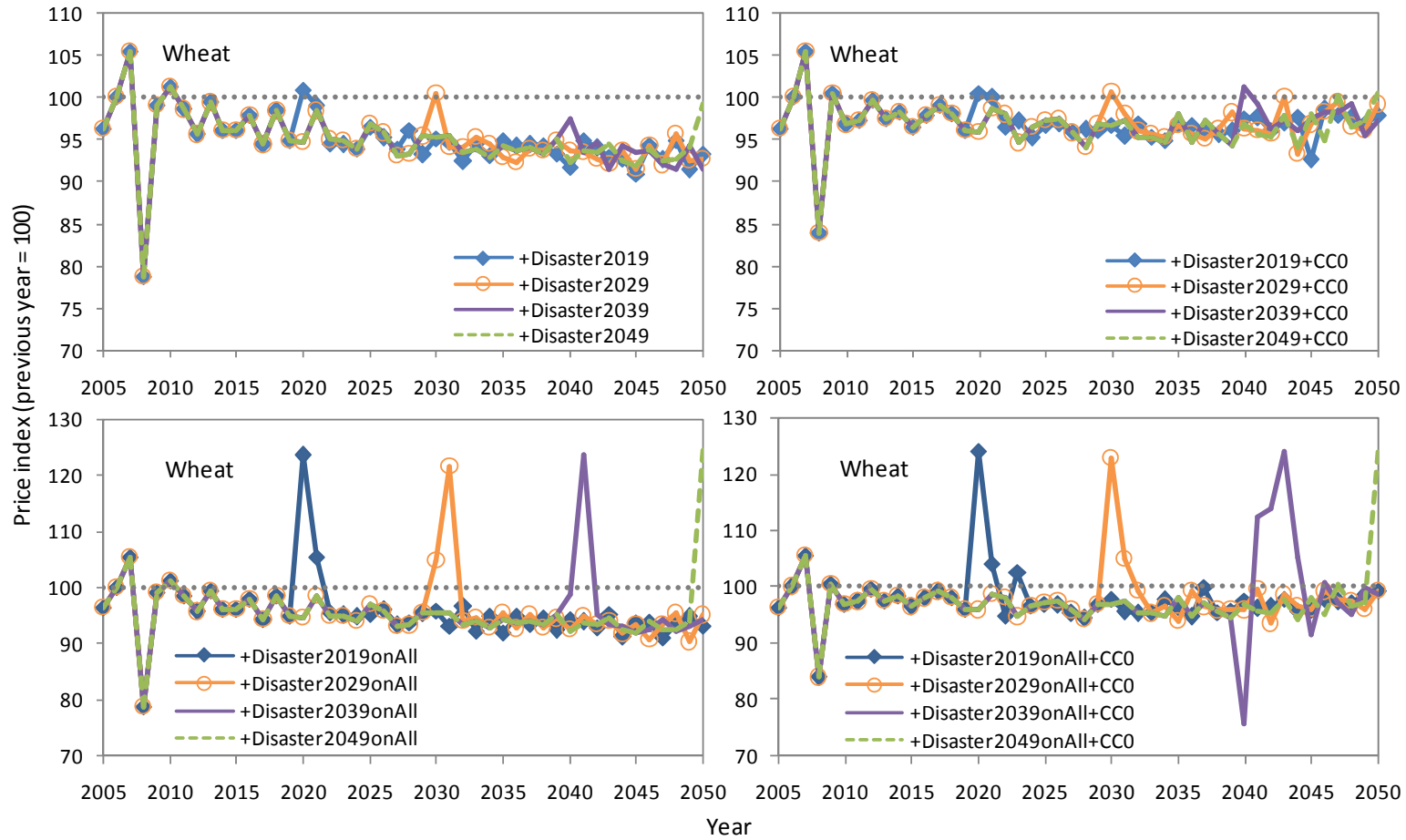


Figure 7-22 Projections of the indexed wheat price with disaster in the years 2019, 2029, 2039, and 2049. The projections are from 2008 to 2050, and price indexes in 2005, 2006, and 2007 are from the NBS census.

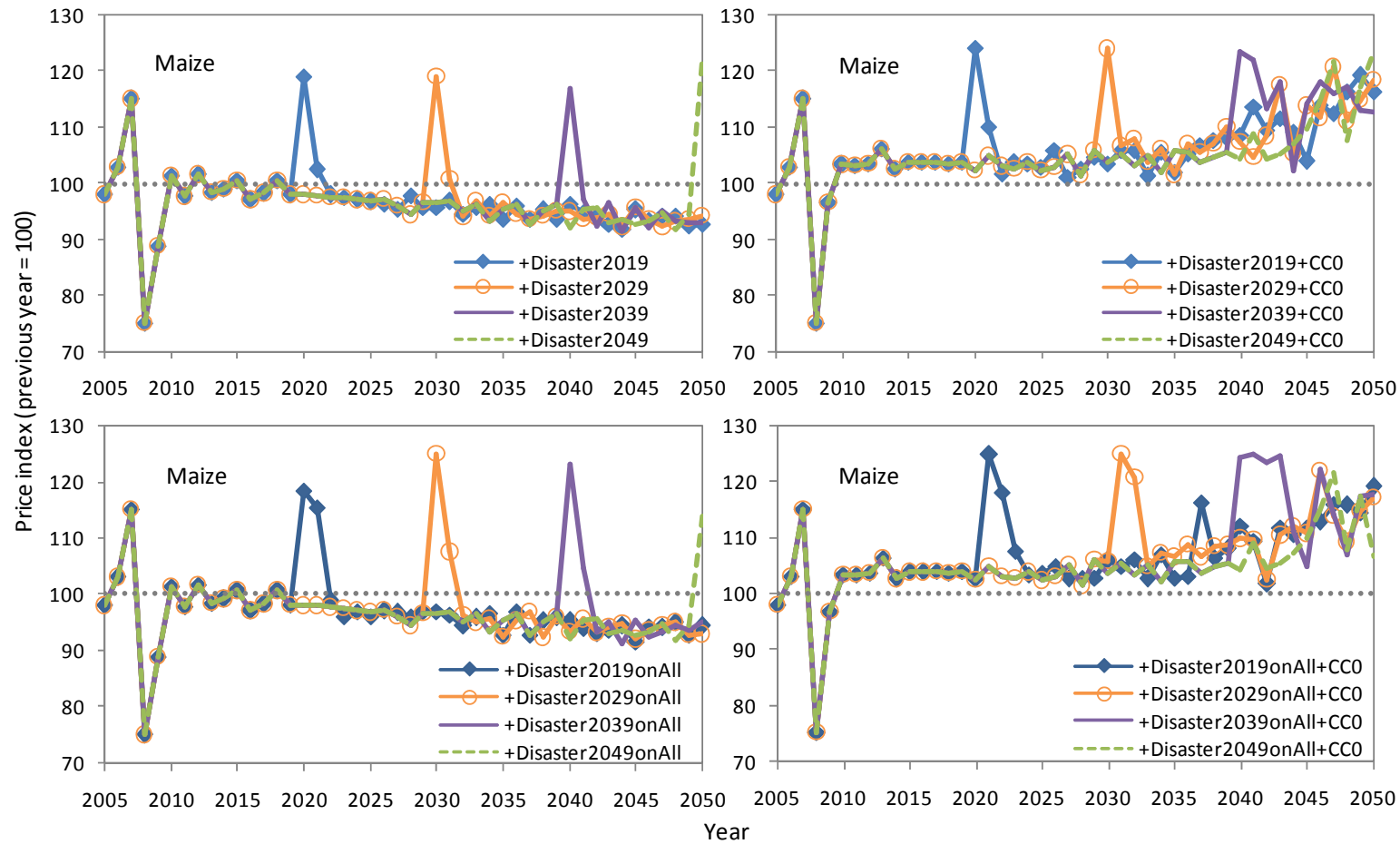


Figure 7-23 Projections of the indexed maize price with disaster in the years 2019, 2029, 2039, and 2049. The projections are from 2008 to 2050, and price indexes in 2005, 2006, and 2007 are from the NBS census.

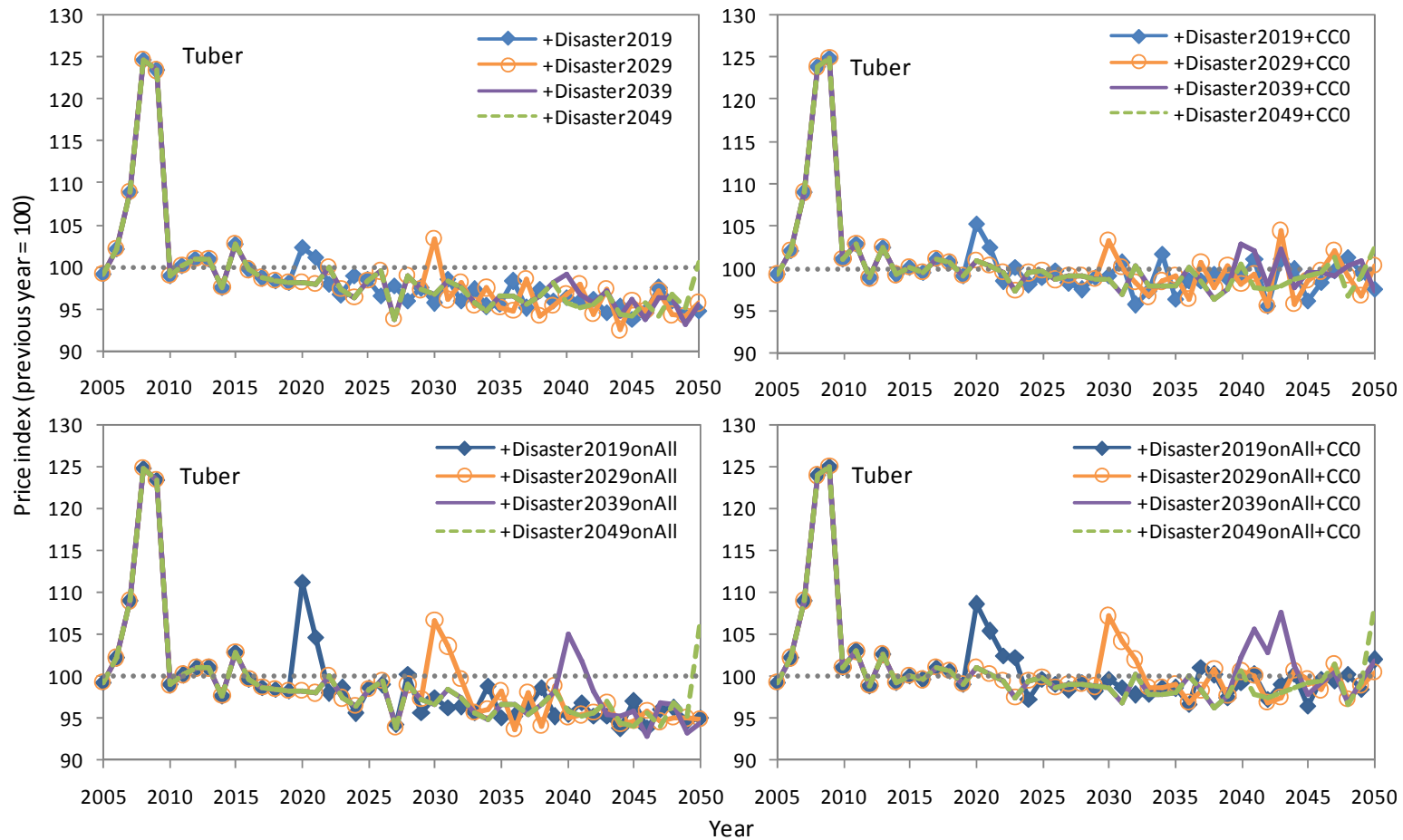


Figure 7-24 Projections of the indexed tuber price with disaster in the years 2019, 2029, 2039, and 2049. The projections are from 2008 to 2050, and price indexes in 2005, 2006, and 2007 are from the NBS census.

7.4 Adaptation options at national level

In Chapter 4, the adaptations options were discussed at farm level in Jilin province, using the bio-physical model, DSSAT. Those adaptations are detailed and feasible for farmers, and their effects are highly affected by the local environmental conditions and traditional agricultural structure.

From a macroscopic point of view, the adaptation options are now considered at the national level in this section through examining the effects of two agricultural policies to alleviate the impacts of climate change on food security at the national level. Investment in agricultural research (P1) reflects the optimal potential increase of crop yield, and effective irrigation (P2) area represents the effect of irrigation facilities that help to realize that potential. In the food economic model, these two policies were placed into the equation of yield. They can therefore be taken as the factors on the supply side.

Although many other macro policies may also provide adaptation options against climate change, the reasons for choosing these two policies were: 1) they are the most crucial factors in agricultural sectors, and well established systematically in China's agricultural sector; 2) it is easy to quantify them and to collect data from each year's census, so that it is possible to track and validate.

The two policies were investigated for their independent effect as well as for their coupling effects. The growth in P1 was 10% with the high scenario, a doubling of the value used in the Best guess scenario. The growth in P2 is 2% under the high scenario, and about 30% higher than the value for the Best guess.

In terms of food availability, the production loss of maize due to climate change could be recovered partly by applying the high level of P1 and coupling the high level of P1 and P2, resulting in the improvement of the self-sufficiency ratio by

about 2% under the these settings. But the single effect of P2 was not sufficient to compensate for the bio-physical loss by climate change.

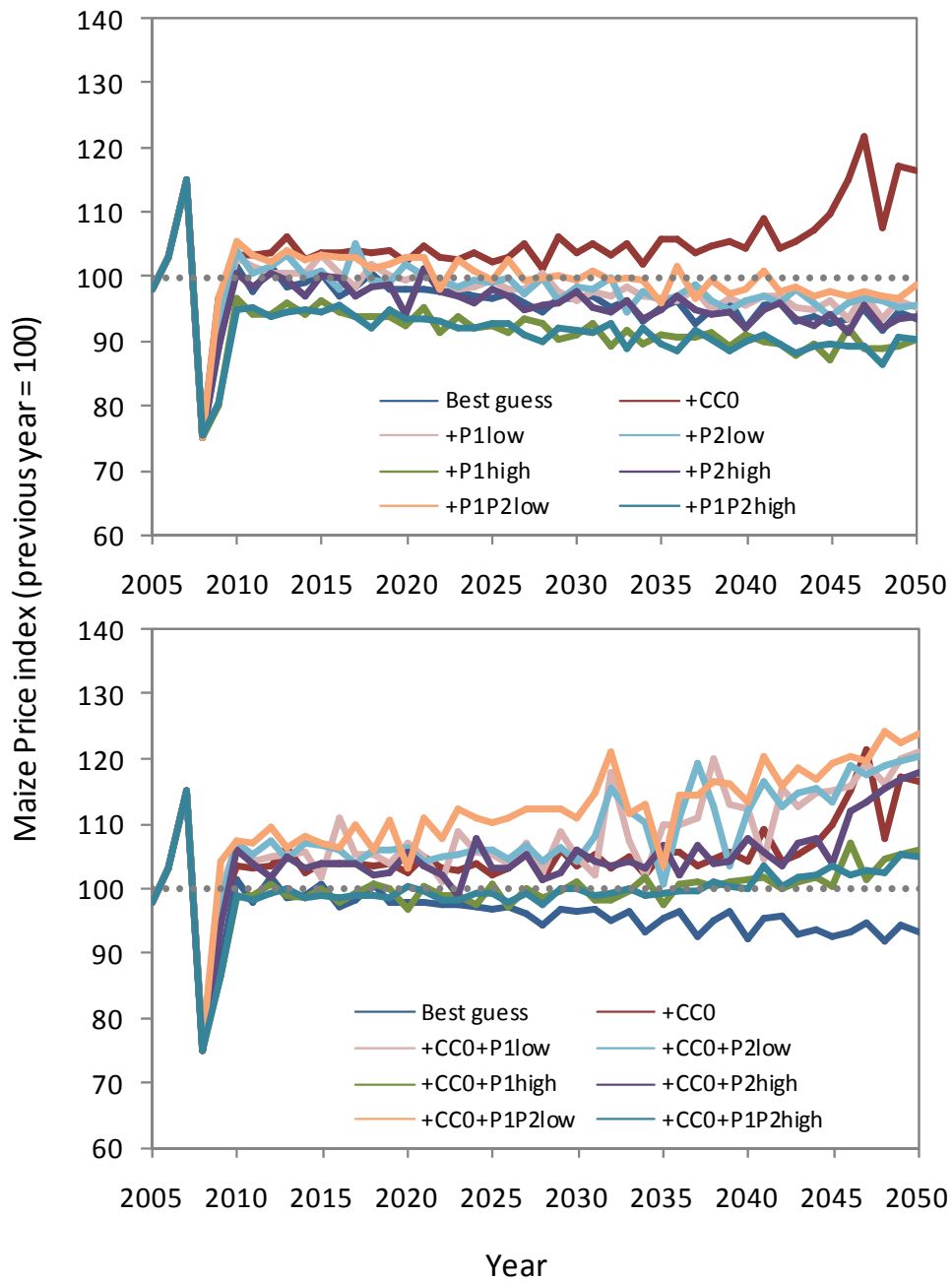


Figure 7-25 Price index of maize with applied adaptations. Projections are from 2008 to 2050, and the data in years 2005, 2006 and 2007 are from NBS yearbooks.

In terms of food access, the high scenarios of a single P1 and coupling P1 & P2 will suppress the price index of maize close to the neutral value of 100, as shown in Figure 7-25. This means that the proper agricultural policies are able to successfully move the price to a stable status.

In summary, improving P1 (supplement investment in agricultural research) is effective in a trade-off of climate change impacts, for both food availability and access. The high growth of P2 (increasing effective irrigation area) will bring some improvement to food access, but its effect is much weaker than P1 for the given high scenario.

7.5 Uncertainties among scenarios

The climate system is inherently uncertain; hence the climate change projections are characterized with high uncertainties (as was discussed in Section 3.3.2, 4.3.2, and 5.2.2). In addition, the socio-economic projections and any economic model results also involve uncertainties. It is important to discuss the range of uncertainty in impact assessments to support the decision-making process in relation to adaptation.

In this section, the uncertainties underlying climate change and socio-economic scenarios (i.e. population, income and policy scenarios) are discussed. Because the uncertainties cannot be fully reflected by the supply-demand balance in the quasi equilibrium status, only the results of price index are given.

The uncertainty in the food economic model is discussed in Chapter 8.

7.5.1 Uncertainty among climate change scenarios

Six climate change scenarios were used, according to the six emission scenarios by IPCC SRES (2000), to produce the damage on bio-physical production of maize as presented in Chapter 5. Also, the median scenario of those climate change scenarios was constructed as a representative in simulations and projections for convenience.

In general, the maize price is projected to keep rising under all climate change scenarios. The optimistic projection appears under the B1 scenario. The first two highest prices are projected by the A1T scenario before 2040 and by the A1FI scenario after 2040. Projections under all the scenarios look similar until 2030, when the disagreement becomes significant. The gap between the lowest and highest projections of price index is about 15% in 2050.

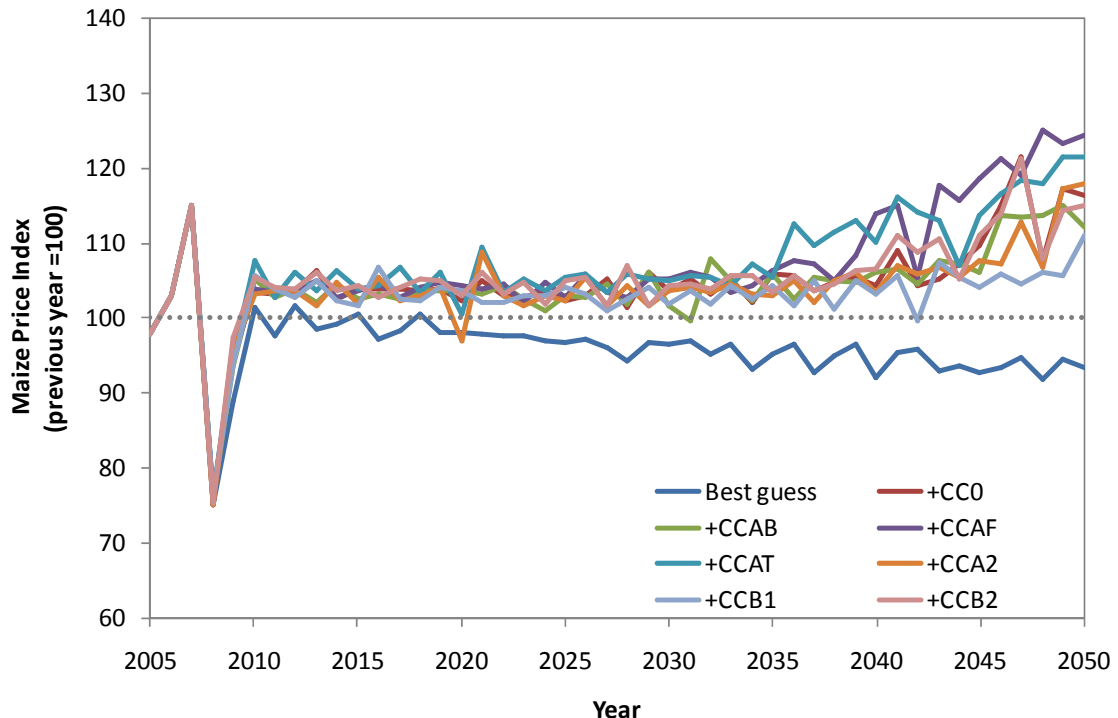


Figure 7-26 The indexed equilibrium price of maize under different climate change scenarios.

7.5.2 Uncertainty among socio-economic scenarios

To examine the uncertainties among socio-economic scenarios, extreme scenarios were considered: the highest growth of income and population, and the lowest growth of these two.

The fundamental pattern of food availability does not change too much among the six socio-economic scenarios. Only under the scenario with the highest growth of both income and population, does the self-sufficiency ratio of maize decline to about 90% after 2045 with climate change. In this case, as income is increasing and population is moving over the peak summit around 2045, the increase of sown area driven by price mechanics is no longer able to catch up to the demand for livestock products, and the yield loss due to climate change aggravates insufficient production.

For food access, the high growth in income (IM) and population (POP) will magnify the increase of the maize price if considering climate change (Figure 7-27), but they are not the drivers that push up the price. The maize price index will rise by 10% to 15% with climate change, under the high scenario for IM and POP. Without climate change, the results are nearly the same as the Best guess, staying below the value of 100.

7.5.3 Extreme cases

Several extreme cases when coupled with scenarios of climate change, income, population and policy are given in Figures 7-29 to 7-33.

The worst case in the group is that which has the low level of agricultural policy with the highest growth of IM and POP under the A1FI scenario. In this case, the price of maize keeps to a high growth rate, about 15%~20%, during the whole

projection period. The best case is that which has the high level of policy with low IM and POP growth under the B1 scenario. In the best case, the price index remains at a low level, its value being less than 100 for almost the whole projection period.

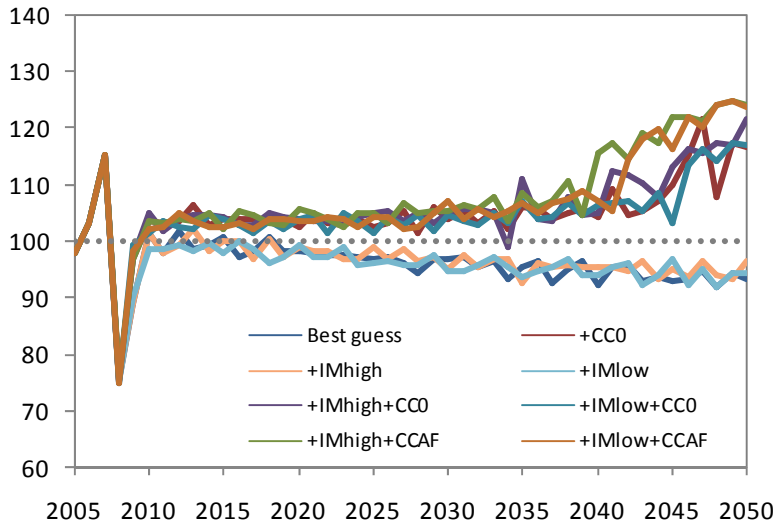
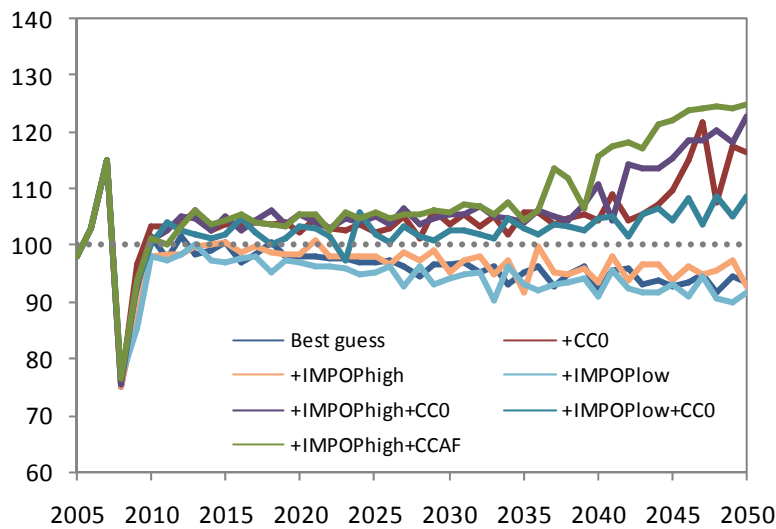
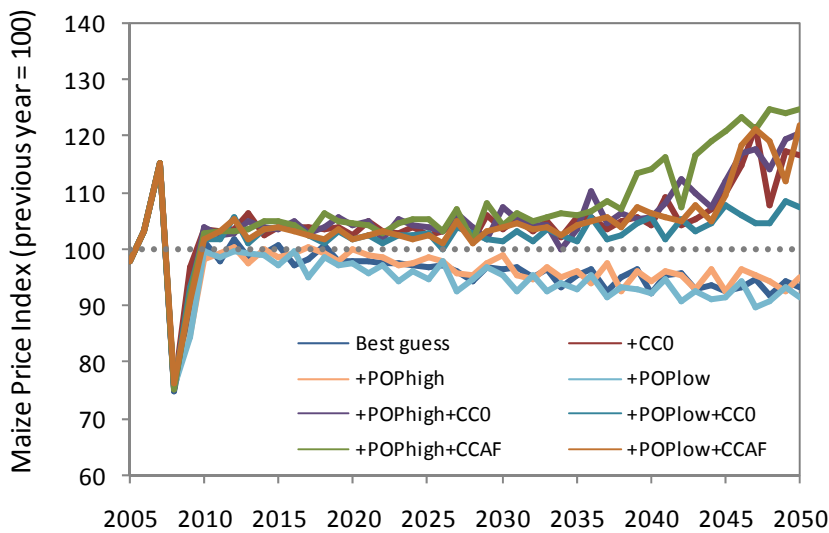


Figure 7-27 Maize equilibrium price under different socio-economic scenarios (time series).



Year

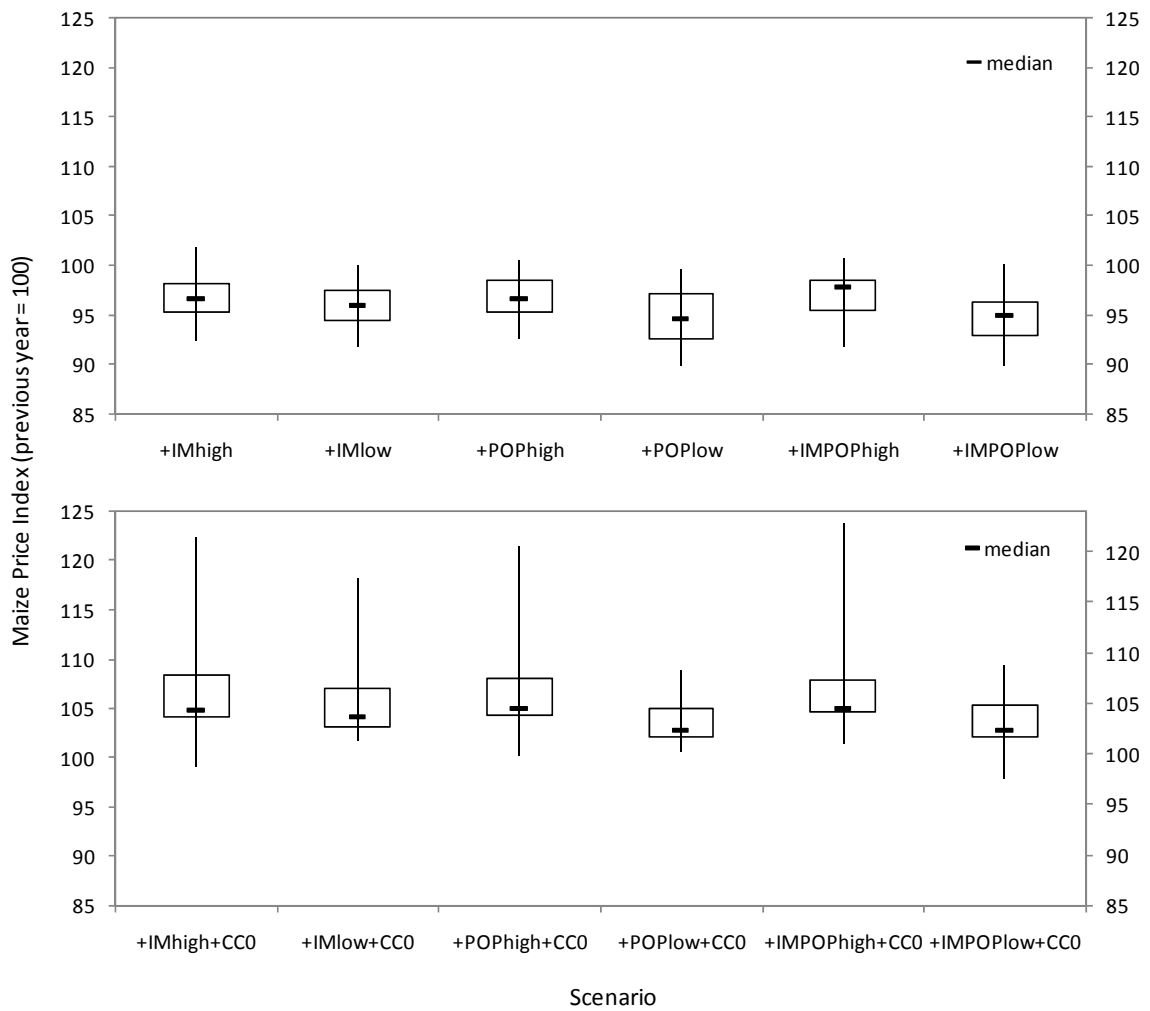


Figure 7-28 Maize equilibrium price under different socio-economic scenarios (box plot). The top and bottom of the box show the 75% and 25% percentiles. The vertical line through the box gives the maximum and minimum values.

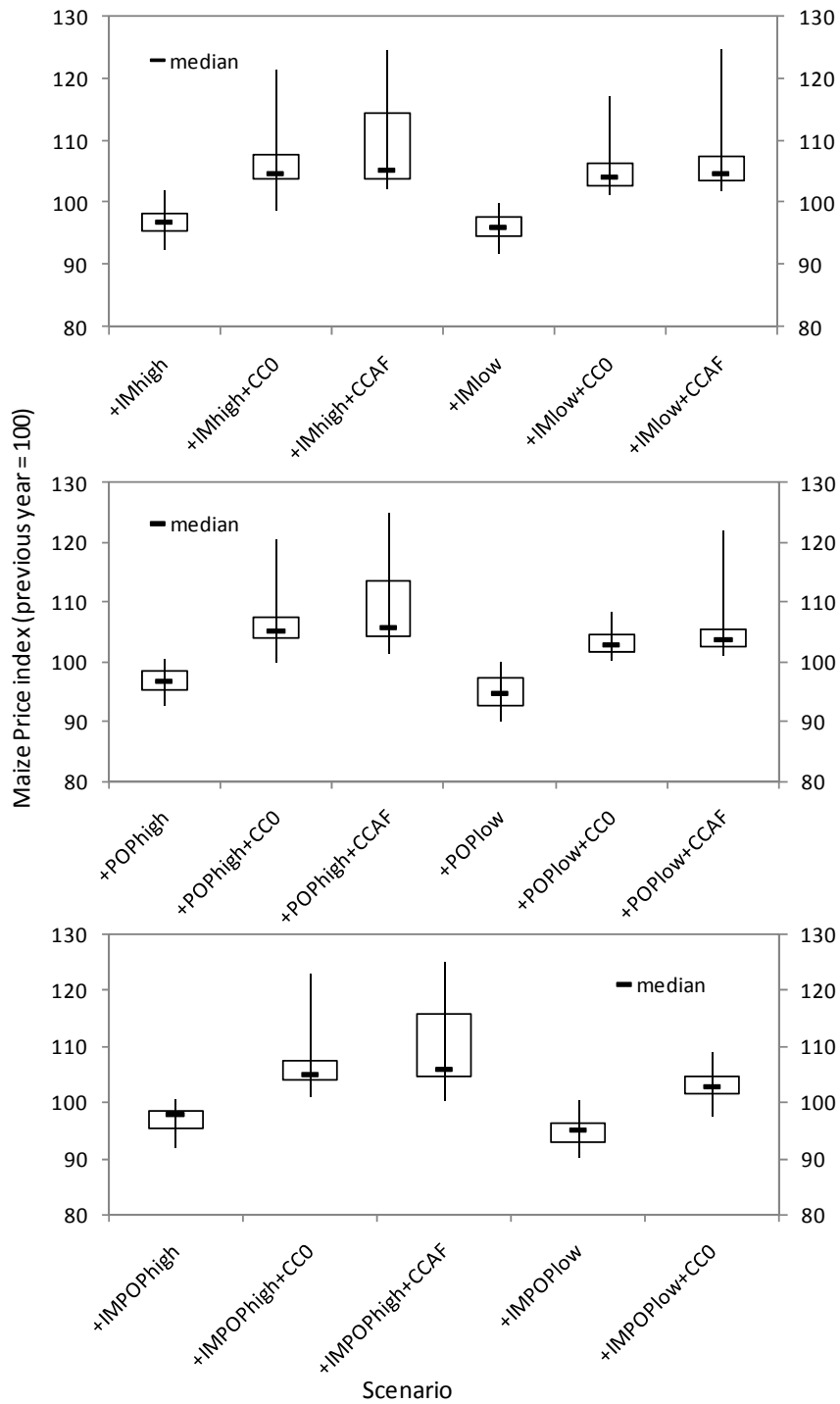


Figure 7-29 Maize equilibrium price under coupling of extreme scenarios for income, population, and climate change (box plot). The top and bottom of the box show the 75% and 25% percentiles. The vertical line through the box gives the maximum and minimum values.

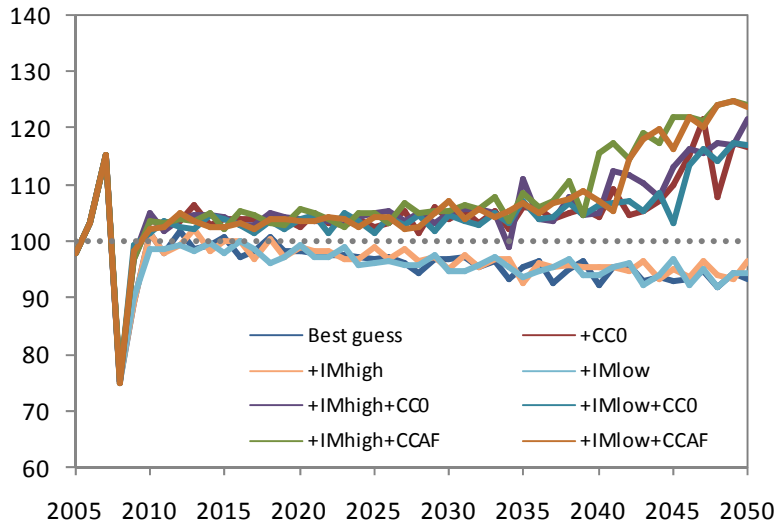
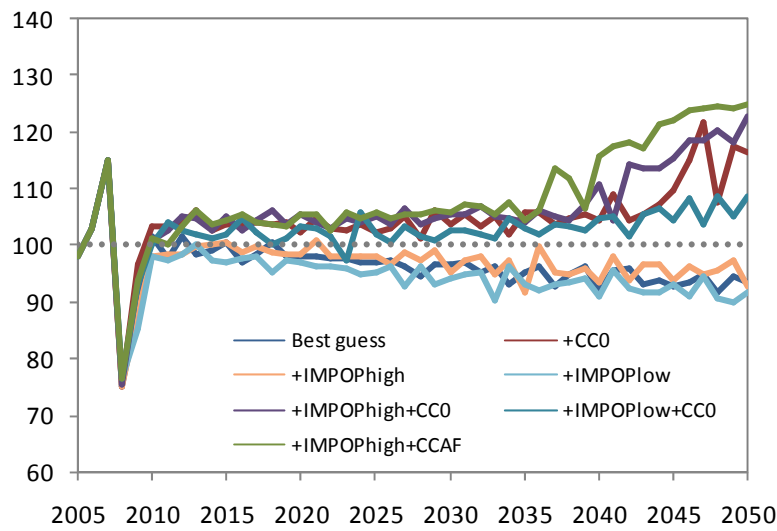
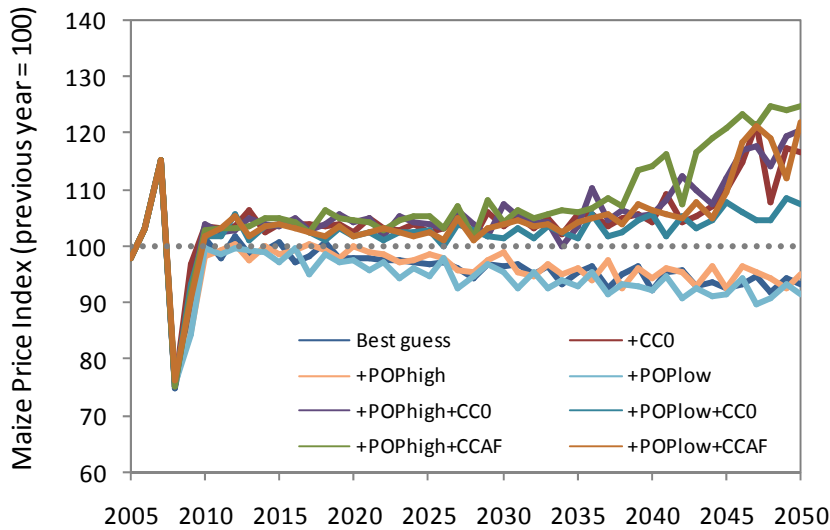


Figure 7-30
Maize equilibrium price under coupling of extreme scenarios for income, population, and climate change (time series).



Year

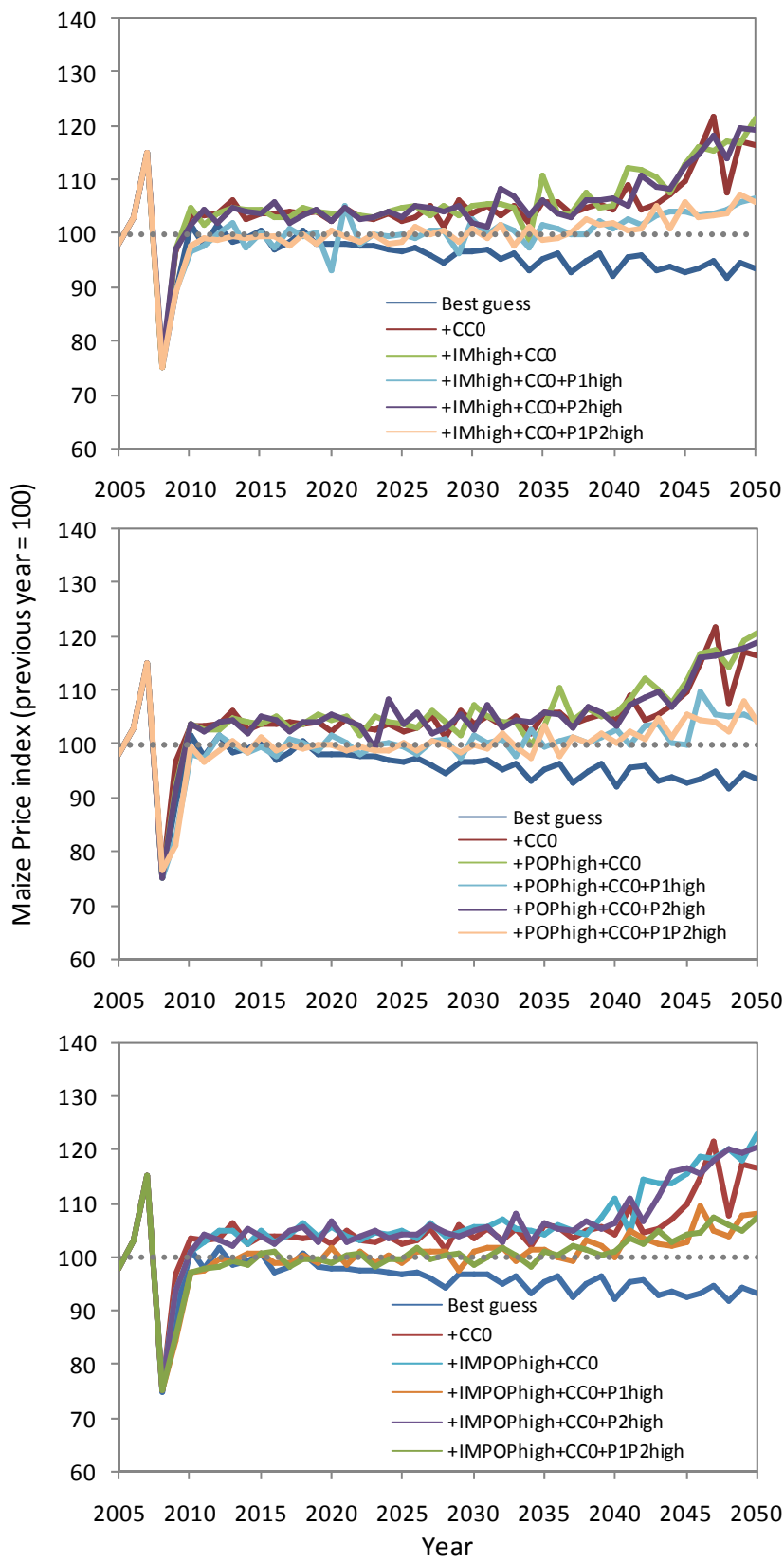


Figure 7-31 Maize equilibrium price under coupling of extreme scenarios for income, population, climate change and policy, part 1 (time series).

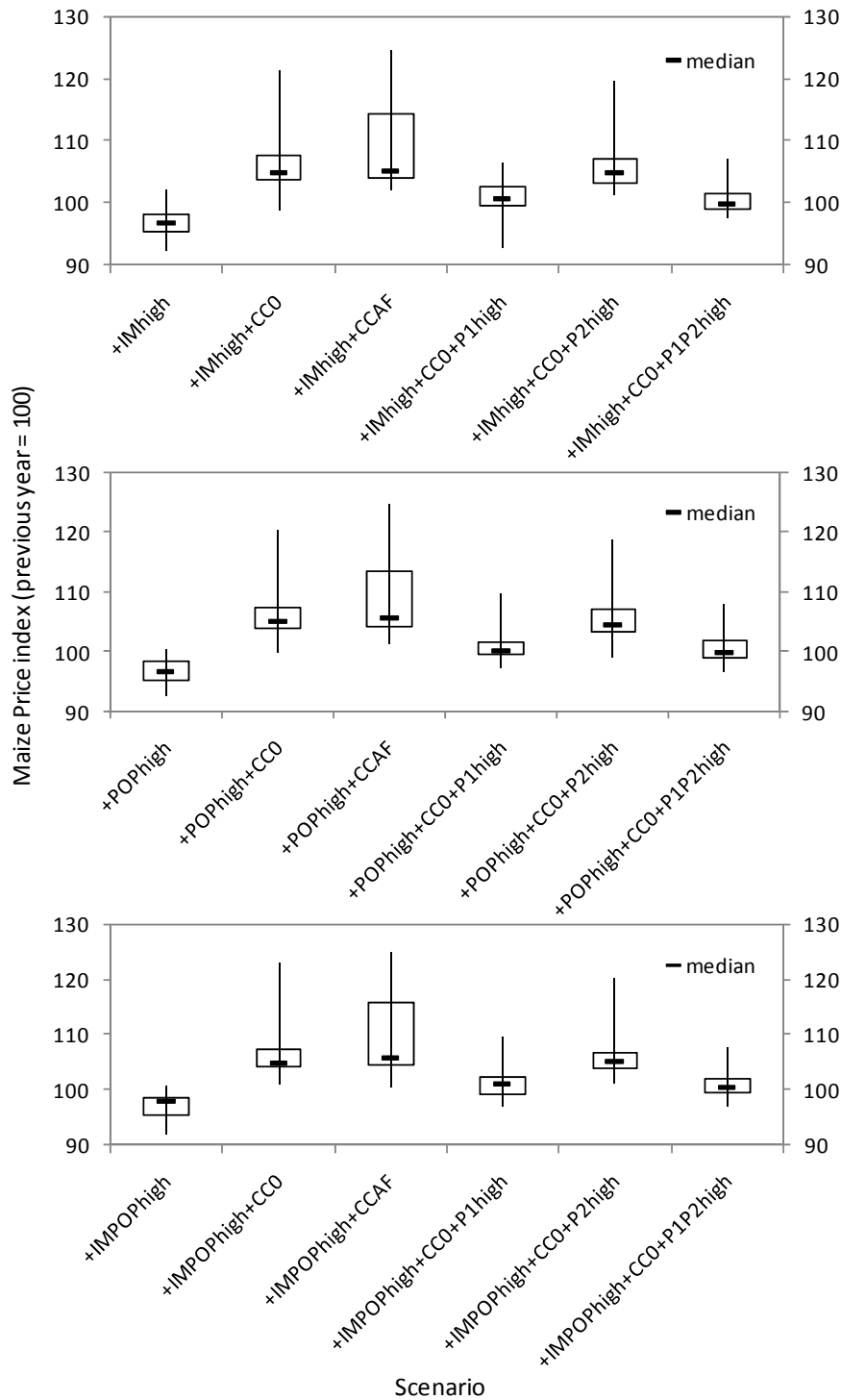


Figure 7-32 Maize equilibrium price under coupling of extreme scenarios for income, population, climate change and policy, part 1 (box plot). The top and bottom of the box show the 75% and 25% percentiles. The vertical line through the box gives the maximum and minimum values.

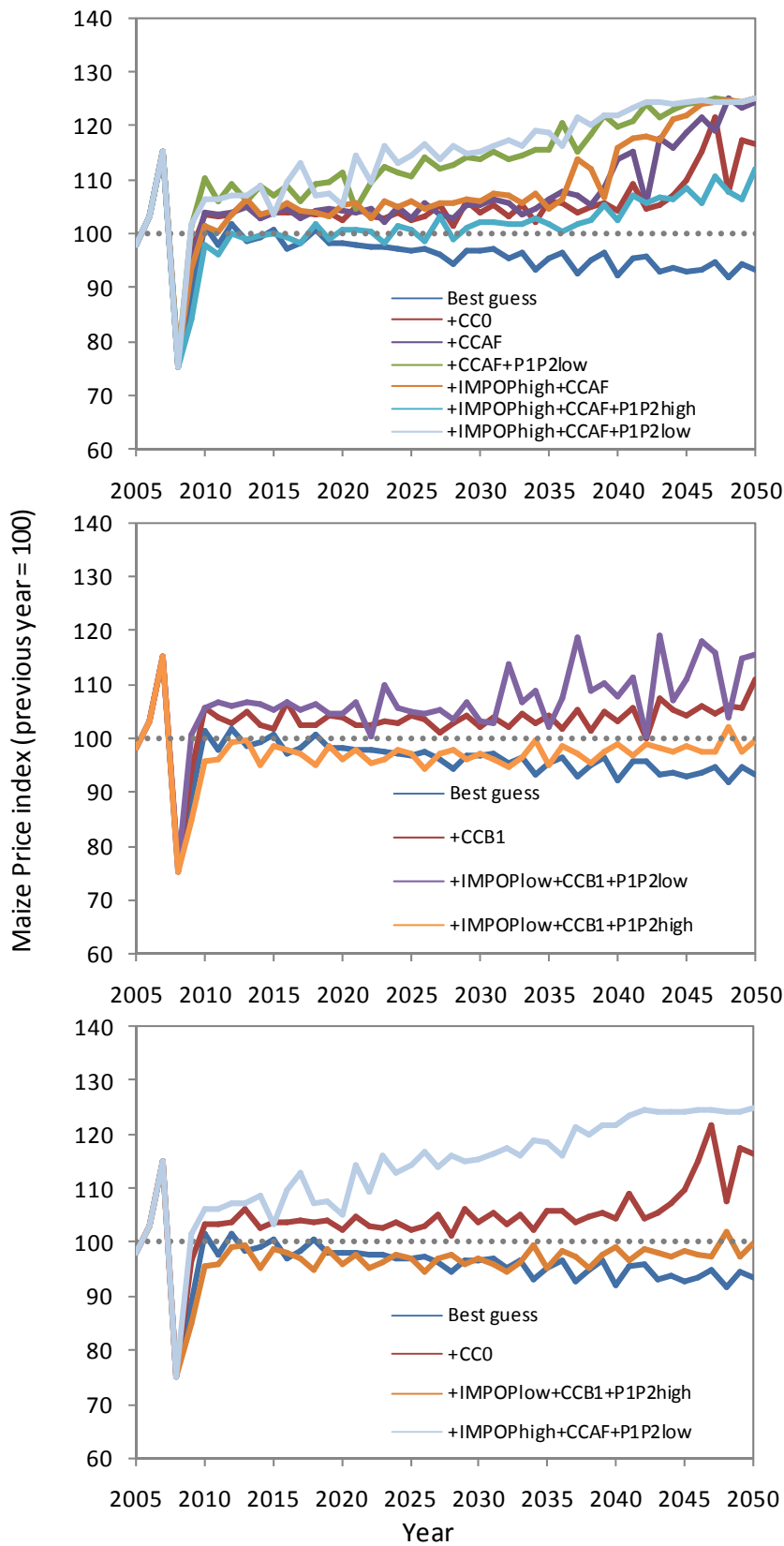


Figure 7-33 Maize equilibrium price under coupling of extreme scenarios for income, population, climate change and policy, part 2 (time series).

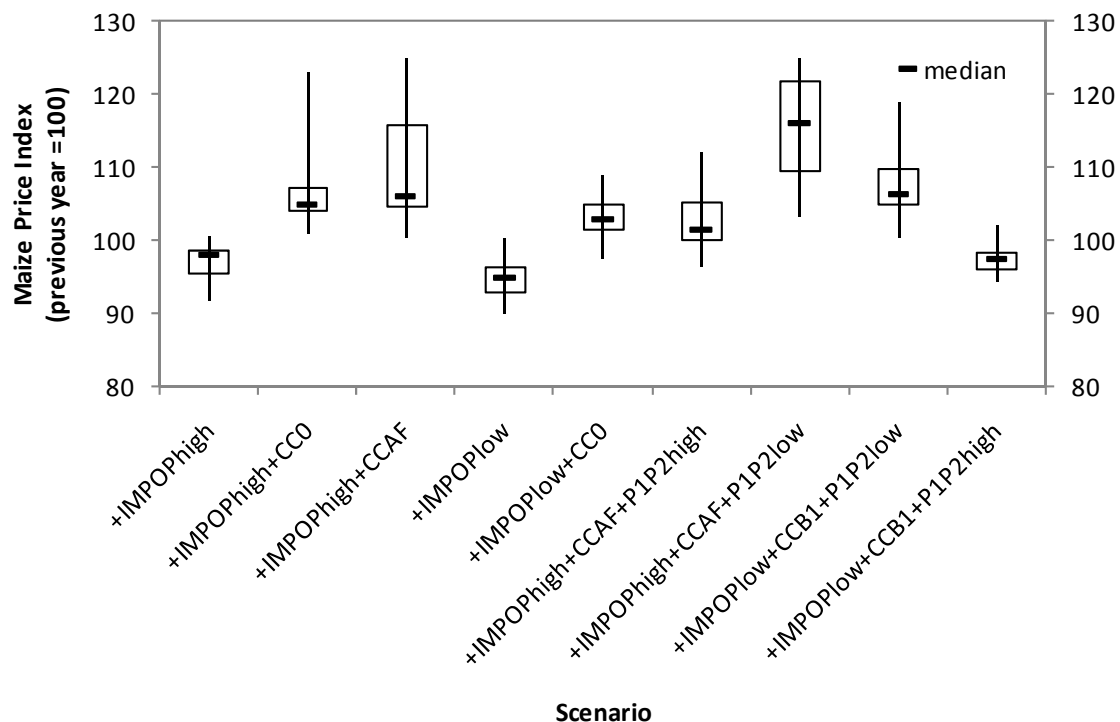


Figure 7-34 Maize equilibrium price under coupling of extreme scenarios for income, population, climate change and policy, part 2 (box plot). The top and bottom of the box show the 75% and 25% percentiles. The vertical line through the box gives the maximum and minimum values.

7.6 Summary

In this chapter the projections of the food system using the economic model under multiple scenarios of climate change, income, population and policy were discussed. The future food security of China was assessed for its availability access and stability, based on the projections of food supply, demand, and price.

The main results are summarized as follows:

The supply and demand of the main grains of China will turn to a "tight" balance in the next few decades. The "tight" balance means the self-sufficiency of a certain grain ranges from 95% to 90%. However, food access and the stability of food security are likely to suffer from the pressure caused by climate change.

The impacts of climate change on bio-physical production of a single crop will likely be slightly alleviated through the economic process due to the price adjustment helping to spread those impacts from a single crop to its substitute crops.

The impacts of climate change are predicted to be limited to an acceptable range in the next twenty to thirty years, but their intensity will rise significantly close to the middle of this century.

The impact of a sudden shock on the food security will last longer, when the impacts of climate change are taken into account.

Improving agricultural policies is likely to reduce the negative effects produced by either climate change or the growth of income and population. The continuing increase of investment in agricultural research is likely to result in the reduction of food security risk.

The uncertainties among climate change and socio-economic scenarios could be large with respect to food access. Therefore it is crucial that government adopts proper adaptations as early as possible to ensure the food security of China in the next few decades.

Chapter 8 Conclusion, Discussion and Outlook

The impacts of climate change on agriculture and the food security of China are both hot topics discussed separately by agricultural science researchers and economists since the 1990s. In recent years, integrated assessment methods focussing on impact research of climate change have been developed and applied to a wide range of areas, including water management, land use, and agriculture. For both scientific practical applications, integrated methods have distinct advantages in impact research of climate change where several natural and socio-economic systems are considered. This typically involves extensive sets of data and models, all of which require updating as scientific understanding and information improve (Warrick, 2009). Several attempts have been done to incorporate agriculture, food economy and climate change in many ways as outlined in Chapter 1. The urgent demand for searching and evaluating adaptation options to climate change by governments and shareholders is increasing. In this respect, computable models are useful and efficient tools to assess quantitatively the effectiveness of adaptations.

The goal of this thesis was to develop an integrated model to assess the food security of China under climate change by coupling the bio-physical and socio-economic processes, and to investigate how food security will be challenged by climate change and economic development in future decades, and how certain adaptations can reduce the vulnerability of food systems.

8.1 Discussion and future work

In this research, a framework was developed for the integrated assessment of food security under climate change, within which the information of bio-physical and

socio-economic processes was coupled across farm and national levels. This information was aggregated up from the local to the national level because of the emphasis on impacts.

Compared to previous studies on the isolated bio-physical and socio-economic aspects, this thesis is an attempt to couple these two fields using a new integrated model method to investigate the impacts of climate change on the crop production and the consequent reflection from food market. The integrated method is an original dynamic and systemic method to incorporate the bio-physical yield with the input of an economic model, which allows the projection of indicators of food security in year-by-year steps.

By applying this integrated model, the thesis not only gave the impacts on the food availability but also discussed the impacts on food price and the resilience of Chinese food system in the future, which has not been studied by other researchers. Multiple climate, policy and socio-economic scenarios and their combinations were also discussed in details, which is a comprehensive analysis of uncertainties in impact researches. The most distinctive contribution are some adaptation options both on farm and country level were assessed quantitatively in this thesis, resorting to the advantages of bio-physical model.

In Chapter 4 and Chapter5, the impacts of climate change on bio-physical yield of maize are simulated in Jilin province and the whole China. The yield reduction due to climate change in main production provinces is about 17% in 2020s, slightly larger than the projection of irrigated maize from Xiong (2009). Both projections were calculated by the DSSAT model and similar global warming scenarios, except the different irrigation methods applied: I used much detailed the irrigation scheme with considering the irrigation quota in reality, which may result in much more

strict limitation on water sufficiency of crop. On the regional scale, as mentioned in Chapter 4, the DSSAT model using my improved sowing and irrigating scheme performed much better in Jilin province than the original version which Xiong (Xiong et al, 2007) used. But in some area, especially Xinjiang, the simulation in this thesis underestimated the maize yield, but Xiong et al. gave a moderate estimation in their paper. The previous authors did not investigate that detailed indicators of changes in growing phase of maize in China. My projected sowing date, about 5 days in advance of current conditions in 2050s is possible, in accordance with the recent observations by the local contacts in Jilin province.

Considering crop model selection, using another model could produce different results to the current projections, even if the model calibrated carefully based on the same observations. As mentioned before, Lobell & Burke (2010) compared three types of statistical model and CERES-Maize model. The results would not only be affected by changes in climate variability but also the variables with high spatial variation, like the cultivar used in different regions, and the noise in weather or climate data. Compared to the other bio-physical based model used in this thesis, the application of fertilizer and irrigation and the planting schedule was considered in daily steps, and the simulation of DSSAT was highly sensitive to the irrigation and planting schedule in the thesis. So, if using the model with different bio-physical processes and without considering these cropping strategies, the results may be different.

In comparison of economic projections without considering climate change, the total grain supply and demand in 2020s in this thesis has the same magnitude as the most previous projections (Liao & Huang, 2004; Lu et al, 2010; Zhang, 2012), i.e. about 700 Mt of supply and 730 Mt of total demand. For specific crops, the projected increase in maize demand matches with the latest projections by International Global Council (IGC, 2013) quite well, with the annual growth rate of

about 5% in the next 5 years. The harvested area for rice projected by Wailes and Chavez (2012) will decline from 29.8 to 28.3 million ha by 2021, which is much slower than my projections, since the base yield (4.59 t/ha) they used is much lower than the Chinese statistic (about 6.5 t/ha) that I employed in the thesis. Comparing the OECD outlook (OECD, 2013), my projection of wheat production and consumption is 10% smaller than the OECD results. It might be caused by 1) the different starting year of projection with different initial conditions; my simulations started from the average of 2004-2007 and theirs started from the very recent 2013, 2) the different estimation of wheat consumption method. The original statistical consumption data from Chinese Statistical Bureau was adjusted by considering the some other household surveys with local information (see details in Chapter 6) and was not used directly in my thesis. The international trade projection of all grains in my thesis is much smaller than all of the studies mentioned above, because the food prices in international market were fixed by external scenarios but not produced internally by the model system. This is the shortcoming of this model, I must admit.

Some limitations of this model should be revisited; because the main goal of this thesis was to develop a model, the food security was not fully assessed at this stage. As mentioned in Chapter 1, the four aspects of food security include: food availability, food access, food utilization and stability of supply. Without modelling the other sectors in economic model, the income input is not obtained internally and the distribution process of food products is not included, so the food access is not fully assessed by the projections of food prices. The food utilization and the stability of food security is not discussed in the thesis either. Furthermore, only maize is considered, so it must be confessed that the assessment is only a test for the integrated model.

The scaling up method allowed for only one-way responses to be assessed: in the economic modelling system, the national government is able to react to the local events, but cannot obtain feedback from the farmers. Moreover, in the current

assessment of food access, only price is considered, and thus it cannot reflect the actual food access for different income groups. Obviously, the poor family is more vulnerable than the rich facing the same increase in food price. Therefore, it will be useful to build a household consumption model connected to the food economic model, to simulate how income affected the consumption pattern of a family, as well as to simulate how the rural family would respond to the macro agricultural policy.

The economic model developed in this thesis was designed for the national level, and does not capture the local or household level information. Much more effort needs to be devoted to aspects of food access and utilization in future. For food access, the household budget process should be predicted based on an investigation of food price and income, and the distribution of crops. The market infrastructure and the evaluation of the transport system would be taken into account to evaluate the amount and frequency of food consumption. In particular, for the purpose of sustainable development, a practicable index system to measure the stability of all these three aspects is required. Compared to studies of food availability, few quantitative assessments have been conducted to investigate climate change impacts on food utilization, which are critical indicators of regional and local food security. It is worth highlighting interactions among multi spatial and time scales in food utilization. Analytical tools are required to capture the quantitative information with respect to regional and household levels, such as changes in income and food consumption pattern due to inter-annual climate fluctuations, and allocation changes of food products at regional scale due to shifts in agro-ecological zones in the long term. Therefore, a micro-economic model grounded in the local context should be developed in order to investigate food consumption patterns with changes in price and income at the household level. Further attempts would lead to incorporating food security at the household level with farm-level adaptation options, e.g. the interactions among cropping diversity, self-use rate of outputs, income, and nutrition level at inter-annual scales. A module to describe the

allocation and transportation of food products between regions is also required in future.

The current food economic model is a partial equilibrium model that considers the four main grains. The availability of other grains and crops and non-food commodities were not included. It would therefore be feasible in future research to add soybean and oil crops and crucial non-food commodities, e.g. fuel and cotton, into the market clearance mode.

Adaptations in the thesis focused on the agricultural research and irrigation at both local and national scales. More options should be included in the future, e.g. subsidy for grain-producers, and introduction of carbon credits. However, it may be difficult to access proper data. In order to address the impacts on the economic dimension at the farm level, it is necessary to consider farmer response by simulating decision-making processes which can deal with different adaptation options at multi temporal and spatial scales, such as the long-term water and land management at a regional scale, short-term cropping practice at farm level, and long- or short-term disaster-resisting activity at both levels.

With regard to measuring adaptation, even using the high level of P2 policy (increasing effective irrigation area) the shortage of maize supply produced by climate change is unlikely to be retrieved. In the next stage, a higher level of P2 policy needs to be tried in order to find out a proper point at which the gap could be filled. Then a cost-benefit analysis of the adaptations could be undertaken, and which would also allow comparison of the advantage and disadvantage from importing or the self-sufficiency ratio.

Some new cultivars used in Section 4.4.2 are theoretical. Using these theoretical cultivars was an attempt to explore which phenological parameters, i.e. P1, P2, and

P5, would be the most important in maize yield in a warming environment. It is only provide some suggestions for breeding or gene engineering to respond to climate change, but it is uncertain that all the theoretical cultivars could be created. Obviously, based on Figure4-18, the larger P1 and P5 parameter will produce higher yield level in Jilin case. It means that the new cultivars requiring longer thermal time in both juvenile and mature stage will be the optional cultivars in future. In fact, introducing new cultivars has already happened in Northeast China, e.g. in Jilin (from local contact). Maize cultivars are rich in gene storage: like in DSSAT there are more than 40 cultivars available for use (Jones, 2003). Genetic engineering and breeding is developing very fast and Chinese government is more open-minded to introducing new cultivars and to genetic engineering than European countries. The first documentation of State Council of China in 2010 aims to promote the industrialization of new genetically-modified cultivars. Chinese government has very positive attitude to push farmers to use new cultivars: Every county in China has its own branch to promote and guide farmers to use new cultivars. So it is possible for China to maintain productivity by switching to new cultivars.

Due to limitations of data and time, only the impacts on maize were discussed in this thesis. In future, it will be worthwhile to add the impacts on rice and wheat in food economic models.

The bio-physical process of livestock production was not included in the framework. In future, it should be possible to add a grazing model which can describe the bio-physical growth of grass linked to land use (like the Atmosphere-Vegetation Interaction Model developed by Ji, 1995) and livestock production.

A risk analysis of yield reduction was presented in Chapter 4, showing that the probability of an event provides very useful information for policymakers. A full risk analysis of food security related to uncertainties in climate change and socio-economic scenarios could be done at a later stage by applying the toolkit for probabilistic calculation developed in Chapter 4. It requires repeating the

projections under multiple yield reduction scenarios, which would be quite time consuming.

Although the effect of increased CO₂ on crop growth was investigated and a noticeable compensation effect was demonstrated on yield, these simulation results were not included in this thesis, because of the uncertainties in current CO₂-enhancement experiments (Kurukulasuriya & Rosenthal, 2003). Further fieldwork and/or laboratory-based experiments are required to validate the modelled CO₂-enhancement effects for computer modelling and simulation.

To sum up, additional work on some of the issues and future research areas discussed above will strongly depend on data availability and computing power.

8.2 Conclusion

This thesis developed a practical methodological framework that integrated the bio-physical and socio-economic processes within the food system across scales. It was applied in China, a country with rapid economic growth and a large population, in order to assess multiple dimensions of food security related to climate change and socio-economic development.

In the framework, an improved bio-physical crop model was coupled with an improved food economic model by scaling up from the farm level to the national level. The bio-physical crop model was developed from a site-based Decision Support System for Agrotechnology Transfer (DSSAT) model in order to investigate the impacts of climate change on the bio-physical production of a crop taking into account environmental factors. The food economic model was developed from a partial equilibrium economic model, China's Agricultural Policy Simulation Model

(CAPSiM), in order to simulate the response of the socio-economic system to the negative consequences on the food economic system from bio-physical changes in crop production due to climate change.

8.2.1 Impacts of climate change on maize

In the case study of Jilin, which is the most important grain-producing province, the maize yield is highly likely to decline in the western and central regions but to increase in the east under climate change. The growing season will be reduced in the central and western parts, leading to a shortened grain-filling period. The average maize yield in the west and central regions is thus projected to decrease 15% or more by 2050 as predicted by 90% of 120 projected scenarios. Two potential adaptation strategies, i.e. improving irrigation facilities and introducing cultivars, were identified from the vulnerability assessment and were further tested for the reduction areas. The results revealed that the increase in effective irrigation by upgrading the irrigation system would help to maintain the current production level, but in the long run, the maize cultivars need to be introduced in line with the future warming climate.

With respect to the whole of China, the maize yield in major cropping areas (i.e. Jilin, Heilongjiang, Liaoning, Shandong, Hebei, Henan, Neimeng, and Sichuan, which historically contribute about 70% of the total maize production of China) is projected to fall significantly in the coming decades, for either spring or summer cultivars. The average reduction of yield is about 3% in the 2020s, 10% in the 2050s, and 14% in the 2070s under the median climate change scenario. In the two important areas of maize production- Jilin and Shandong, the maize yield is likely to decline by about 30% of the baseline yield in the year 2070. Future climate change is projected to have favourable effects on maize yield in the areas along the northeast to southwest maize zone, including the marginal areas of Northeast China,

northern parts of Hebei, parts of Shaanxi and Shanxi, and the boundary areas of the Chengdu plain in Sichuan. In those areas where maize yield is likely to decline, the growing days to maturity are also shortened significantly. The spring maize area in the Northeast suffers the largest reduction in maturity period, about 20 days shorter in the worst case in the year 2070. Improvements in thermal conditions induced by a warming climate in those areas may produce a prolonged growing season synchronous with the increasing yield of maize. However, the profitable effect on maize production produced by a warming climate is not only narrowed within a quite small spatial scope, but also limited in certain time periods. The difference between the worst prediction of maize yield under A1FI and that under B1 will be more than 10% of the baseline yield in the year 2070. The response of the provincial average yield to the six emission scenarios is very different from that on the national scale.

8.2.2 Food security of China related to climate change

This relationship can be summarised as follows:

- The supply and demand of the main grains of China will likely move towards a "tight" balance in the next few decades. However, food access and stability of food security are likely to suffer the pressure caused by climate change. The self-sufficiency ratio of maize will likely drop less than 92% in 2050.
- The impacts of climate change on bio-physical production will likely be slightly alleviated through the economic process. Price adjustment helps to spread those impacts from a single crop to its substitute crops.
- The impacts of climate change are predicted to be limited in the next 20 to 30 years, but their intensity will likely increase dramatically, close to the middle of this century.

- When the impacts of climate change are considered, it will take 3 or 4 years longer for the food system to return a balance status after a sudden than the baseline setting.
- Improving agricultural policies is likely to reduce the negative effects produced by either climate change or the growth of income and population. The continuing increase of investment in agricultural research will assist in reducing food security risks.
- The uncertainties among climate change and socio-economic scenarios could be large with respect to food access. Therefore it is crucial for government to adopt proper adaptations as early as possible to ensure the food security of China in next few decades.

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Appendix A Parameters in the Food Economic Model

A.1 Conversion rates of raw food materials into commercial products

Raw material	Commercial product
1 kg raw paddy-rice	0.7 kg milled rice
1 kg raw soybean	0.15 kg soybean oil
1 kg oil crop output ^a	0.43 kg vegetable oil
1 kg sugar crop output ^b	0.1225 kg sugar
1 kg milk powder	7 kg milk fluid

^a Oil crops include oilseed, peanut, sesame seed, sunflower, and palm (except soybean). Here, their average oil productivity is taken as 0.43, retrieved from <http://www.lengzoer.com/>

^b Sugar crops include sugar beet and sugar cane. Their sugar productivity is 11.9% and 12.3%, respectively, retrieved from <http://www.ynsugar.com>.

A.2 Income elasticity of demand

	Urban	Rural		Urban	Rural
Rice	-0.18	-0.03	Fruits	0.15	0.8
Wheat	-0.15	-0.01	Nonfood	0.2	0.2
Maize	-0.18	-0.05	Pork	0.04	0.15
Tubers	-0.12	-0.05	Beef	0.15	0.22
Coarse Grain	-0.12	-0.03	Mutton	0.15	0.2
Soybean	-0.15	0.1	Poultry	0.12	0.5
Oil	0.13	0.12	Egg	0.11	0.3
Sugar	-0.12	-0.15	Milk	0.15	0.5
Vegetables	-0.05	-0.12	Fish	0.15	0.5

A.3 Cross price elasticity of demand in urban areas

	Rice	Wheat	Maize	Tubers	Other grain	Soybean	Oil crop	Sugar crop	Vegetables	Fruits	Non-food
Rice	-0.02	0.008	0.0003	0.0002	0.0003	-0.0002	0.0005	-0.0005	-0.002	0.0012	0.0155
Wheat	0.0051	-0.0125	0.0003	0.0003	0.0003	-0.0003	0.0008	-0.0003	-0.0012	0.0006	0.014
Maize	0.0103	0.0181	-0.028	0.0005	0.002	0	0.0009	0.0002	-0.0005	0.0018	0.0084
Tubers	0.0104	0.0197	0.0006	-0.025	0.002	0	0	0	-0.0002	0	0.0002
Other grain	0.005	0.0089	0.0009	0.0007	-0.028	-0.0001	0.0009	0.0002	-0.0005	0.0018	0.0153
Soybean	-0.001	-0.0018	0	0	-0.0001	-0.0125	0.0003	0.0002	0.0008	0.0011	0.0079
Oil crop	-0.0009	-0.0002	0	0	-0.0001	-0.0002	-0.02029	-0.0007	-0.0023	-0.0001	0.0018
Sugar crop	-0.0037	-0.0035	0	0	-0.0001	-0.0001	-0.002	-0.012	0.0015	0.003	0.0038
Vegetable	-0.0032	-0.0038	-0.0001	-0.0001	-0.0002	-0.0004	-0.0013	0.0001	-0.0103	0.0136	-0.0169
Fruits	-0.0024	-0.0039	-0.0001	-0.0001	-0.0001	-0.0006	-0.0014	0.0001	0.0172	-0.00808	-0.0479
Non-food	-0.0027	-0.0038	-0.0001	-0.0001	-0.0002	-0.0008	-0.0014	-0.0004	-0.0046	-0.0039	-0.02023
Pork	-0.00058	-0.00074	-0.00002	0	-0.00002	-0.00006	0.00036	0.00002	0.00038	-0.0002	-0.003
Beef	-0.0034	-0.0067	0	0	0	-0.0003	0.0016	0.0004	-0.0018	-0.0029	-0.0376
Mutton	-0.0034	-0.0064	0	0	0	0.0006	0.0016	0.0006	-0.0018	-0.0029	-0.0501
Poultry	-0.0033	-0.0045	-0.0001	0	-0.0001	-0.0004	0.0036	0.0001	-0.0008	0.0021	-0.0149
Egg	-0.0019	-0.0036	0	0	0	0.0001	0.0021	0.0004	0.0008	0.0011	-0.002
Dairy	-0.00143	-0.00203	-3.33E-05	-3.33E-05	-0.0001	-0.00027	-0.001	-0.0002	-0.00127	-0.00207	-0.01183
Aquatic	-0.003	-0.0041	-0.0001	-0.0001	-0.0002	0	0.0012	-0.0001	-0.0013	0.0013	-0.0237

A.3 Cross price elasticity of demand in urban areas (continued)

	Pork	Beef	Mutton	Poultry	Egg	Dairy	Aquatic
Rice	-0.003	-0.0003	-0.0002	-0.001	-0.0003	0.0001	-0.0003
Wheat	-0.0025	-0.0006	-0.0004	-0.0011	-0.0009	0.0001	-0.0004
Maize	0.0011	0.0005	0.0003	0.0006	0.001	0.0003	0.0002
Tubers	0	0	0	0	0	0	0
Other grain	0.0021	0.0006	0.0004	0.0006	0.0011	0.0001	0.0002
Soybean	0.0019	0.0002	0.0006	0.0004	0.0009	0.0005	0.0028
Oil crop	0.0077	0.0006	0.0004	0.005	0.0019	-0.0004	0.0033
Sugar crop	0.002	0.0005	0.0005	0.001	0.001	0.0002	0.001
Vegetable	0.0021	-0.0002	-0.0002	-0.0004	-0.0002	0.0001	-0.0001
Fruits	-0.0064	-0.0008	-0.0005	0.0003	-0.0008	-0.0011	0.0004
Non-food	-0.0074	-0.0009	-0.0007	-0.0021	-0.0016	-0.0003	-0.0027
Pork	-0.00104	0.00058	0.00046	0.00016	-0.00012	0.00002	0.00046
Beef	0.0342	-0.0129	0.0137	0.0107	0.0008	-0.0003	-0.0014
Mutton	0.0411	0.0205	-0.01357	0.0107	-0.0002	-0.0003	-0.0014
Poultry	0.0017	0.0028	0.0018	-0.01733	0.0058	-0.0003	0.0037
Egg	-0.0014	0.0004	0.0001	0.0083	-0.00963	0.0033	0.0021
Dairy	-0.00213	-0.00027	-0.00017	-0.00103	0.0017	-0.00285	-0.00097
Aquatic	0.0031	-0.0004	-0.0003	0.0023	0.0003	-0.0002	-0.00834

A.4 Cross price elasticity of demand in rural areas

	Rice	Wheat	Maize	Tubers	Other grain	Soybean	Oil crop	Sugar crop	Vegetable	Fruits	Non-food
Rice	-0.00933	0.005	0.001	0.0005	0.001	-0.0004	0.0001	-0.0005	-0.0015	0.0005	0.004
Wheat	0.0051	-0.00917	0.0011	0.0005	0.0011	-0.0005	0.0006	-0.0003	-0.0021	0.0004	0.0027
Maize	0.0104	0.0108	-0.025	0.001	0.005	0	0.0007	0.0002	-0.0003	0.0013	0.0068
Tubers	0.0147	0.0144	0.0031	-0.028	0.005	0	0	0	-0.0002	0	0.005
Other grain	0.0142	0.0147	0.0075	0.0025	-0.028	-0.0001	0.0008	0.0002	-0.0002	0.0014	-0.0046
Soybean	-0.0047	-0.0057	-0.0005	-0.0002	-0.0004	-0.01505	0.0002	0.0002	0.0002	0.0011	0.0171
Oil crop	-0.0045	-0.0024	-0.0008	-0.0004	-0.0005	-0.0003	-0.023	-0.0002	-0.0046	0.0002	0.0068
Sugar crop	-0.0194	-0.0126	-0.0006	-0.0005	-0.0005	-0.0001	-0.002	-0.01	0.0015	0.003	0.0052
Vegetable	-0.01	-0.011	-0.0016	-0.0005	-0.001	-0.0005	-0.0031	0.0001	-0.007	0.0101	-0.0054
Fruits	-0.0069	-0.007	-0.0008	-0.0007	-0.0005	-0.0003	-0.001	0.0005	0.0239	-0.01116	-0.0317
Non-food	-0.0139	-0.0139	-0.0024	-0.0009	-0.0019	-0.0008	-0.0023	-0.0003	-0.0045	-0.0026	-0.04515
Pork	-0.00128	-0.00124	-0.00028	-0.0001	-0.00014	-0.00008	0.0003	0.00002	-0.00014	-0.00012	-0.00326
Beef	-0.0086	-0.0085	-0.0015	-0.0005	-0.0009	0	0.0013	0.0003	-0.0047	-0.0024	-0.0255
Mutton	-0.0095	-0.008	-0.0017	-0.0005	-0.0009	0.0009	0.0013	0.0005	-0.0047	-0.0024	-0.0289
Poultry	-0.00485	-0.00475	-0.0009	-0.00025	-0.0006	-0.00005	0.00165	0.0001	-0.00185	0.0013	-0.0142
Egg	-0.007	-0.0078	-0.0008	-0.0004	-0.0005	0.0004	0.001	0.0004	-0.0018	0.0006	0.0032
Dairy	-0.00473	-0.00397	-0.00023	-0.0003	-0.0004	0.000233	-0.00103	3.33E-05	-0.00287	-0.00147	-0.01547
Aquatic	-0.0139	-0.0122	-0.0019	-0.0006	-0.0012	0.0008	0.0009	0.0002	-0.0048	0.0021	-0.021

A.4 Cross price elasticity of demand in rural areas (continued)

	Pork	Beef	Mutton	Poultry	Egg	Dairy	Aquatic
Rice	-0.0005	-0.0001	-0.0001	-0.0004	-0.0005	0	-0.0007
Wheat	-0.0004	-0.0001	-0.0001	-0.0004	-0.0006	0	-0.0005
Maize	-0.0004	0	-0.0001	-0.0003	0.0001	0.0002	-0.0001
Tubers	0	0	0	0	0	0	0
Other grain	0.0022	0.0001	0.0001	-0.0003	0.0002	0.0001	0
Soybean	0.0008	0.0004	0.0007	0.0008	0.0013	0.0005	0.0028
Oil crop	0.0075	0.0004	0.0003	0.0021	0.0003	0	0.0011
Sugar crop	0.002	0.0005	0.0005	0.001	0.001	0.0002	0.001
Vegetable	-0.0027	-0.0006	-0.0004	-0.0011	-0.001	-0.0002	-0.0011
Fruits	-0.0077	-0.0009	-0.0006	0.0016	-0.0004	-0.0003	0.0015
Non-food	-0.0146	-0.0008	-0.0006	-0.0022	-0.0014	-0.0002	-0.0016
Pork	-0.00107	0.00026	0.00018	0.00062	0.00036	0.00004	0.00038
Beef	0.0241	-0.01079	0.0097	0.0087	0.0036	-0.0003	-0.0013
Mutton	0.0251	0.0145	-0.01147	0.0087	0.0026	-0.0003	-0.0013
Poultry	0.0114	0.00175	0.00115	-0.00382	0.0043	-0.00015	0.00185
Egg	0.0178	0.0018	0.0009	0.0098	-0.01895	0.0048	0.0012
Dairy	0.000233	-0.0004	-0.00027	-0.001	0.010833	-0.00453	-0.00077
Aquatic	0.0111	-0.0006	-0.0004	0.0034	0.0004	-0.0002	-0.00067

A.5 Price elasticity of crop sown area

	Rice	Wheat	Maize	Tubers	Other grain	Soybean	Oil crop	Sugar crop	Vegetable	Fruits	Cotton
Rice	0.28	-0.066	-0.044	-0.0137	-0.0137	-0.0137	-0.0137	-0.0137	-0.0137	-0.0137	-0.0137
Wheat	-0.074	0.26	-0.0378	-0.011	-0.011	-0.011	-0.011	-0.011	-0.011	-0.011	-0.011
Maize	-0.0611	-0.0473	0.26	-0.0115	-0.0115	-0.0115	-0.0115	-0.0115	-0.0115	-0.0115	-0.0115
Tubers	-0.0457	-0.0329	-0.028	0.22	-0.0126	-0.0126	-0.0126	-0.0126	-0.0126	-0.0126	-0.0126
Other grain	-0.0629	-0.0445	-0.0417	-0.0179	0.26	-0.0088	-0.0088	-0.0088	-0.0088	-0.0088	-0.0088
Soybean	-0.0425	-0.0307	-0.0253	-0.0116	-0.0077	0.1	0.008	0.008	0.008	0.008	0.008
Oil crop	-0.0376	-0.0272	-0.0224	-0.0103	-0.0068	0.0071	0.4	-0.0657	-0.0657	-0.0657	-0.0657
Sugar crop	-0.2859	-0.2052	-0.1703	-0.0786	-0.0517	0.0541	-0.4993	0.59	0.2923	0.2923	0.2923
Vegetable	-0.0517	-0.0376	-0.0292	-0.0138	-0.0103	0.0091	-0.0867	0.0528	0.34	-0.0563	-0.0563
Fruits	-0.075	-0.0543	-0.0425	-0.0202	-0.0149	0.0133	-0.1254	0.0749	-0.0839	0.38	0.008
Cotton	-0.0828	-0.0597	-0.0512	-0.0232	-0.0137	0.0166	-0.1574	0.0929	-0.1201	0.0112	0.3

A.6 Price elasticity of livestock production

	Pork	Beef	Mutton	Poultry	Egg	Dairy	Aquatic
Pork	0.5						
Beef		0.5					
Mutton			0.5				
Poultry				0.55			
Egg					0.55		
Dairy						5.5	
Aquatic							0.5

A.7 The share of feeding modes in livestock production

Livestock	Mode	2005	After 2015
Pork	Backyard	0.217	0.17
	Specialized	0.483	0.38
	Commercial	0.3	0.45
Beef	Backyard		
	Specialized	0.8	0.7
	Commercial	0.2	0.3
Mutton	Backyard		
	Specialized	0.8	0.7
	Commercial	0.2	0.3
Poultry	Backyard		
	Specialized	0.35	0.3
	Commercial	0.65	0.7
Egg	Backyard		
	Specialized	0.6	0.5
	Commercial	0.4	0.5
Dairy	Backyard		
	Specialized	0.7	0.6
	Commercial	0.3	0.4
Aquatic	Backyard		
	Specialized	0.6	0.55
	Commercial	0.4	0.45

A.8 The use share of grains in the feed industry

Livestock	Mode	Rice	Wheat	Maize	Tubers	Other
Pork	Backyard	0.29	0.13	0.19	0.15	0.04
	Specialized	0.31	0.15	0.15	0.13	0.04
	Commercial	0.08	0.03	0.58		
Beef	Backyard					
	Specialized		0.06	0.15	0.04	0.09
	Commercial		0.02	0.6		
Mutton	Backyard					
	Specialized		0.06	0.15	0.04	0.09
	Commercial		0.02	0.6		
Poultry	Backyard					
	Specialized	0.13	0.05	0.17	0.06	0.12
	Commercial	0.01	0.02	0.55		
Egg	Backyard					
	Specialized	0.14	0.04	0.17	0.05	0.1
	Commercial	0.02	0.02	0.53		
Dairy	Backyard					
	Specialized		0.06	0.16	0.04	0.09
	Commercial		0.02	0.6		
Aquatic	Backyard					
	Specialized		0.08	0.25	0.03	0.08
	Commercial		0.04	0.18		

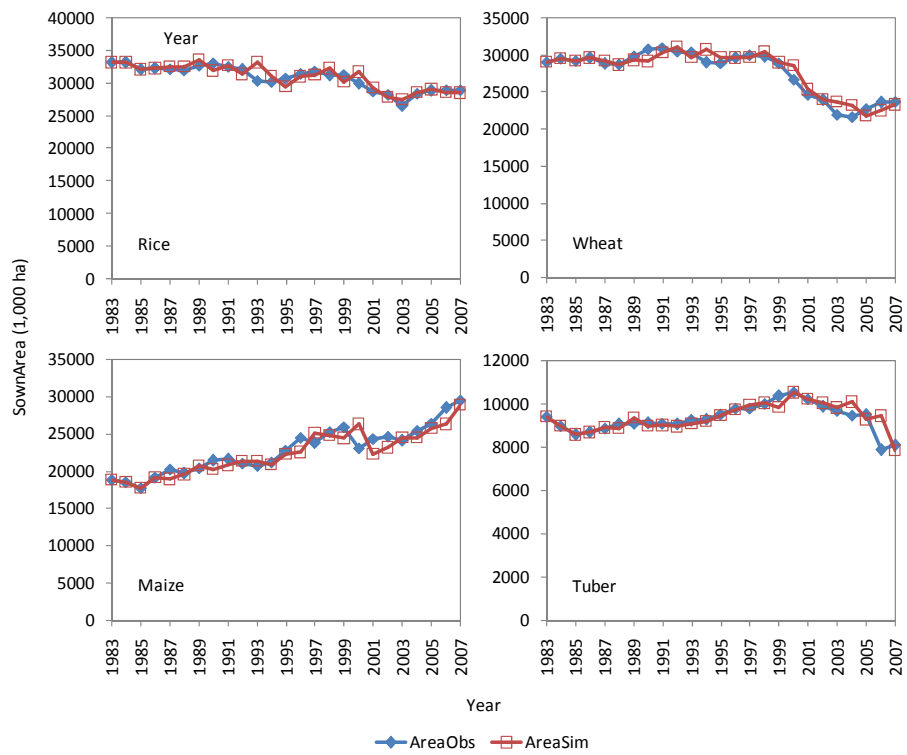
A.9 The feed-meat conversion rates in three feeding modes

Livestock	Mode	2005	After 2015
Pork	Backyard	2.1	2.1
	Specialized	2.9	2.9
	Commercial	3.5	3.5
Beef	Backyard		
	Specialized	1.5	1.5
	Commercial	2.5	2
Mutton	Backyard		
	Specialized	1.5	1.5
	Commercial	2.5	2
Poultry	Backyard		
	Specialized	2.5	2.5
	Commercial	2	2
Egg	Backyard		
	Specialized	2	2
	Commercial	2.5	2.2
Dairy	Backyard		
	Specialized	0.4	0.4
	Commercial	0.3	0.3
Aquatic	Backyard		
	Specialized	1.8	1.8
	Commercial	2	1.8

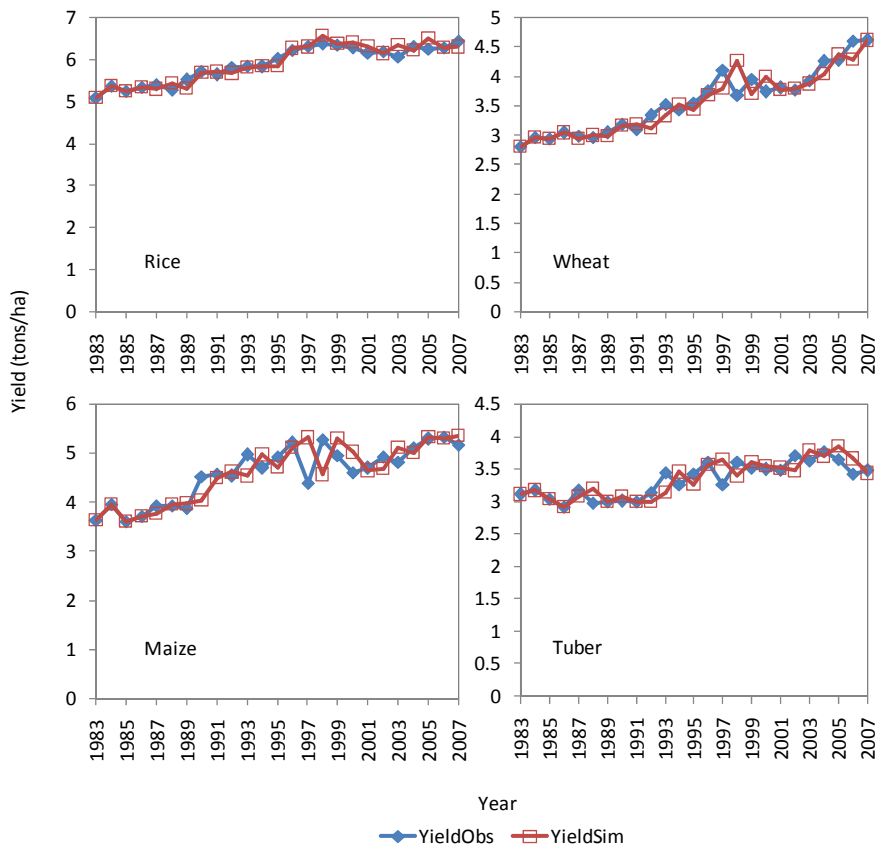
Appendix B Terms, Definitions and Figures

B.1 Terms and definitions

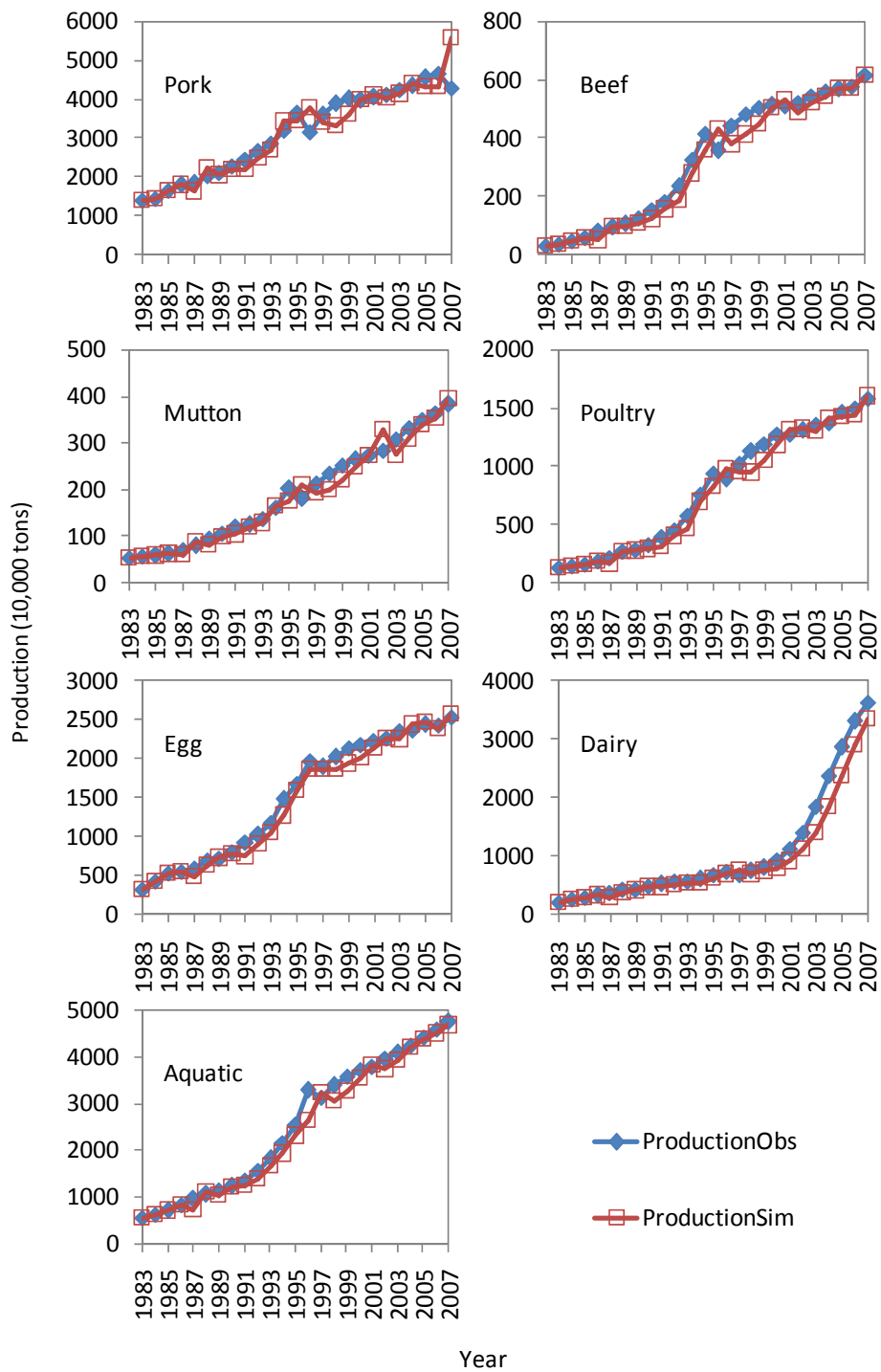
term	Definition
Grain	Rice, wheat, maize, tubers, other coarse grains and beans (including soybean)
Fine grain	Rice and wheat
Coarse grain	sorghum, millet, oats, and miscellaneous beans, except maize
Starch	Tubers including sweet potato and potato
Engel's coefficient	The % of expenditure on food in the total consumption expenditure. Engel's coefficient = $\frac{\text{ExpenditureOnFood}}{\text{TotalConsumptionExpenditure}} \times 100\%$
Cobb-Douglas function	$Q = \alpha \cdot \prod_i X_i^{\beta_i}$, where X_i is the quantities of input factors, such as capital, labour, and land; the Q is the quantity of output; and α and β are the empirical parameters.



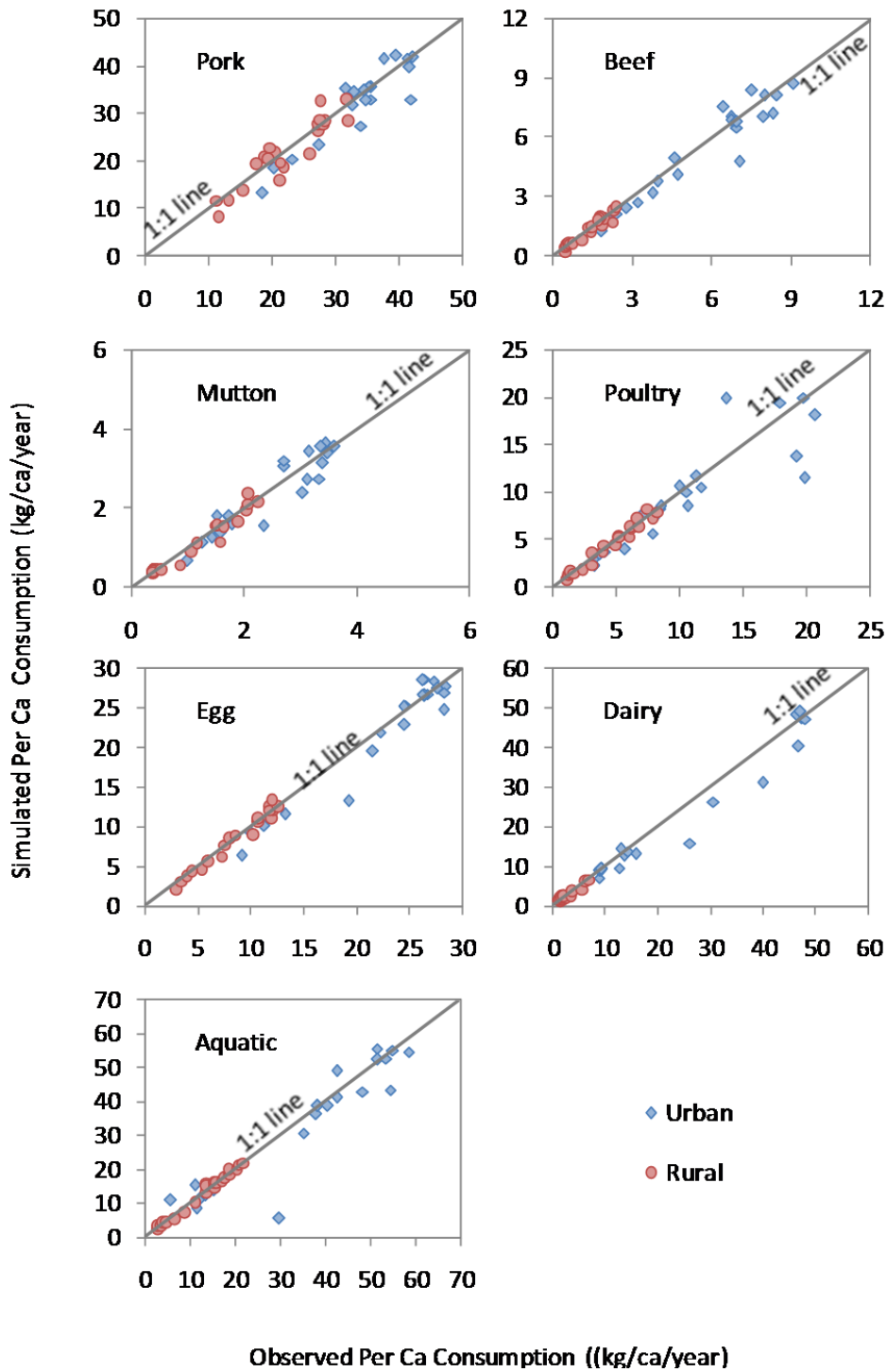
B.2 Historical (AreaObs) and simulated (AreaSim) sown area of 4 main staples (i.e. rice, wheat, maize, tuber).



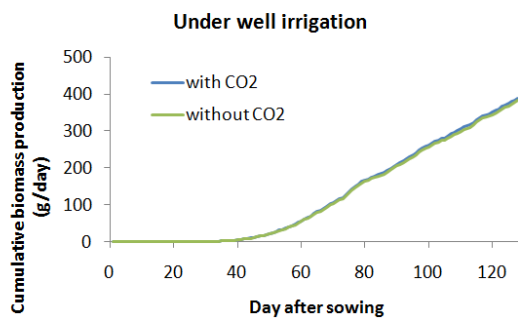
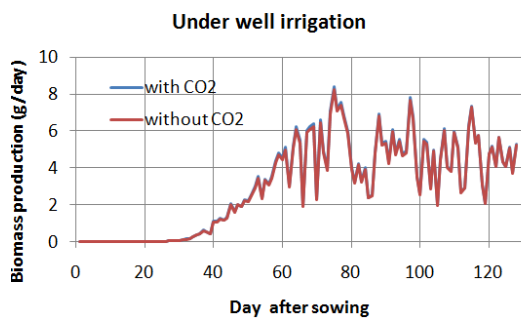
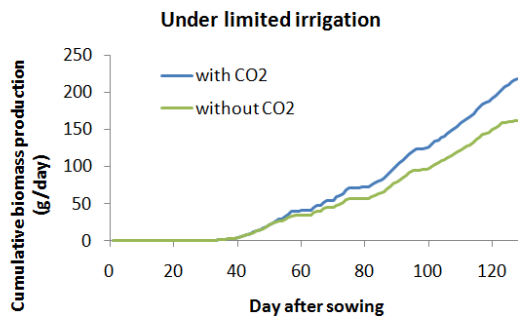
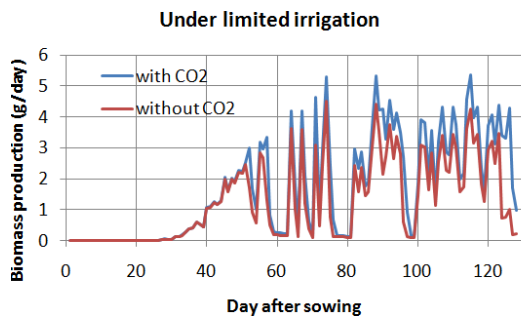
B.3 Historical (YieldObs) and simulated (YieldSim) yield of 4 main staples (i.e. rice, wheat, maize, tuber).



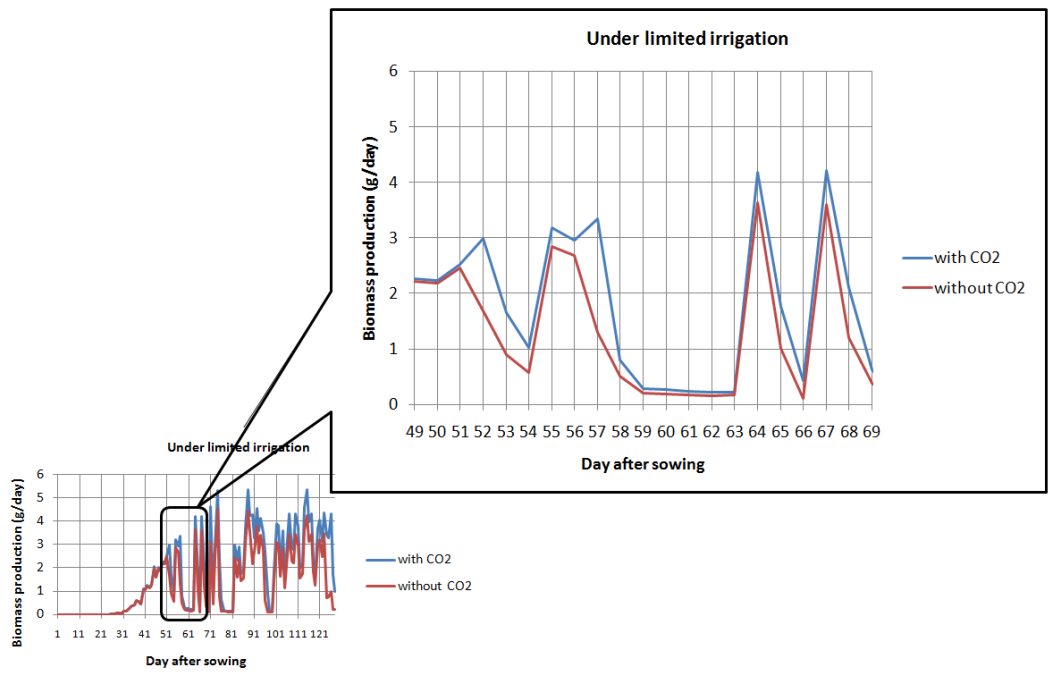
B.4 Historical (ProductionObs) and simulated (ProductionSim) production of livestock products.



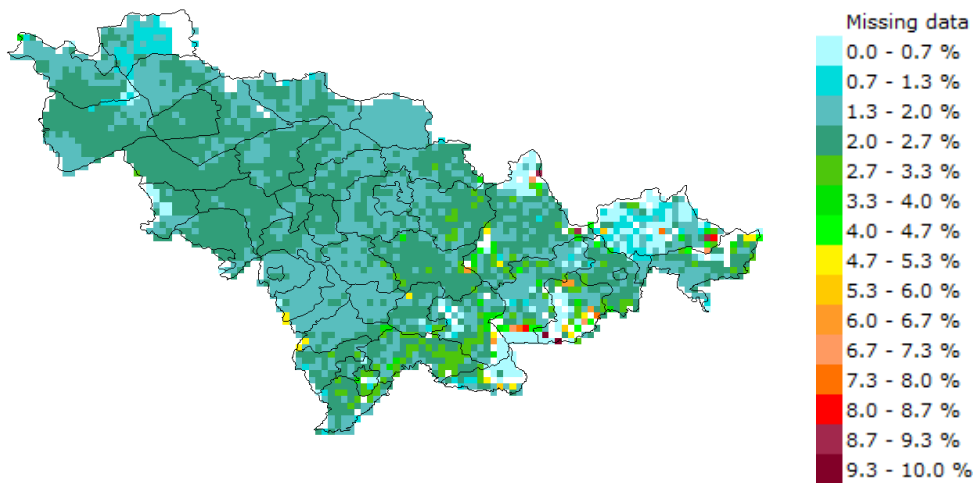
B.5 Historical and simulated per capita consumption of livestock. The urban and rural are shown in blue and red dot separately. The gray line in the chart is the 1:1 line of the historical and simulated data.



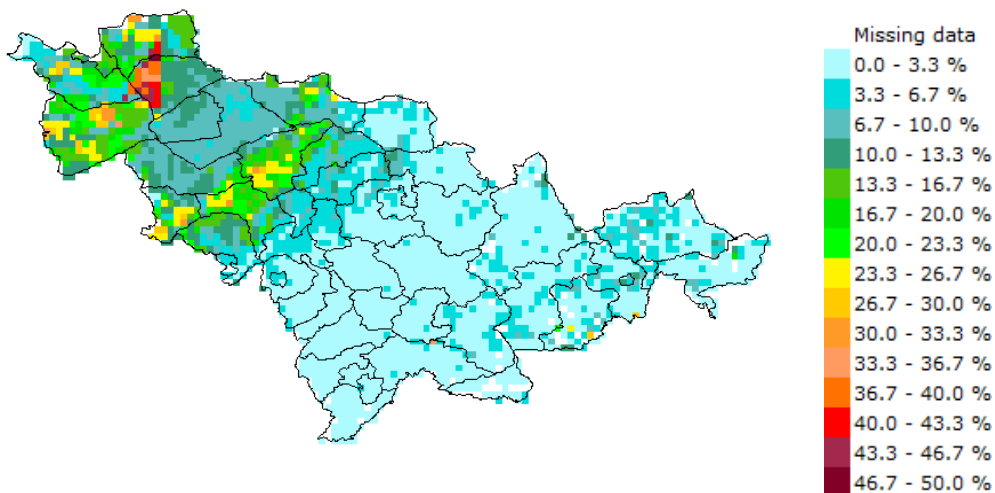
B.6 The biomass productions of maize under the limited and sufficient irrigation at a sample grid (123.46E longitude and 45.6N latitude), with and without considering CO₂ fertilizer effect. On the left, two figures are daily biomass productions(g/day): the top chart gives the daily biomass production under limited irrigation (with an annual irrigation quota = 350mm) scenario; and the bottom one gives that under sufficient irrigation (or called well irrigation, provide enough water to crop) scenario the . On the right are the cumulative biomass productions(g/day).



B. 7 An example of water stresses on daily biomass production of maize caused by insufficient water irrigation at a sample grid (123.46E longitude and 45.6N latitude), with and without considering CO₂ fertilizer effect.



B.8 The different between the reduction of baseline maize yield with and without considering CO₂ fertilization effect under the sufficient irrigation and A1FI climate scenario in 2020, Jilin province. The positive value means the reduction with considering CO₂ effect is lower than that without considering CO₂ effect.



B.9 The different between the reduction of baseline maize yield with and without considering CO₂ fertilization effect under the limited irrigation (annual irrigation quota = 350mm) and A1FI climate scenario in 2020, Jilin province. The positive value means the reduction with considering CO₂ effect is lower than that without considering CO₂ effect.