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# Scenario-based assessment of future food security

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**Abstract:** This paper presents a scenario-based assessment of global future food security. To do that, the socio-economic and climate change scenarios were defined for the future and were linked to an integrated modeling framework. The crop yields simulated by the GIS-based Environmental Policy Integrated Climate (EPIC) model and crop areas simulated by the crop choice decision model were combined to calculate the total food production and per capita food availability, which was used to represent the status of food availability and stability. The per capita Gross Domestic Product (GDP) simulated by IFPSIM model was used to reflect the situation of food accessibility and affordability. Based on these two indicators, the future food security status was assessed at a global scale over a period of approximately 20 years, starting from the year 2000. The results show that certain regions such as South Asia and most African countries will likely remain hotspots of food insecurity in the future as both the per capita food availability and the capacity of being able to import food will decrease between 2000 and 2020. Low food production associated with poverty is the determining factor to starvation in these regions, and more efforts are needed to combat hunger in terms of future actions. Other regions such as China, most Eastern European countries and most South American countries where there is an increase in per capita food availability or an increase in the capacity to import food between 2000 and 2020 might be able to improve their food security situation.

**Keywords: scenario; food security; per capita food availability; per capita GDP; model; assessment**

## 1 Introduction

Although human has made a great success in continuously increasing food supply to meet the demands of their populations over the past decades, there are still a number of people

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living in an insecure food situation. According to the Food and Agriculture Organization (FAO) report, approximately 1.02 billion people are undernourished worldwide in 2009 (FAO, 2009). More and better-targeted investments, innovations, and policy actions are thus required to focus on human resources, rural infrastructure, water resources, and farm- and community-based agricultural and natural resources management to achieve the goal of food security (Rosegrant and Cline, 2003). All these are necessarily based on a better understanding of the dynamics, risks and forces that shape the factors affecting food security. In this regard, food security assessment will be high on the policy agenda for most countries (Godfray *et al*., 2010).

Referring to literature overview, there has been considerable progress in assessing food security at different space and time scales as a consequence of changes in population, world trade, changing agricultural policies and production technology, and the diversification of the regional economy (Ewert *et al*., 2005; Parry *et al*., 2005; Adejuwon, 2006; Deng *et al*., 2006; Lobell *et al*., 2008; Battisti and Naylor R, 2009; Tao *et al*., 2009). All these previous studies have provided important information about the condition of food security, and they have been used to support policy enactment for fighting against the food crisis and eradicating poverty and hunger.

However, despite the importance of future food security for human-environment system, our knowledge of them is usually precarious. How will future food security status evolve in time and what are the major reasons of these changes? Indeed, we have little precious knowledge of the future food security status at all. Improved foresight of food security can help to better inform policy decisions. Because the future has not happened, it offers no facts, presents or testimonies, and provides no means for immediate verification. Uncertainties in social, political and economic development both globally and regionally make it not possible to predict future food security. Instead, it is possible to explore what might happen given certain assumptions about future societal developments and environmental changes through the construction of scenarios. Scenario are usually used to explore alternative, plausible outcomes if basic assumptions about the people, places and things that might constitute the world of future, how these constituents might interact, and the impacts that might transpire, are changed. Thus, scenario-based studies provide an appropriate tool to develop plausible visions of future pathways of food security (Shearer, 2005). This study aims to make an assessment of future food security at a global scale using an integrated modeling framework under a given scenario condition.

## 2 Methods

### 2.1 General framework

Food security exists when all people, at all times, have physical, social, and economic access to sufficient, safe, and nutritious food that meets their dietary needs and food preferences for an active and healthy life (Schmidhuber and Tubiello, 2007). This definition comprises four key dimensions of food security: availability, access, utilization and stability. Food availability relates to the availability of sufficient food, i.e., to the overall ability of the agricultural system to meet food demand. Access to food refers to the ability of a unit of individuals to obtain access to acquire appropriate foods for a nutritious diet. Food utilization refers to individual or household capacity to consume and benefit from food. More recently, as climate change issues have caught great attention from the world, food stability, which relates to individuals who are at high risk of temporarily or permanently losing their access to the resources needed to consume adequate food, is also considered one important component of food security (Ericksen, 2008).

Figure 1 shows the general framework used for future food security assessment in this study. Under this framework, the biophysical, social and economic factors were combined together to assess the future food security. Food production as a biophysical factor can directly influence the local food supply. Future food supply will have to heavily rely on domestic production when the purchasing power is not strong enough. Population as a social factor can largely influence the total demand for food. A higher population growth generally requires an increasing amount of food supply, and may impose threat to local food security. Gross Domestic Product (GDP) as an economic factor can impact the purchasing power of consumers. Although some countries can produce enough food to feed their entire population, there are still a large number of hungry populations because many people are very poor and cannot afford to purchase sufficient food on the market. Moreover, when local food production cannot meet the growing demand for food, a high per capita GDP can allow their people to purchase the needed food from the market, and thus remains food security.

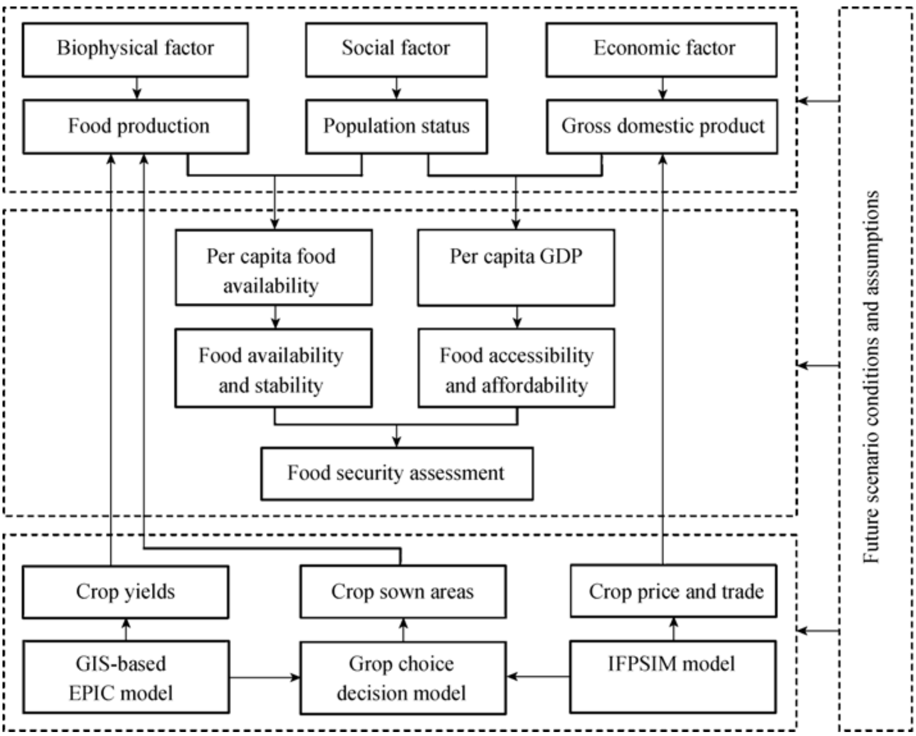


**Figure 1** General framework for assessment of future food security

Based on these three factors, two indicators were used to cover the four dimensions of food security. One indicator denotes the per capita food availability and was used to represent the status of food availability and stability. The other indicator describes the per capita GDP and was used to reflect the situation of food accessibility and affordability. The per capita food availability was determined by total food production and population, while the per capita GDP was determined by total GDP and population. These two indicators were linked to an integrated modeling framework, which includes three models. The total food production was defined by crop yields and crop areas. Of these, the crop yields were analyzed with the GIS-based Environmental Policy Integrated Climate (EPIC) model, while the crop areas were estimated with the crop choice decision model. The per capita GDP was analyzed with the International Food Policy and Agricultural Simulation (IFPSIM) model. All of these three models were driven and limited by a list of given scenario conditions and assumptions, which are archetypal descriptions of alternative images of the future.

## 2.2 Model constructions

### **2.2.1** GIS-based EPIC model

The EPIC model was initially developed by United States Department of Agriculture, Agricultural Research Service in 1984 with the purpose of understanding the relationship between soil erosion and crop productivity. In EPIC, a general plant growth model with crop-specific parameters is used to simulate the growth of rice, wheat, maize, sorghum and soybean, among others. The EPIC was originally a site-specific model, and uses a daily time increment to simulate weather, hydrology, soil erosion by wind and water, nutrient cycling, tillage, crop management and growth, and field scale costs and returns. It is thus not possible to use the original EPIC model directly for large-area applications. However, by integrating EPIC with GIS, the GIS-based EPIC model gains the possibility of estimating crop yields from field level to small country or sub-regional scale (Yang *et al*., 2007). It treats each grid cell as a site and simulates the crop-related processes for each predefined grid cell with spatially distributed inputs.

In this study, the GIS-based EPIC model (Version 8120) was adopted to estimate the potential yields of different crop types under a given biophysical and agricultural management environment (Wu *et al*., 2008). The EPIC calculates daily potential biomass as a function of solar radiation, leaf area index (LAI), and a crop parameter for converting energy to biomass. The potential plant growth is driven by photosythentically active radiation. The amount of solar radiation captured by the crop is a function of LAI and the amount of solar radiation converted into plant biomass is a function of the crop-specific radiation use efficiency. The daily potential biomass is decreased by stresses caused by water shortage, temperature extremes, nutrient insufficiency and soil aeration inadequacy. The daily potential biomass is decreased in proportion to the severity of the most severe stress of the day. Crop yield is estimated by multiplying above-ground biomass at maturity by a water stress adjusted harvest index (Williams *et al*., 1990).

### **2.2.2** Crop choice decision model

This crop choice decision model developed by Wu *et al*. (2007a and 2007b) was used to analyze the changes in crop areas by investigating changes in crop choice decisions among a variety of available alternatives. The general hypothesis of this model is that the sown area of particular crops is directly linked with human decisions on crop choice for farmland. Thus, it is possible to track and estimate changes in the crop sown areas over time and space through capturing the essential features of individual human decision processes on crop choice. To do that, the term "utility" was introduced to describe a mathematical function that expresses the preferences of discrete crop choices of land users in a utility maximizing framework. Using these relative crop utilities, farmers seek to maximize their income by allocating their lands to those crop cultivation activities that they perceive will provide the greatest return or that will carry the least risk. The allocation of land to specific crop types is then translated into the conversion of an area from one crop coverage to another. The utility ($U_i$) of each possible crop is assumed to comprise two parts:

$$U_i = V_i + \varepsilon_i \tag{1}$$

where $V_i$ is the systematic and observed component of the latent utility for crop *i*, and $\varepsilon_i$ is the random or "unexplained" component.

Because of the random component, scientists can never expect to predict choices perfectly. This leads to the expression for the probability of choice. Assuming that the random error terms are distributed independently and identically and follow the Gumbel distribution, the probability that a crop, *i*, is chosen for cultivation can be estimated using the Multinomial Logit model (Seo and Mendelsohn, 2008; Wu *et al*., 2008):

$$P_i = e^{V_i} \Big/ \sum_{i=1}^{N} e^{V_i} \tag{2}$$

where *i* denotes the crop types used for analysis ($i=1, 2, \ldots, N$), $P_i$ is the probability for crop type *i*, and $V_i$ is the observed utility of crop type *i*, which can be stated as:

$$V_i = a_i + \sum_{j=1}^{M} b_j x_j \tag{3}$$

where $a_i$ is an alternative specific constant for crop type *i*, *j* is the number of explanatory variables ($j=1, 2, \ldots, M$), *x* is the explanatory variable, and $b_j$ is the coefficient to be estimated for the variable $x_j$.

#### **2.2.3** IFPSIM model

The IFPSIM model is a multi-commodity, multi-regional and multi-period world agricultural trade and policy simulation model developed and designed on the Ohga Model Building System (Ohga and Yanagishima, 1996). It is a partial equilibrium and interactive model, allowing for the simultaneous determination of supply, demand, trade, stock levels and prices for 14 commodities of the world. In this study, the IFPSIM was utilized to evaluate the price of crops in the international market.

Food demand in each country or region is divided into three kinds: demand for food for human consumption, for livestock and for the production of processed food, and it is described by individual income, population and the consumer purchase price of the crop in question. Food supply in the same country or region is comprised of the supply of crops and the supply of livestock products. The supply of crops is described by crop yields, sown areas and the producer price for each crop. The total food demand or supply in the world is determined from the summation of the demand or supply in each region. In the international market, crop price is determined by the level at which world supply is equal to world demand, where all variables are simultaneously determined, while world market clearing prices are derived by equating the sum of gross imports and the sum of gross exports (Ohga and Yanagishima, 1996).

## 2.3 Scenario development and parameterization

In this study, a scenario describing the socio-economic development and climate change for the future was constructed to drive the models so as to make an assessment of future food security. The model application was designed to run over a period of approximately 20 years, starting from the year 2000. The reason why the future period of 2000–2020 was selected is mainly due to two reasons. First, this time period is most relevant to large agricultural investments, which typically take 15 to 30 years to realize full returns. Second, a shorter period will lead to smaller changes in some factors, such as adaptation, diet patterns, etc (Lobell *et al*., 2008). According to the FAO statistical database, the four crops of rice, maize, wheat and soybean make up nearly 80% of the global cereal harvested area and 86% of global cereal production. Only these four major crops were taken into account in this study.

### **2.3.1** Socio-economic scenarios

The socio-economic scenario describes the key elements, such as demography, economic development, technology, and policy interventions, which together provide the description of a possible future state of the world. The socio-economic scenario organizes the perceptions on the driving forces for crop price and crop yield model.

In this study, the global-scale scenario of socio-economic development was taken from the Intergovernmental Panel on Climate Change (IPCC) Special Report on Emissions Scenarios (SRES) framework. The four SRES storylines (A1, A2, B1 and B2) represent different world futures in two dimensions: a focus on economic or environmental concerns, and global or regional development patterns (Arnell *et al*., 2004). There is little difference between the different scenarios in terms of GDP and population development in the relatively short time span between 2000 and 2020. Thus, this study mainly focused on the A1 scenario because this scenario tends to highlight potential future problems the most at the global scale (Westhoek *et al*., 2006). The recent downscaled population and GDP data for A1 scenario by the International Institute for Applied Systems Analysis (IIASA) were used here for future simulation. The IIASA datasets were produced with a 30 arc-minute resolution for the period 2000–2100. The projections of future population and GDP follow the qualitative scenario characteristics of the original SRES scenarios (Grübler *et al*., 2007).

As for the modern agricultural technology, Genetically Modified Organism (GMO) was taken into consideration in estimation of future crop yields as it is one of the highest rates of crop technology adoption in agriculture and reflects the growing acceptance of GM crops by farmers in both industrial and developing countries (Brookes and Barfoot, 2006). To understand the future scenarios of GM crop development and their yield effects in our analysis, this study followed the historical trend of average annual growth rate and average yield effects of GM crops for major countries (such as USA, Argentina, Brazil, China, Canada and India). The impacts of GMO were then embedded into the GIS-based EPIC model to simulate the crop yields under future scenario conditions. Furthermore, the future scenarios for major agricultural policy intervention, such as the fixed Direct Payment program in USA and the Common Agricultural Policy in European commission, were also included. However, some other socio-economic variables, such as road accessibility and agricultural management measures (irrigation, pesticides and fertilizers), were assumed to be the same as they are currently in the future simulation since it is not possible to collect these data for the future.

### 2.3.2 Climate change scenarios

The climatic scenario defines the major features of future climate change, which may strongly drive changes in crop yield in the future. In this study, for constructing the future climate change scenario, both the historical and future monthly climate data on maximum temperature, minimum temperature and precipitation between 2000 and 2020 were obtained from the high resolution projections of MIROC (Model for Interdisciplinary Research on Climate) 3.2 (K-1 model developers, 2004). This dataset consists of monthly time-series of climate data for the period 1990–2100 covering the global land surface at a grid resolution of 1.1° of latitude and longitude. In order to reduce the abnormal variations of climate change, the 10-year average data was calculated for the year 2000 (1991–2000) and 2020 (2011–2020).

However, it should be noted that the coarse spatial resolution of MIROC and large uncertainty in their output make it inappropriate to directly use the projection data for yield simulation with the GIS-based EPIC model. It is thus necessary to calibrate the projected climate data before using them. In this study, a statistical algorithm was used to calibrate the original MIROC dataset by taking the historical observation climate data from the Climate Research Unit (CRU) of the University of East Anglia as the reference data. To do that, a grid by grid regression analysis was made first between the MIROC-simulated data for the historical period of 1901–2000 and the CRU observed data for the same period of 1901–2000. And then the regression function was applied to the MIROC projected future data for the period of 2000–2020 to calibrate the bias for each grid cell.

## 2.4 Steps for future food security assessment

Based on the crop yields and crop areas, the changes in total food production were firstly assessed by comparing the food production in the year 2020 with those in the baseline year 2000. Change ratio of total food production (*CR_p*) was computed using the following Equation 4.

$$CR\_p = \frac{\sum_{i=1}^{4} Y_i^{2020} * A_i^{2020}}{\sum_{i=1}^{4} Y_i^{2000} * A_i^{2000}} \tag{4}$$

where *CR_p* is change ratio of total food production, *Y* is the crop yield for crop type *i*, *A* is the crop areas for crop type *i*, and *n* is the total number of crops.

A *CR_p* value higher than one in a grid cell means the total food production in that grid cell will increase in the future, while a *CR_p* value lower than one means the total food production will decrease. Yet, it should be noted that assessment of food security by thinking only the total food production and disregarding the population status remains limited. Even though the overall food production will not decrease for some regions, per capita food availability may decrease when considering future population growth. To understand whether the projected changes in total food production will influence the overall food availability, relative changes in per capita food availability (*CR_a*) for the same period were calculated using the following Equation 5.

$$CR\_a = \frac{\sum_{i=1}^{4} Y_i^{2020} * A_i^{2020} \Big/ POP^{2020}}{\sum_{i=1}^{4} Y_i^{2000} * A_i^{2000} \Big/ POP^{2000}} \tag{5}$$

where $CR\_a$ is change ratio of per capita food availability, $Y$ is the crop yield for crop type $i$, $A$ is the crop areas for crop type $i$, and $POP$ is total population.

Secondly, a separate analysis for changes in per capita GDP was undertaken because it can strongly impact the purchasing power and determine whether a country or region is able to import more food from outside during the study period. The overall global increase in per capita GDP between 2000 and 2020 was first computed as done in Liu *et al*. (2008). The relative difference between the growth rate of per capita GDP in a grid cell with the global average per capita growth rate was then calculated. In case that the growth rate of per capita GDP in a grid cell is higher than the global average per capita growth rate during the period of 2000–2020, it was assumed that people in this grid may have more purchasing power and financial capacity to import food when the per capita food availability in this grid decreases in the future. In case that the growth rate of per capita GDP is lower than the global average growth rate, it was assumed that less food per capita will be purchased in that grid cell.

Finally, the changes in per capita food availability and the changes in per capita GDP were combined to examine the hotspots of potential risks of food insecurity for the study period through identifying the areas with both decreased per capita food availability, as well as a slower growth rate of per capita GDP than the average growth rate.

## 3 Results and analysis

### 3.1 Changes in crop yields and crop areas

Figure 2 presents the change ratio of crop yields for four crops during the period of 2000–2020. The results show that except that crop yields of these four crops in many regions remain unchanged in the next 20 years, there are considerable changes in crop yields. According to our results, rice in some regions in northern India, northern China and Japan may benefit more from global climate change, while yields of rice crop in Southeast and South Asia will decrease. Maize yields show an obvious decrease in some regions located in southwestern and northern China, Western Europe, Northern Great Plains in USA and southern Brazil. In other regions, maize gains the increase in yields. Similar to maize, the yields of wheat will be dominantly reduced in 2020 compared to 2000, which is indicated by the change ratio being generally lower than one in most regions. Soybean may benefit from climate change in Argentina and northern China, but it may decrease in Brazil, southern China and Northern Great Plains in USA.

The global geospatial distribution of sown areas for four crops in 2000 and 2020 is shown in Figure 3. For the globe as a whole, rice, maize and wheat crops generally showed a constant growth in global total sown areas during the period of 2000–2020, while soybean crop showed a slight decrease trend during the simulation period. The global totals of sown areas were projected to increase from 151,160 and 207 million ha in 2000 to 204, 208 and 251 million ha in 2020 for rice, maize and wheat, respectively. By 2020, the total sown areas of

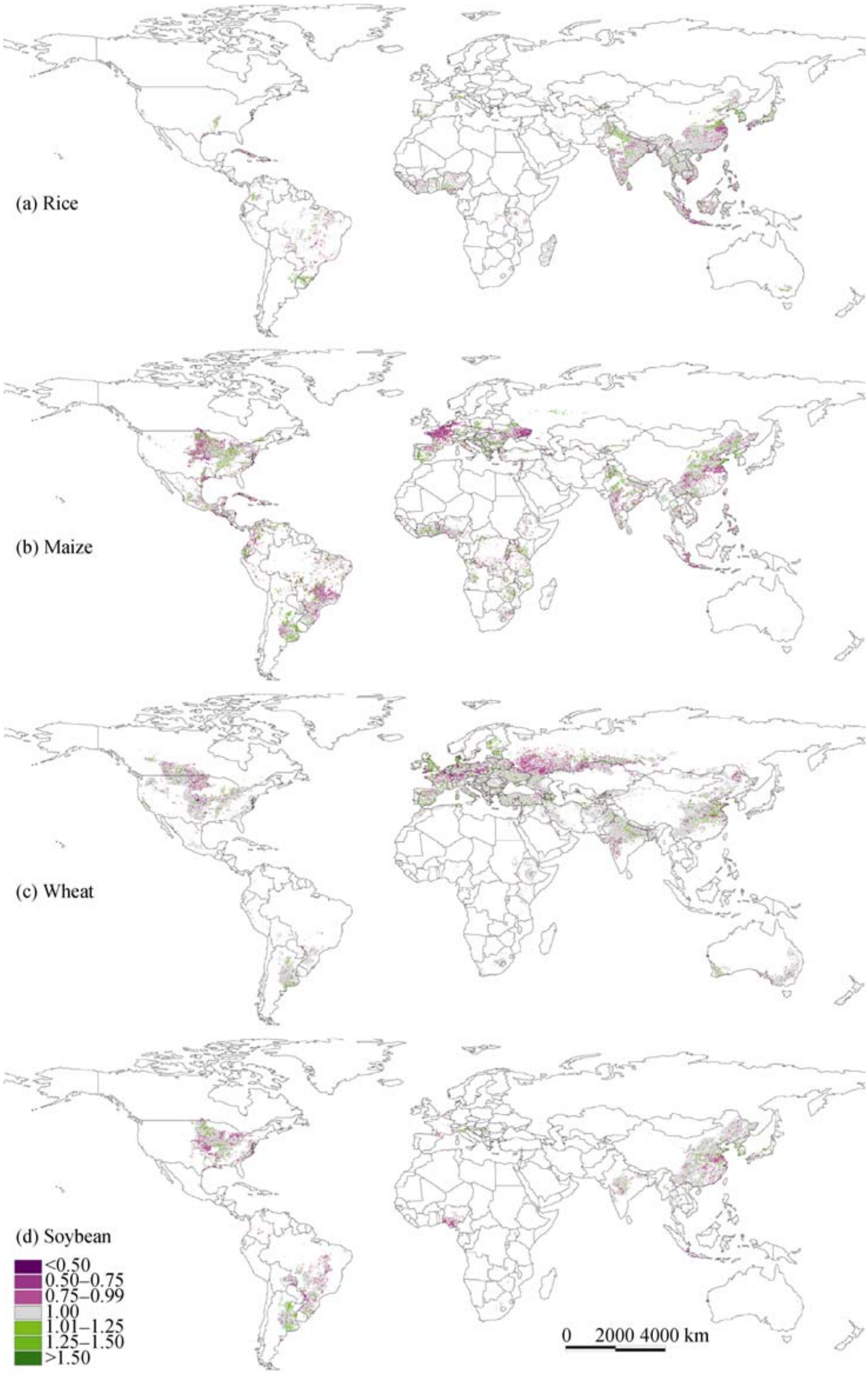


**Figure 2** Changes in crop yields during 2000–2020 for (a) rice; (b) maize; (c) wheat and (d) soybean (Note: the legend less than one means that crop yields will decrease between 2000 and 2020, more than one means that crop yields will increase between 2000 and 2020. For instance, the legend 0.5–0.75 means a reduction between 50%–25%)

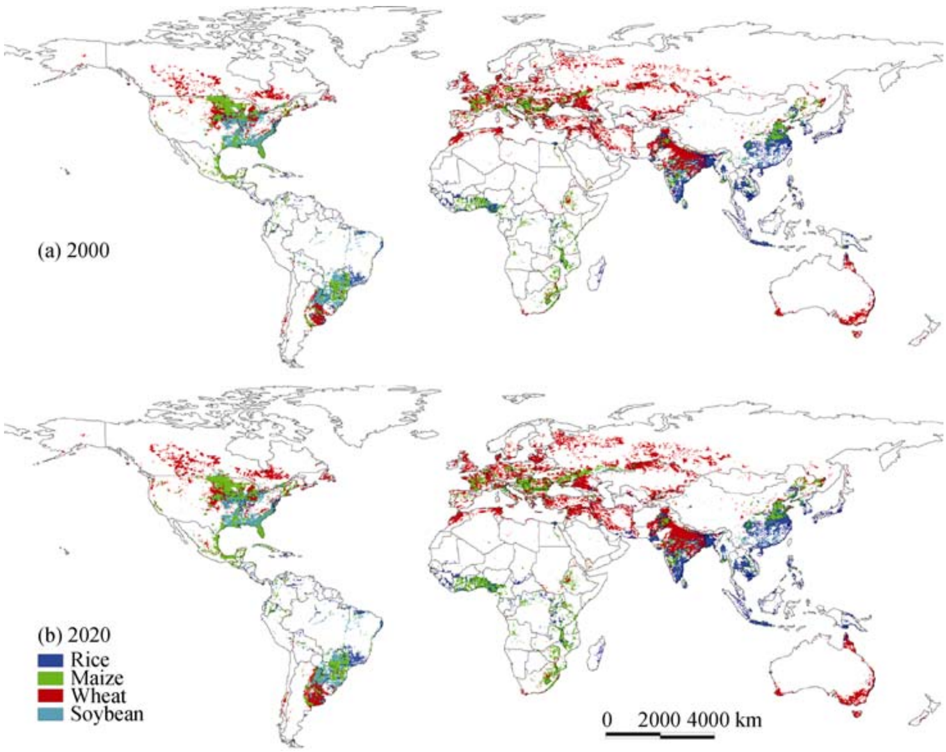


**Figure 3** Global distribution of sown areas for major crops in (a) 2000 and (b) 2020

soybean were projected to be about 86 million ha, with a decrease of 2% with respect to 2000. Figure 4 illustrates the simulated sown areas and their predicted changes for four major crops during the period 2000–2020 in six continental regions. Generally, changes in sown areas of individual crops vary across regions of the world. The sown areas of rice, maize and wheat were predicted to increase at different rates from 2000 to 2020 in each of the continental areas. In particular, rice in Asia, maize in Africa and Latin America, and wheat in Asia and Europe showed a significant increasing trend over time. In Oceania, only wheat crop showed a substantial increase in sown areas while other three crops displayed little or no changes. The changes in sown areas for soybean were uneven across the world.

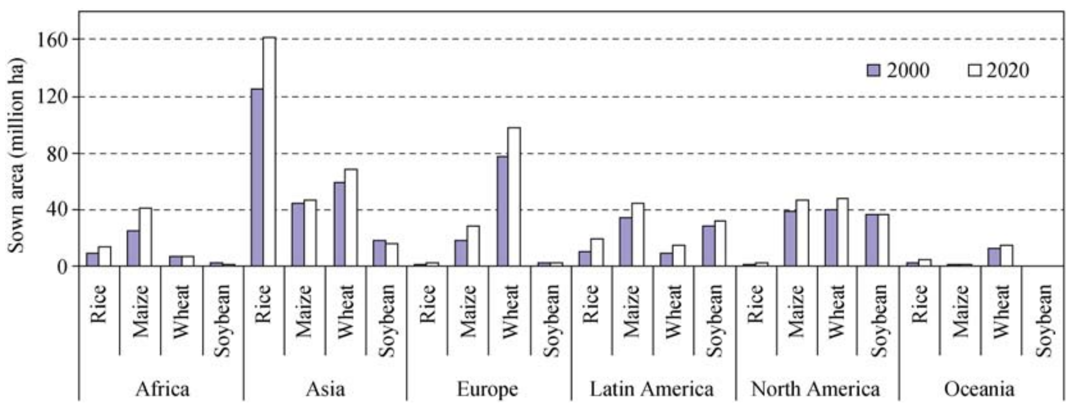


**Figure 4** Changes in sown areas of major crops in different regions during 2000–2020

Sown areas of soybean in Africa, Asia and North America declined, while the other regions showed a tendency to slightly increase the sown areas of soybean.

### 3.2 Changes in per capita food availability and per capita GDP

Figure 5 shows the change ratio of food production (*CR_p*) during the period of 2000–2020. It can be seen that climate change will result in a reduction in total food production in several regions such as southeastern China, South and Southeast Asia, Western and Eastern Europe, Northern Great Plains in USA, Brazil and some African countries. In contrast, climate change will lead to an increase in total food production in some regions in northern China, northern India, Northern Europe, Central USA, Argentina, Australia and some East African countries such as Kenya and Zimbabwe. Considering the population growth, the changes in per capita food availability between 2000 and 2020 may present different trends (Figure 5). Figure 6 shows the changes in per capita food availability (*CR_a*) between 2000 and 2020. A substantial increase in per capita food availability can be found in some parts located in northeastern and southwestern China, Eastern and Southern Europe, USA and Brazil. Noticeable increase can be also found in some regions in Southeast Asia, Argentina,

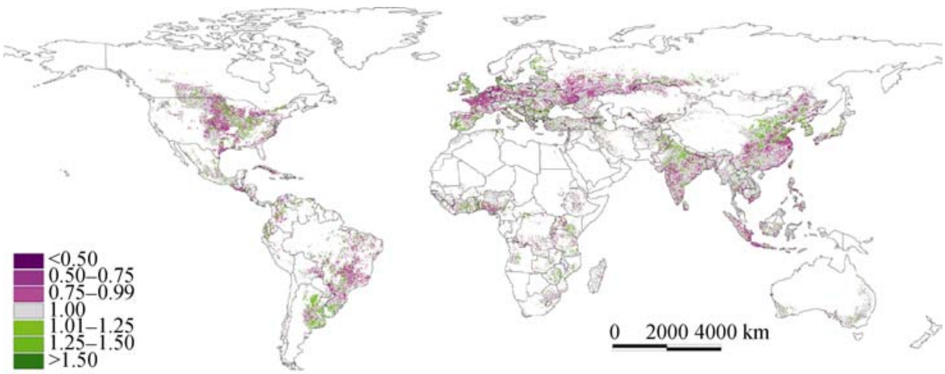


**Figure 5** Changes in total food production during 2000–2020 (Note: the legend less than one means that total food production will decrease between 2000 and 2020, more than one means that total food production will increase between 2000 and 2020. For instance, the legend 0.5–0.75 means a reduction between 50%–25%)

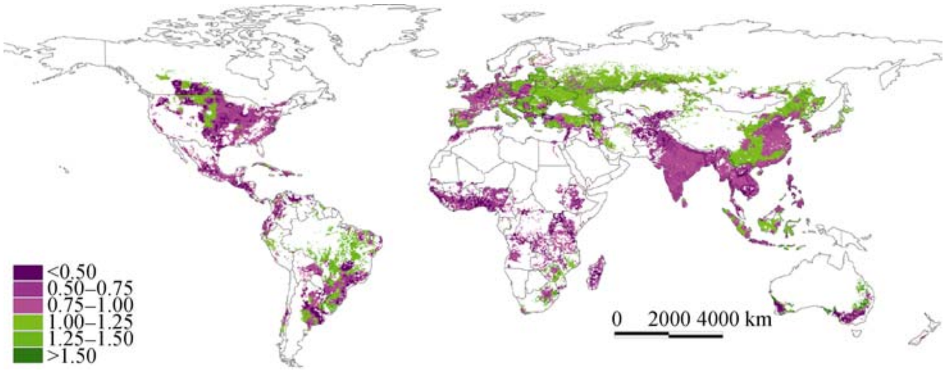


**Figure 6** Changes in per capita food availability during 2000–2020 (Note: the legend less than one means that per capita food availability will decrease between 2000 and 2020, more than one means that per capita food availability will increase between 2000 and 2020. For instance, the legend 0.5–0.75 means a reduction between 50%–25%)

Southeast Africa and Australia. Grid cells with decreased per capita food availability during 2000–2020 are located in northern and southern China, most South and Southeast Asian countries, Western Europe, USA, Brazil, Argentina, and most African countries.

The relative changes in per capita GDP with respect to global average were calculated and shown in Figure 7. Not surprisingly, areas with the highest growth rate of GDP per capita during 2000–2020 are located in developing countries such as China, Southeast Asian countries and Latin American countries. Some North African countries such as Botswana, Mozambique, Morocco and Egypt also have a projected higher growth rate of GDP relative to global average growth rate. These areas with a relative higher GDP growth are likely to have the capacity of being able to import food in the future. The increasing purchasing power in these areas may compensate the decrease in per capita food availability. The areas in particular located in South Asian countries and most African countries are likely to experience a dramatic decrease in the capacity to import food on a per capita basis than currently as the growth rates of GDP in these areas are 35%–50% lower than the world average growth rate between 2000 and 2020. The food supply in these regions will strongly rely on the local food production due to their low capability of purchasing food from outside. It can be also found that most developed countries have the lower growth rate of GDP per capita relative to global average. The lower growth rates of GDP per capita in these developed countries may also have some impacts on their food supply.

### 3.3 Future food security status

Based on the changes in per capita food availability (shown in Figure 6) and the changes in per capita GDP (shown in Figure 7), it is possible to identify the future hotspots of food insecurity by identifying those grid cells where the per capita food availability will decrease and the growth rate of per capita GDP will be below the world average during the period of 2000–2020. These results can be categorized into three classes as shown in Figure 8. Both the classes shown in green tones and blue tones might be able to improve their food security situation due to either an increase in per capita food availability or an increase in the capacity to import food between 2000 and 2020. According to our results, China, most Eastern European countries and most South American countries are not likely to face severe food insecurity in the next 20 years. However, the grid cells in red tones located South Asian and most African countries will likely remain hotspots of food insecurity in the future. In these regions, both the per capita food availability and the capacity of being able to import food will decrease between 2000 and 2020. The local food production may not be able to meet their food demands and their populations are also not able to purchase more foods from outside through trade, thus more efforts are needed to combat hunger in terms of future actions (such as food aid and development programs). It should be noted that although some developed countries such as Western European countries, USA and Japan will also experience both a decrease in per capita per capita food availability and a decrease in per capita GDP, their populations will still be food-secure as their populations less relies on subsistence agriculture and their high capabilities of importing food due to the strong purchasing power and financial support, as well as the substantial adaptive capacity and proactive food management systems.

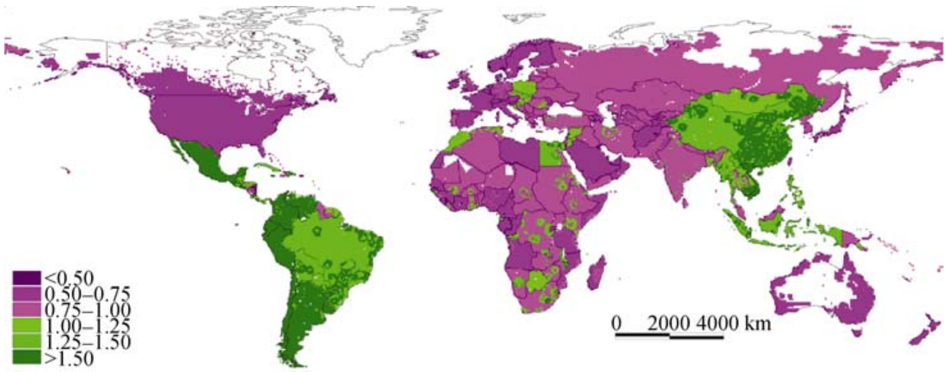


**Figure 7** Changes in per capita GDP during 2000–2020 (Note: the legend less than one means a lower growth rate of GDP than the world average growth rate between 2000 and 2020, and more than one indicates a higher growth rate of GDP than the world average growth rate between 2000 and 2020. For instance, the legend 1.25–1.5 means the growth rate of GDP is 25%–50% higher than the world average growth rate)

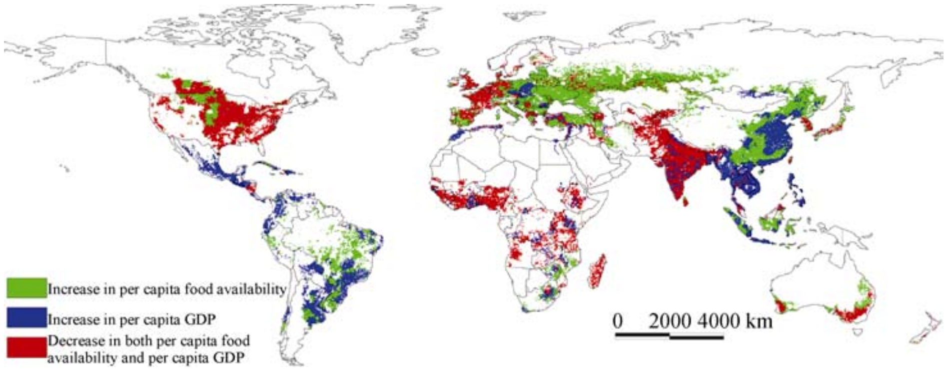


**Figure 8** Future food security status at a global scale

## 4 Conclusions and discussion

This paper presents a scenario-based assessment of global future food security. The socio-economic and climate change scenarios were defined for the future and were linked to an integrated modeling framework. The crop yields simulated by the GIS-based EPIC model and crop areas simulated by the crop choice decision model were combined to calculate the changes in total food production and per capita food availability, which represent the status of food availability and stability. The calculated changes in per capita GDP reflect the situation of food accessibility and affordability. Based on these two indicators, the food security status was assessed at a global scale over a period of approximately 20 years, starting from the year 2000.

The results show that multiple biophysical, social and economic factors can interactively impact the food security status of a certain region, of which low food production associated with poverty is the determining factors to starvation. Thus, those studies on food security assessment by only considering food production or food supply remain rather limited, as food security is concerned not only with food availability but also with access to and stability and utilization of food. Although increases in the food production have resulted in successes in reducing the prevalence of hunger and improving nutrition worldwide, these successes are shadowed by serious concerns about other aspects of food systems that pose threats to social, economic and environmental goals and hence undermine food security. For instance, a number of people went undernourished in African countries not because there is not enough food, but because people are too poor to buy it. The crucial issue for their food security is not whether food is ‘‘available’’, but whether the monetary and non-monetary resources at the disposal of the population are sufficient to allow them access to adequate quantities of food. Thus, to achieve the goal of food security in the future, on the one hand, cultivation intensification will be the dominant means for increasing production in the future as there is little new suitable land that can be brought into cultivation for many regions of the world. Increasing the number of crops sown on a particular area of land or by increasing the yield per unit area of individual crops by continued technological developments, or both, is expected to be the main way to increase food production to meet the demands of food security (Gregory *et al*., 2005; Wu *et al*., 2010). On the other hand, development of effective adaptation to the changing environments is an increasingly urgent agenda for most countries. In particular, adaptation and mitigation measures should be taken soon to combat the adverse effect of climate change on crop production. These can involve management-level adaptation options such as investing in agricultural inputs such as fertilizer rates, irrigation and improved varieties/species, altering the timing of cropping activities, improving the effectiveness of pest and weed control, and water and soil management practices. However, adaptations at this level can be influenced strongly by government policy decisions to establish or strengthen conditions favorable for effective adaptation activities through fostering free trade and promoting investments in new technologies and infrastructure, building adaptation capacity of user community and institutions, and in general modifying the decision-making environment under which management-level adaptation activities typically occur (Howden *et al*., 2007; Brown and Funk, 2008). All these can help to increase steady local and international production, improve fast access to food supplies, and provide secure and stable food supplies for the future.

This study also contains some uncertainties. First, the SRES socio-economic scenario and the MIROC climate change scenario were used to drive the models. All the future scenario interpretations, parameterization were based on judgments that may be subjective, and thus have high uncertainties. When these future scenarios data were used as the input for model simulation, it might contain some uncertainties. Second, the models on which future scenario analysis on food security were made also contain certain uncertainties. Furthermore, this study only considered the globally widespread four crops and ignored other region-specific crop types, and considered limited adaptive capacity such as the use of new crop varieties and crop management options. This could underestimate the food production for some regions. All these together could influence the assessment results of food security to some extent. Thus, these results of future food security assessment do not constitute a “prediction” of the future, but highlight the hotspot regions where there is a high potential risk of food insecurity.

## References

Adejuwon J O, 2006. Food crop production in Nigeria: II. Potential effects of climate change. *Climate Resources*, 32(3): 229–245.

Arnell N W, Livermore M J L, Kovats S *et al*., 2004. Climate and socio-economic scenarios for global-scale climate change impacts assessments: Characterising the SRES storylines. *Global Environmental Change*, 14: 3–20.

Battisti D S, Naylor R, 2009. Historical warnings of future food insecurity with unprecedented seasonal heat.

*Science*, 323: 240–244.

Brookes G, Barfoot P, 2006. GM crops: The first ten years: Global socio-economic and environmental impacts. ISAAA Brief No.36. ISAAA: Ithaca, NY.

Brown M E, Funk C C, 2008. Food security under climate change. *Science*, 319: 580–581.

Deng X, Huang J, Rozelle S *et al*., 2006. Cultivated land conversion and potential agricultural productivity in China. *Land Use Policy*, 23: 372–384.

Ericksen P J, 2008. Conceptualizing food systems for global environmental change research. *Global Environmental Change*, 18: 234–245.

Ewert F, Rounsevell M D A, Reginster I *et al*., 2005. Future scenarios of European agricultural land use: I. Estimating changes in crop productivity. *Agriculture, Ecosystems and Environment*, 107: 101–116.

FAO, 2009. The state of food Insecurity in the world 2009. Food and Agriculture Organization, Rome, Italy.

Godfray H C J, Beddington J R, Crute I R *et al*., 2010. Food security: The challenge of feeding 9 billion people. *Science*, 327: 812–818.

Gregory P J, Ingram J S I, Brklacich M, 2005. Climate change and food security. *Philosophical Transactions of the Royal Society B*, 360: 2139–2148.

Grübler A, O'Neill B, Riahi K *et al*., 2007. Regional, national, and spatially explicit scenarios of demographic and economic change based on SRES. *Technological Forecasting & Social Change*, 74: 980–1029.

Howden S M, Soussan J F, Tubiello F N *et al*., 2007. Adapting agriculture to climate change. *Proceedings of the National Academy of Science*, 104: 19691–19696.

K-1 Model Developers, 2004. K-1 coupled model (MIROC) description, K-1 technical report No.1. Center for Climate System Research, University of Tokyo.

Liu J, Fritz S, Van Wesenbeeck C F A *et al*., 2008. A spatially explicit assessment of current and future hotspots of hunger in Sub-Saharan Africa in the context of global change. *Global and Planetary Change*, 64: 222–235.

Lobell D B, Burke M B, Tebaldi C *et al*., 2008. Prioritizing climate change adaptation needs for food security in 2030. *Science*, 319: 607–610.

Oga K, Yanagishima K, 1996. International Food and Agricultural Policy Simulation Model. JIRCAS Working Paper No.1. Japan International Research Center of Agricultural Sciences, Ministry of Agriculture, Forestry and Fisheries.

Parry M, Rosenzweig C, Livermore M, 2005. Climate change, global food supply and risk of hunger. *Philosophical Transactions of the Royal Society B*, 360: 2125–2138.

Rosegrant M W, Cline S A, 2003. Global food security: Challenges and policies. *Science*, 302: 1917–1918.

Schmidhuber J, Tubiello F N, 2007. Global food security under climate change. Proceedings of the National Academy of Science, 104: 19703–19708.

Seo S N, Mendelsohn R, 2008. An analysis of crop choice: Adapting to climate change in South American farms. *Ecological Economics*, 67: 109–116.

Shearer A W, 2005. Approaching scenario-based studies: Three perceptions about the future and considerations for landscape planning. *Environment and Planning B*: *Planning and Design*, 32: 67–87.

Tao F, Yokozawa M, Liu J *et al*., 2009. Climate change, land use change, and China's food security in the twenty-first century: An integrated perspective. *Climatic Change*, 93: 433–445.

Westhock H J, Van den Berg M, Bakkes J A, 2006. Scenario development to explore the future of Europe's rural areas. *Agriculture, Ecosystems and Environment*, 114: 7–20.

Williams J R, Dyke P T, Fuchs W W, 1990. EPIC-Erosion/Productivity Impact Calculator. United State Department of Agriculture, Agricultural Research Service. Technical Bulletin Number 1768. Springfield, VA, USA.

Wu W, Shibasaki R, Yang P *et al*., 2007a. Global-scale modelling of future changes in sown areas of major crops. *Ecological Modelling*, 208(2–4): 378–390.

Wu W, Shibasaki R, Yang P *et al*., 2010. Modeling changes in rice sown areas in Asia. *Sustainability Science*, 5: 29–38.

Wu W, Yang P, Tan G *et al*., 2007b. Global-scale modeling of future changes in sown areas for major crops based on a Logit model. *Acta Geographica Sinica*, 62(6): 589–598. (in Chinese)

Wu W, Yang P, Meng C *et al*., 2008. An integrated model to simulating sown area changes for major crops at a global scale. *Science in China* (Series D), 51(3): 370–379.

Yang P, Wu W, Zhou Q *et al*., 2007. Assimilating remotely sensed LAI into GIS-based EPIC model for yield assessment on regional scale. *Transactions of the Chinese Society of Agricultural Engineering*, 23(9): 130–136.