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 **Foresight**

Foresight Project on Global Food and Farming Futures

Synthesis Report C4: Food system scenarios and modelling

This Report has been commissioned as part of the UK Government's Foresight Project on Global Food and Farming Futures. The views expressed are not those of the UK Government and do not represent its policies.

Contents

C4.1	Introduction	3
C4.2	Drivers included in this analysis	3
C4.3	Scenarios and models of the food system	4
C4.4	Main scenarios	6
	C4.4.1 Assumptions	6
	C4.4.2 Main scenarios: results	7
C4.5	Other simulations	12
	C4.5.1 Assumptions	12
	C4.5.2 Production: simulation results	13
	C4.5.3 Governance: simulation results	23
	C4.5.4 Demand: simulation results	25
C4.6	Uncertainties in our analysis	28
C4.7	Key conclusions	31
	References	32

About this Report

This Report has been commissioned as part of the UK Government's Foresight Project on Global Food and Farming Futures and forms one of a set of 13 'Synthesis Reports' synthesising the evidence base of over 80 independent reviews commissioned by the Project. For the Final Project Report and a map of all the Foresight Project publications please see the project CD or website at www.bis.gsi.gov.uk/foresight

C4. Scenarios and modelling

C4.1 Introduction

The future of the food system is uncertain, especially considering a long-term horizon out to 2050. In spite of the uncertainty, policy formulation that has long-term implications is required now – waiting for the uncertainties to be resolved before acting is to invite high risks of failure. To support the development of strategies, therefore, it is necessary to explore possible futures. One approach is to develop quantitative scenarios, using empirical models that are internally consistent and incorporate what is known of future trends and drivers. Scenario analysis was pioneered by Shell in the early 1970s to prepare strategies that were robust to the uncertainties surrounding the energy system¹. A useful definition of a scenario is 'a description of potential future conditions, developed to inform decision-making under uncertainty'². Scenario analysis does not aim to predict the future. Instead it presents a range of plausible futures, often without placing a judgement on the relative likelihood of their outcomes.

This Project report explores a number of scenarios and simulations using empirical models that incorporate a number of the important yet uncertain drivers of change that will influence developments in the future. Scenario analysis is necessarily limited in scope, including only aspects of drivers for which there are adequate data and models that incorporate them. Uncertainty about the future means that it is not possible to credibly assign probabilities to the absolute results of the scenarios, but the analysis does allow exploration of a range of plausible futures while acknowledging the inherent uncertainties of the approach. The drivers and the models that were used are described below.

C4.2 Drivers included in this analysis

We consider a number of major drivers suggested in the driver reviews that are amenable to scenario analysis with empirical models and that have an impact on food demand, production and governance. They are:

- population growth: high, medium and low growth (demand)
- income growth: high, medium and low growth (demand)
- governance: agricultural support and trade policies, including changes in subsidies and protectionism versus open trade strategies (governance)
- growth in crop yield: various assumptions (production)
- water: competition for water and irrigation efficiency (production)
- climate change: various climate change scenarios from global circulation models (production)
- particular climate shocks (droughts) simultaneously affecting production in a few countries, with different trade policy responses (production and governance)
- a significant increase in energy prices (production)
- a major overall increase in protectionism (governance)
- increase in the demand for meat: focus on demand shifts in India and China (demand).

¹ Wack (1985)

² Parson et al. (2007)

C4.3 Scenarios and models of the food system

There have been at least 30 different major long-term model-based simulations of global food supply and demand over the second half of the 20th century³. More recent studies have used scenarios and models to expand the range of plausible futures for decision-makers to explore. A review commissioned by the project found a diversity of scenario types and modelling frameworks⁴. Outcomes for food security are often conceptualised by their effects on food availability, accessibility and utilisation⁵. The actual outcomes described in these various scenarios are simplified somewhat by the models used to frame their narratives. Nevertheless, international trade appears to be a crucial determinant of outcomes for the food system. In particular, while climate change is likely to widen the difference in cereal yields between high- and low-income countries, international trade may prevent particularly negative outcomes⁶.

Two types of models for the global food system predominate: computable general equilibrium (CGE) models and partial equilibrium (PE) models. Computable general equilibrium models take a whole-economy approach to simulate supply, demand and trade of a range of commodities in various sectors, including agriculture, across the global economy. Partial equilibrium models focus specifically on agriculture in order to produce a more detailed analysis for agricultural commodities⁷. Each approach has a limited domain of applicability for decision-making (see Box 4.1)⁸. More complicated modelling frameworks for integrated assessments 'soft link'⁹ a range of models across scientific disciplines and biophysical scales, but this process can be time consuming and the soft-linking process is imprecise¹⁰.

After three international workshops on food system modelling and consultation with experts in this field, the project decided to commission scenarios using two global models: (1) the IMPACT partial-equilibrium model and (2) the GLOBE CGE model. These models are described in summary in Box 4.1, and complete technical descriptions are referenced there. The IMPACT model is dynamic and is used to explore scenarios concerning the evolution of the global food system to 2050. The GLOBE model is static and is used to explore the impact on the global economy, focusing on the food system, of the various 'shocks' arising from the various drivers. In the IMPACT model, the various scenarios are compared with a dynamic baseline run to 2050, which provides a reasonable comparator that reflects a plausible path given existing trends and responses to the drivers. In the GLOBE model, the scenarios provide a 'before and after' picture of the global economy given changes in a driver or exogenous shock, without specifying the time horizon of the adjustment process. Both models are used to explore the sensitivity of the results to changes in assumptions and drivers, and to evaluate the robustness of the results in terms of lessons for policy formulation.

The Project used these two global models to create three main scenarios that represented plausible futures of population and income growth, and to develop several further simulations that test the sensitivity of food security outcomes to possible shocks or perturbations highlighted in the project driver reviews.

3 McCalla and Revordo (2001)

4 DRI0A (Annex E refers)

5 Ericksen (2008)

6 Parry et al. (2004)

7 DRI0A (Annex E refers)

8 Devarajan and Robinson (2002)

9 In 'soft-linked' modelling frameworks, output variables from one model are used to select the values for the input variables or parameters of another model but the different models are not formally merged; see DRI0A (Annex E refers).

10 Ewert et al. (2009)

Box C4.1: The IMPACT and GLOBE global models

The IMPACT model was developed at the International Food Policy Research Institute (IFPRI) and is an advanced version of a family of agriculture-focused, multi-market partial equilibrium models. It represents the agricultural sector in great detail at the cost of more simplified modelling of its relationship with other parts of the economy¹¹. The model simulates growth in crop production, determined by crop and input prices, externally determined rates of productivity growth and area expansion, investment in irrigation, and water availability. Demand is a function of prices, income and population growth and contains four categories of commodity demand – food, feed, biofuels and other uses. The 2009 version of the model includes a hydrology model and links to the Decision Support System for Agrotechnology Transfer (DSSAT) crop simulation software, with yield effects of climate change at 0.5°C intervals aggregated up to the food production unit level¹². Economy-wide competition for factors of production such as land, labour or capital is not simulated. The model solves simultaneously for all prices that clear the balance of supply and demand in all markets for agricultural commodities.

The GLOBE model is in the tradition of multi-country, trade-focused CGE models developed to analyse the impact of global trade negotiations and regional trade agreements¹³. This version of GLOBE is based at the Institute of Development Studies (IDS) at the University of Sussex. The model consists of a set of individual country or region models that provide complete coverage of the global economy and are linked through international trade in a multi-region model system. It solves the within-country models and between-country trade relationships simultaneously. The country models simulate the operation of factor and commodity markets, solving for wages, land rent, profits and commodity prices that achieve supply–demand balance in all markets. Each country engages in international trade, supplying exports and demanding imports. The model determines world prices that achieve supply–demand balance in all global commodity markets, simulating the operation of world markets.

The domain of applicability of partial equilibrium models like IMPACT is limited to analysis of the production, consumption and trade of agricultural commodities, subject to policies or scenarios that will have little feedback effects on the allocation of factors of production throughout the economy. Processed food products represent an increasing share of world trade, but their production is based in the non-agricultural part of the economy and they are not considered in these models. However, the strength of the PE models is that they can provide a detailed simulation of supply, demand and trade in primary commodities.

Multi-country CGE models such as GLOBE represent the full economy, including the agricultural sector. Their strength is that they include the value chain from crops, through processing and distribution, and finally to demand for food by households. They also incorporate links between agricultural and non-agricultural sectors, and the links between production, factor payments and household income. Current CGE models, however, include little or no modelling of biophysical processes and a simplified representation of the complexities of the agricultural sector. Multi-country CGE models are well suited to analysis of policies or scenarios that will change the volume and structure of production, demand and international trade, and the allocation of factors of production throughout the economy.

Using a quantitative model to simulate a complex food system is hugely challenging, and this analysis is necessarily qualified by the underlying data and methods that have been used to produce the results¹⁴. The various uncertainties surrounding these results are discussed later in this report in section C4.6.

¹¹ Rosegrant et al. (2008)

¹² Nelson et al. (2010)

¹³ McDonald et al. (2007)

¹⁴ Rotmans and van Asselt (2001)

C4.4 Main scenarios

C4.4.1 Assumptions

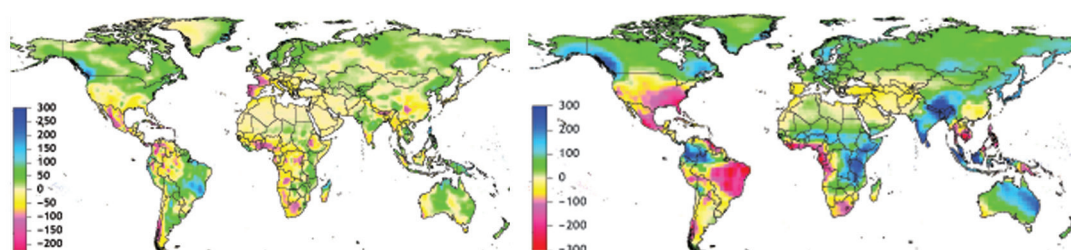
For the IMPACT modelling framework, three main dynamic scenarios (optimistic, baseline and pessimistic) were developed as plausible futures of population and income growth.

Scenario	Population	Income growth
Optimistic	United Nations (UN) low variant, 2008 revision	Highest of gross domestic product (GDP) growth rates from either the Millennium Ecosystem Assessment scenarios ¹⁵ or the baseline assumption
Baseline	UN medium variant, 2008 revision	Based on values from World Bank study ¹⁶ updated for sub-Saharan Africa and South Asia
Pessimistic	UN high variant, 2008 revision	Lowest of GDP growth rates from either the Millennium Ecosystem Assessment scenarios or the baseline assumption

Box C4.2: Simulating the impact of climate change on agriculture¹⁷

The simulated impact of climate change on agriculture depends on the climate model that is used¹⁸. Four different ways of simulating climate change were chosen here. Two climate models have been used: the Center for Climate System Research (University of Tokyo), National Institute for Environmental Studies, and Frontier Research Centre for Global Change, Japan, MIROC model; and the Commonwealth Scientific and Industrial Research Organization (CSIRO), Australia, CSIRO model. Both models are used to simulate future temperature and precipitation outcomes, based on the A1B and B1 emission scenarios of the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report¹⁹. All these scenarios have higher temperatures in 2050, resulting in higher evaporation and increased precipitation as this water vapour returns to earth in the form of rain. The CSIRO A1B and B1 scenarios represent a 'drier' future and the MIROC A1B and B1 scenarios represent a 'wetter' future. Global averages conceal substantial regional variability and potential changes in seasonal patterns.

Figure C4.1: Change in average annual precipitation, 2000–50, A1B (mm). Drier CSIRO results on left, wetter MIROC results on right



Source: Nelson et al. (2010).

¹⁵ Carpenter et al. (2006)

¹⁶ Margulis et al. (2010)

¹⁷ Nelson et al. (2010)

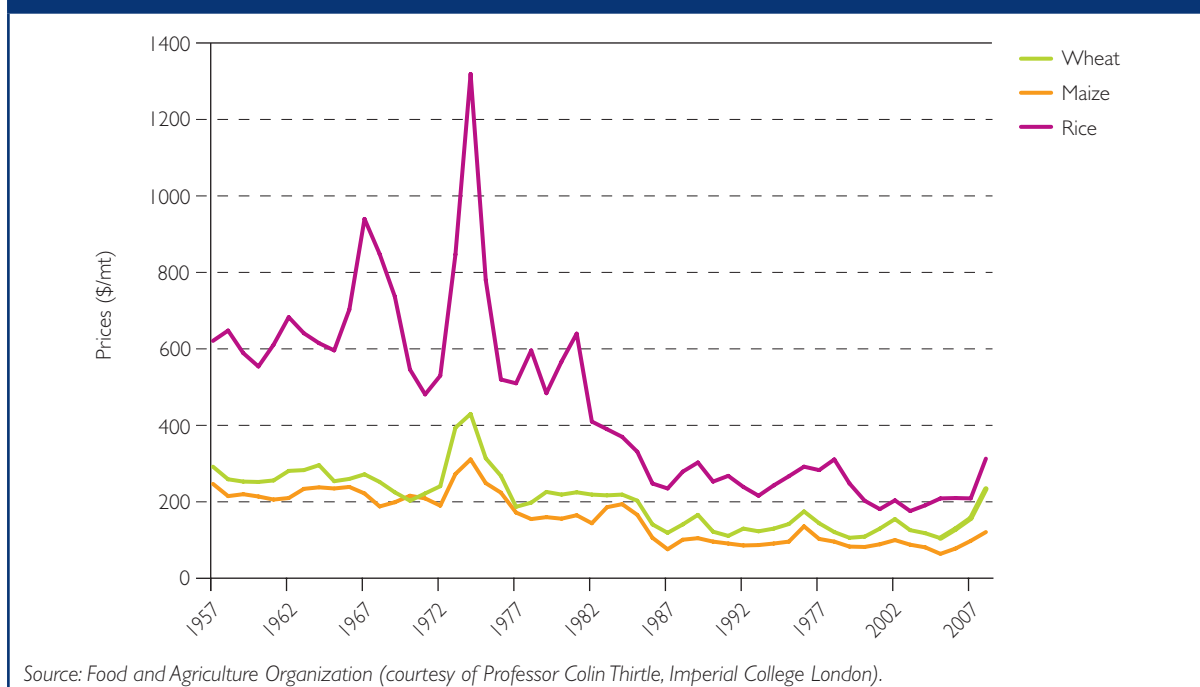
¹⁸ Parry et al. (2004); Fischer et al. (2005)

¹⁹ Nakicenovic et al. (2000)

C4.4.2 Main scenarios: results

The main scenario results use the daily amount of kilocalories available to the average person in each country or region as an indicator for food security outcomes. This indicator is calculated for different countries as a function of commodity prices, demand elasticities, per capita income and total population. The results also use as an indicator the number of malnourished children under the age of five. The analysis of food prices focuses on maize, rice and wheat because they are the most important crops for calorie consumption²⁰.

Figure C4.2: Historical real prices for maize, wheat and rice, 1957–2009 (US\$/metric tonne). Real prices refer to nominal prices adjusted for changes in the US Producer Price Index (2000 = 100). Prices are based on maize (US No. 2, yellow, US Gulf), rice (white rice, Thai 100% B second grade, fob Bangkok) and wheat (US No.2, soft red winter wheat, US Gulf). Fob, free on board

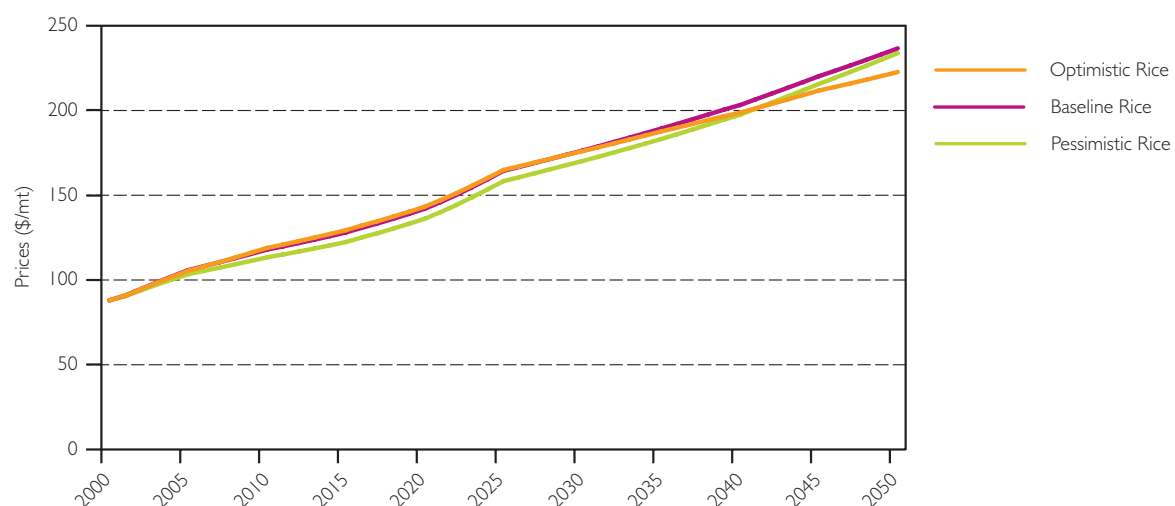


Real food prices increase in a major reversal of the trend of the later part of the 20th century (Figures C4.2 – C4.5)²¹. Nevertheless, economic development has a large positive impact on food security outcomes in developing countries (Figure C4.6)²². World food prices increase in the main scenarios driven, on the demand side, by growth from population growth, nutrition transition and urbanisation, and, on the supply side, from the assumptions made about crop yield growth and from the negative productivity effects of climate change. Although there is sufficient capacity in global supply to cater for increased demand, prices rise principally because there is an assumption that agricultural productivity does not grow quickly enough to keep real prices at current levels (see Boxes C4.3, C4.4 and C4.5 for a fuller discussion of food prices and agricultural productivity growth). Food price rises are lowest in the optimistic scenario because, even with higher per capita consumption based on increased incomes, population is lower and overall demand is less. Under a pessimistic scenario for development, with lower incomes and higher population growth, food security outcomes deteriorate and stall. In particular, the number of malnourished children in low-income developing countries actually increases by 18% from 2010 to 2050 (Figure C4.7).

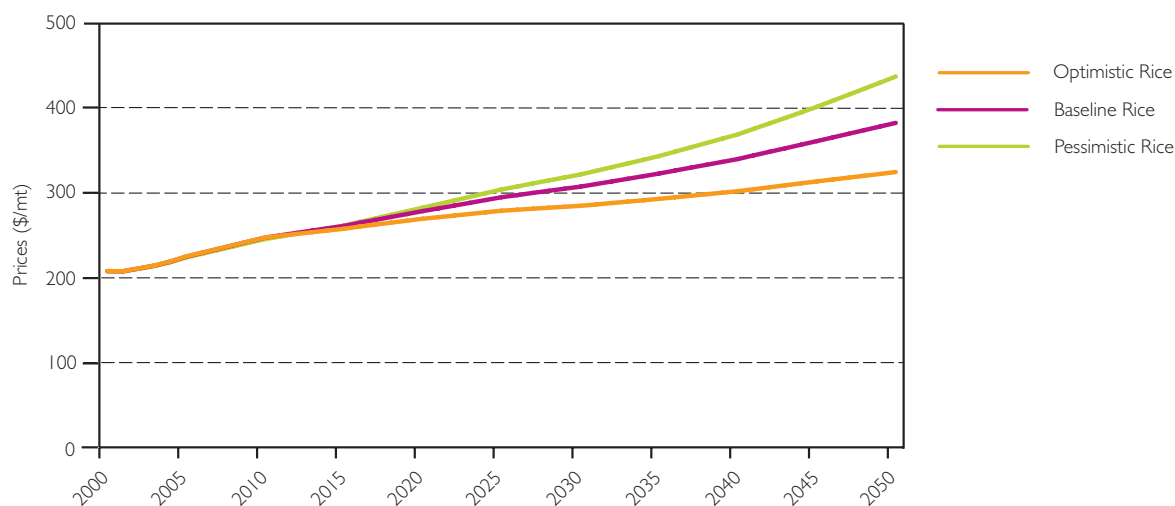
20 FAOSTAT (2010)

21 Hazell and Wood (2008)

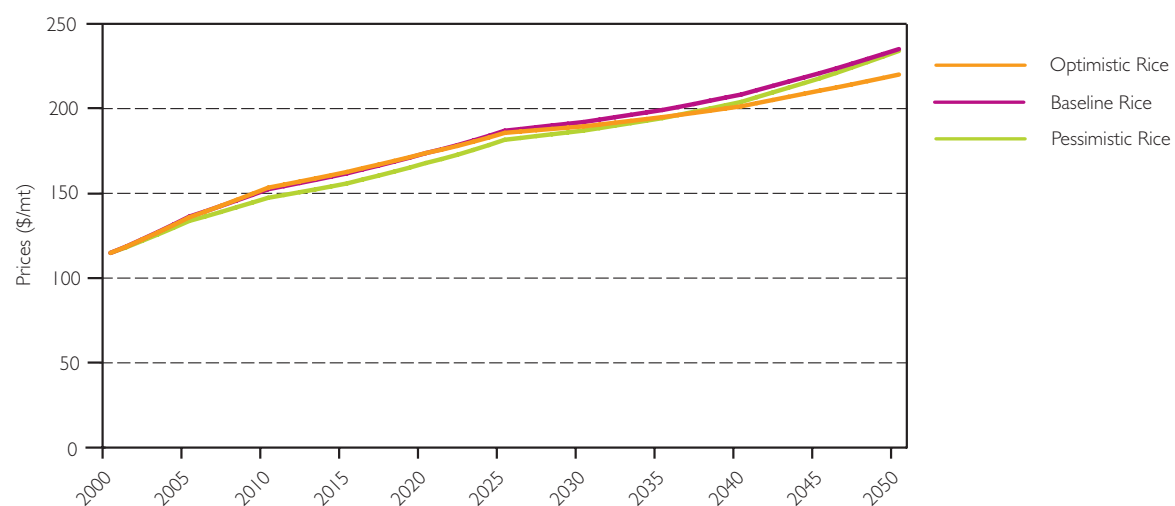
22 Developing countries include low- and middle-income developing countries.

Figure C4.3: Real prices for maize, 2010–50 (US\$/metric tonne)

Source: International Food Policy Research Institute.

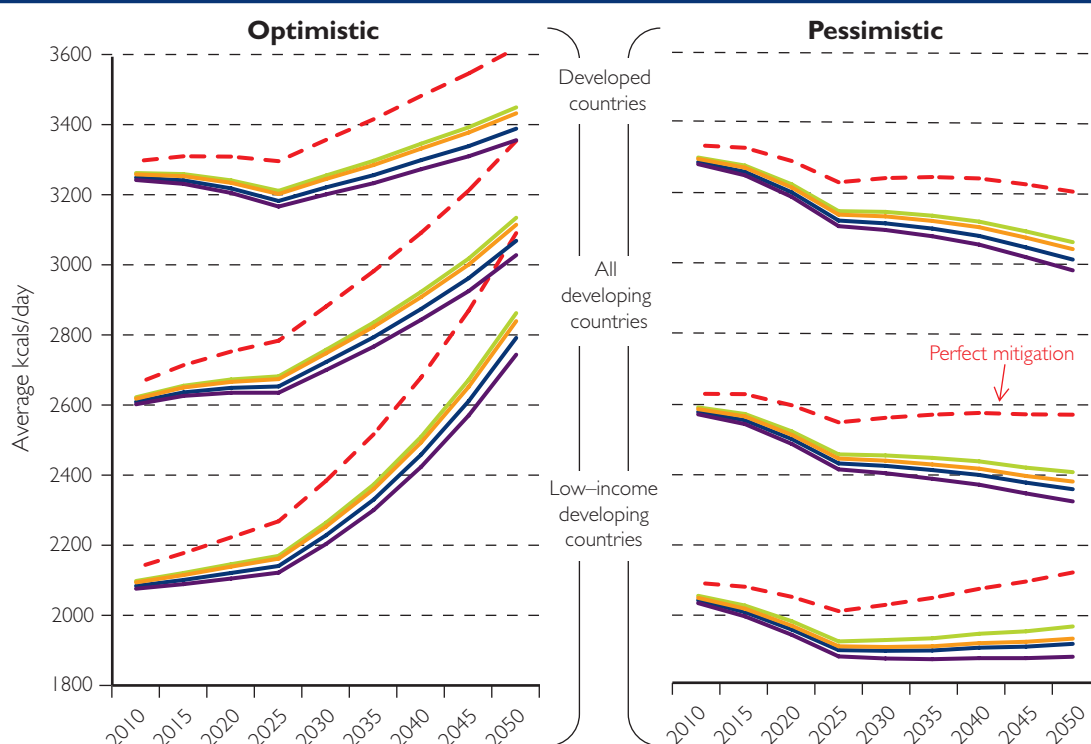
Figure C4.4: Real prices for rice, 2010–50 (US\$/metric tonne)

Source: International Food Policy Research Institute.

Figure C4.5: Real prices for wheat, 2010–50 (US\$/metric tonne)

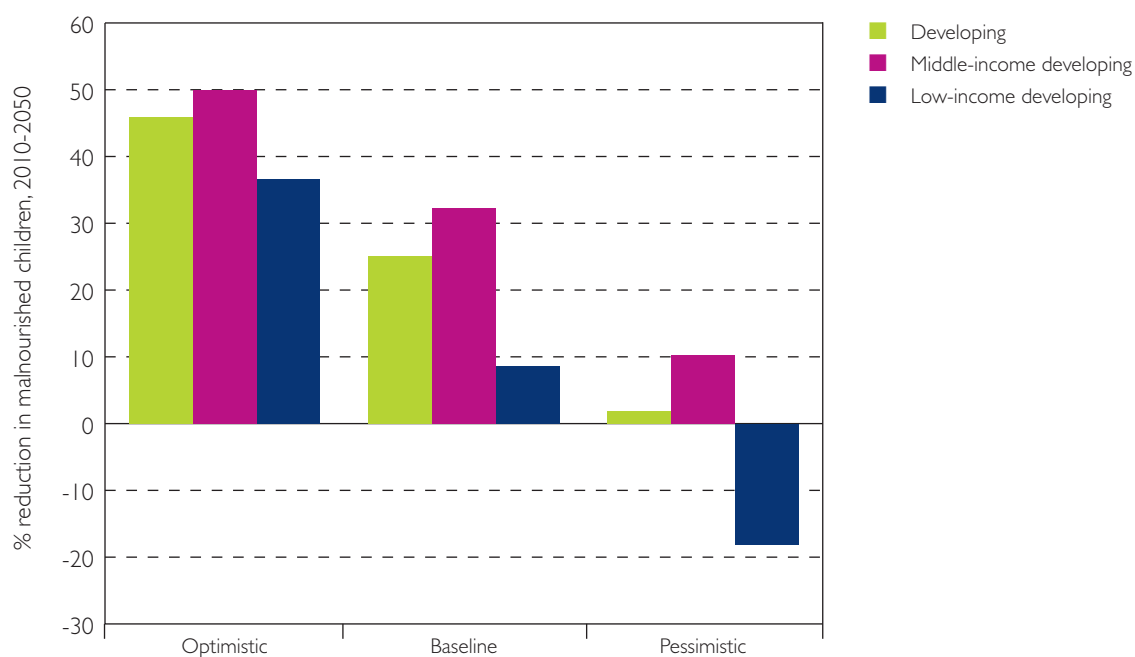
Source: International Food Policy Research Institute.

Figure C4.6: Average per capita daily kilocalorie availability in the main scenarios. For each group of countries the dashed line represents a future with no impact from climate change. The cluster of lines below the top line is the outcomes with four different climate scenario combinations. Results are provided for four climate scenarios (CSIRO A1B, CSIRO B1, MIROC A1B, MIROC B1) and assuming perfect mitigation (no climate change)



Source: Nelson et al. (2010).

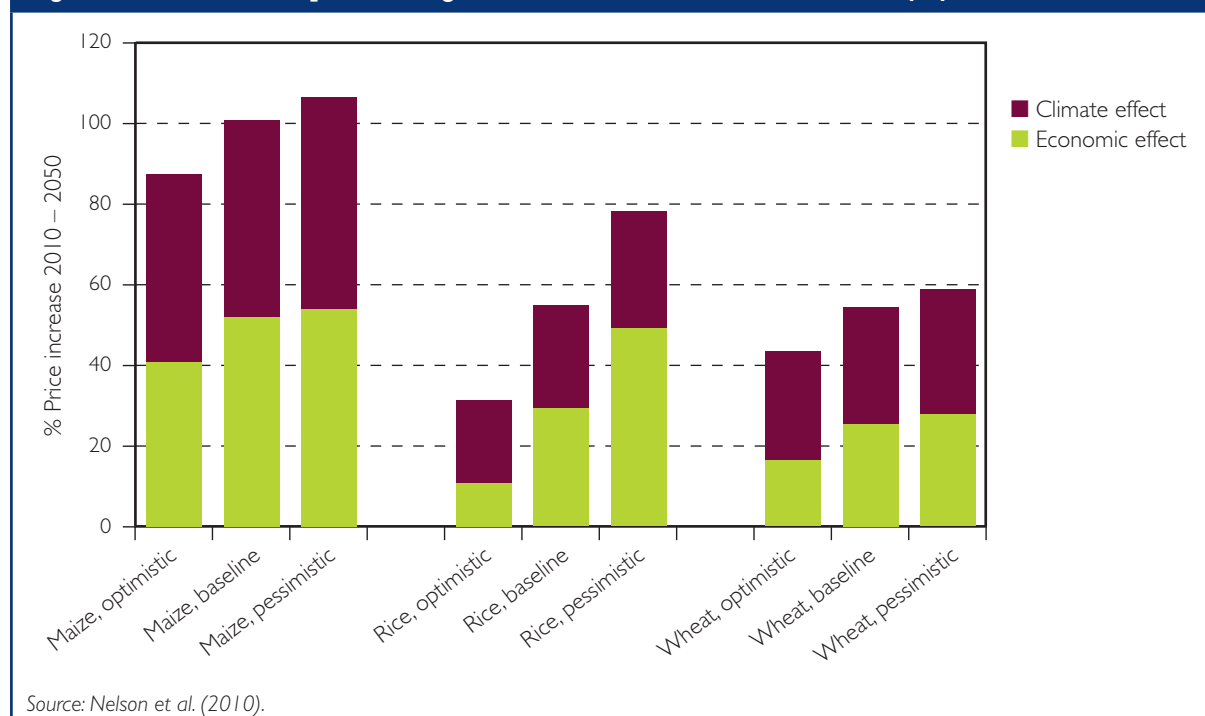
Figure C4.7: Percent reductions in the number of malnourished children, 2010–50 (%)



Source: Nelson et al. (2010).

Climate change increases world food prices because overall it reduces crop yields²³. Figure C4.8 illustrates the effect of climate change on food prices from 2010 to 2050. In 2050 prices are 18–34% higher, depending on the scenario and crop. There is also a 9–10% increase in the number of malnourished children in developing countries in 2050 compared with the scenario where climate change is mitigated.

Figure C4.8: Real food price changes for the main scenarios, 2010–50 (%)



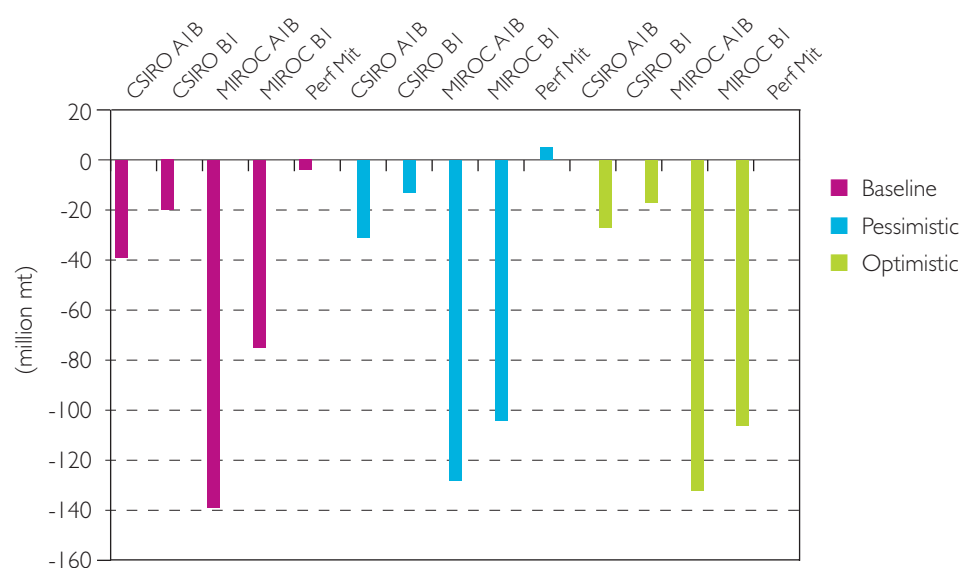
Although the impact of climate change on world prices appears relatively modest, there are actually large regional differences in temperature and precipitation effects. International trade plays an important role in reducing the unequal distribution of these effects. In the results, regions of the world experiencing less deleterious effects supply to those experiencing more deleterious effects. The trade outcomes differ depending on the climate model used. For example, with the CSIRO climate model net cereal exports from developed countries decline, whereas with the MIROC climate model developed countries actually become net cereal importers, mostly as a consequence of the negative effects of climate change on US maize production (Figure C4.9). These results demonstrate both the uncertainty surrounding the impact of climate change on agriculture and the importance of trade²⁴. Without the smooth well-functioning international markets assumed by the IMPACT modelling framework, food security outcomes would be considerably worse. The results quoted here focus on the horizon of 2050, but other research suggests that the major climate stressors for agricultural production occur from 2050 to 2080²⁵.

23 There is a cautious assumption about the positive effects of carbon fertilisation. Whereas the climate models assume the higher CO₂ concentrations of the A1B and B1 scenarios to simulate temperature and precipitation outcomes, the DSSAT crop model assumes a lower atmospheric concentration of 369 ppm. A lower concentration is used in DSSAT so that the uncertain biophysical effects of CO₂ fertilisation in the field are not overestimated; see Long et al. (2006).

24 Parry et al. (2004, p. 66) used results from the IPCC Third Assessment and found that 'production in the developed countries generally benefits from climate change, compensating for declines projected for developing nations'. The IMPACT modelling framework uses the IPCC Fourth Assessment.

25 DR2 (Annex E refers); Parry et al. (2004); Nelson et al. (2009); Nelson et al. (2010)

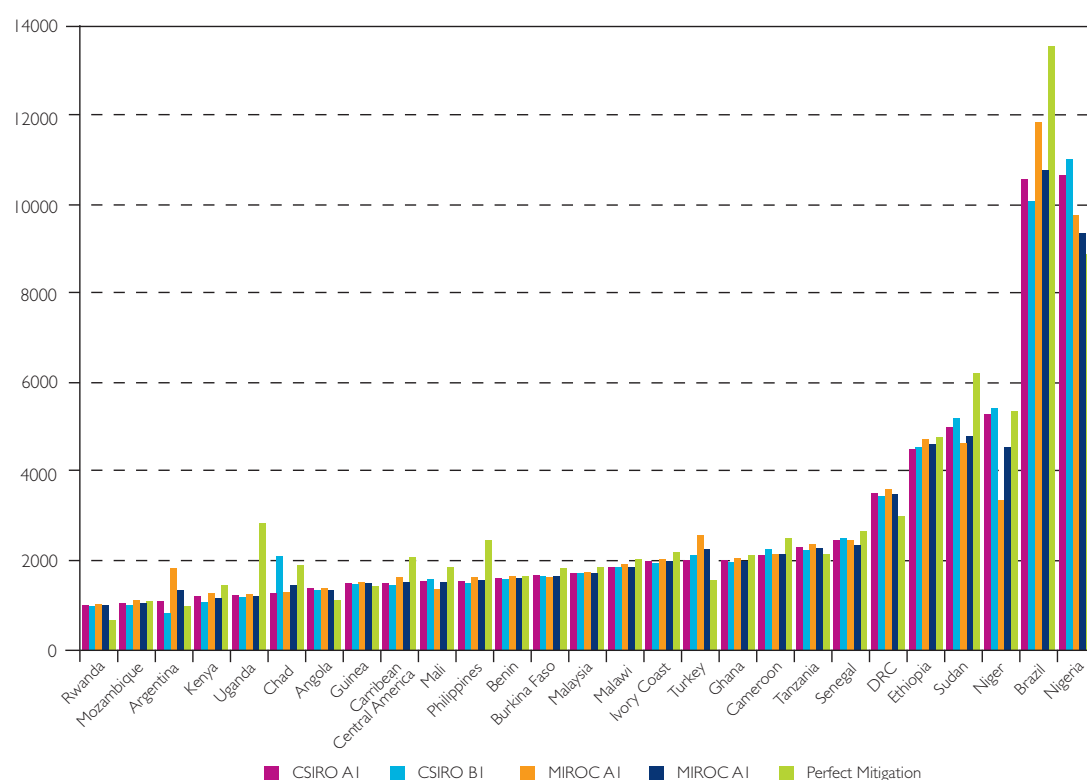
Figure C4.9: Change in net cereal trade in developed countries under the main scenarios, 2010–50 (million metric tonnes). Results are provided for four climate scenarios (CSIRO A1B, CSIRO B1, MIROC A1B, MIROC B1) and assuming perfect mitigation (no climate change)



Source: Nelson et al. (2010).

The overall change in crop harvested area in the scenarios is relatively small but, again, there are large regional differences. Developed countries experience a decline in harvested area of 9–13% whereas low-income developing countries have an increase of 18–25%. The area in China and India declines by around 10% and 9% respectively. Several developing countries experience area increases of more than one million hectares (Figure C4.10).

Figure C4.10: Countries with increases of crop harvested area of more than one million hectares (thousand hectares). Results are provided for four climate scenarios (CSIRO A1B, CSIRO B1, MIROC A1B, MIROC B1) and assuming perfect mitigation (no climate change)



Source: Nelson et al. (2010).F

C4.5 Other simulations

C4.5.1 Assumptions

The project also developed a number of simulations to test the sensitivity of food security outcomes to possible shocks, or perturbations, highlighted in the project driver reviews. These scenarios vary the assumptions of the baseline scenario. The IMPACT modelling framework is used as before but some simulations from the multi-country CGE model GLOBE are also introduced (Box C4.1). The GLOBE simulations are particularly useful when the scenario has a significant impact on, and feedback from, the wider economy. The scenarios for the simulations are focused on production, demand and governance.

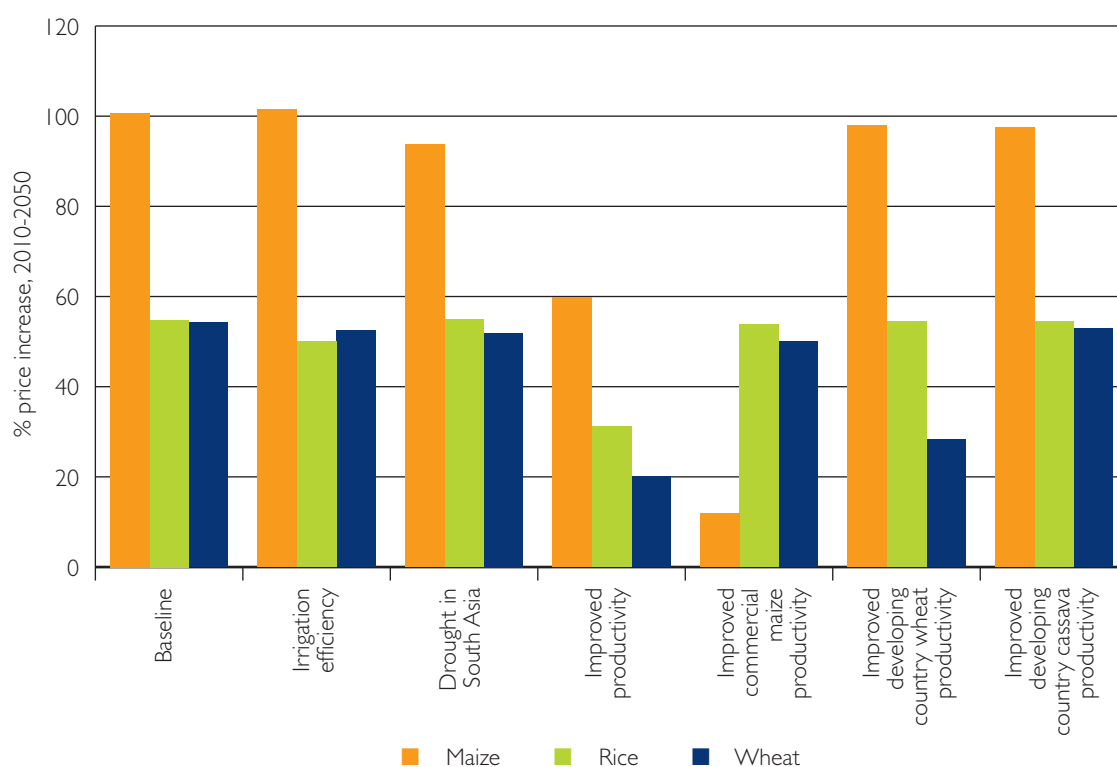
Table C4.1: Assumptions of other simulations

Scenario	Difference from baseline scenario	Model
<i>Production</i>		
Improvements in irrigation efficiency	15% increase in irrigation efficiency in the developing world 2010–50	IMPACT
Drought in South Asia between 2030 and 2035*	Rainfed crop areas in Bangladesh, India and Pakistan are reduced by 2% per annum from 2030 to 2035 and return to baseline gradually over the next five years	IMPACT
Improvements in overall productivity	Intrinsic productivity growth* rates in developing countries increased by 40% from 2015 to 2050	IMPACT
Improvements in commercial maize productivity	Intrinsic productivity growth* rates for maize increased to 2% per annum in USA, Mexico, China, Europe, France, Brazil, Argentina and South Africa from 2015 to 2050 (80% of current maize production)	IMPACT
Improvements in wheat productivity	Intrinsic productivity growth* rates for wheat increased to 2% per annum in India, Pakistan, Argentina, Iran, Ukraine, China and Kazakhstan from 2015 to 2050 (40% of production in 2000)	IMPACT
Improvements in cassava productivity	Intrinsic productivity growth* rates for cassava increased to 2% per annum (or existing rate if greater) in Brazil, Democratic Republic of Congo, Indonesia, Ghana, Nigeria and Thailand from 2015 to 2050 (around 63% of production in 2000)	IMPACT
Significant increase in energy prices	Fossil fuels (and other mineral) resources are 20% lower than expected	GLOBE
<i>Governance</i>		
Drought in the North American Free Trade Agreement area, China and India and a protectionist response	1) 20% yield drop in USA, Canada, Mexico, China and India, followed by 2) 25% export tax in exporting regions	GLOBE
Major increase in protectionism	Import duties double from 2005 rates across all regions	GLOBE
<i>Demand</i>		
Additional increase in demand for meat in China and India	Share of consumer spending on livestock products increases by 10% and spending on services decreases by the same amount	GLOBE
*Intrinsic productivity growth rate assumptions are subsequently adjusted for the effects of climate change and producer responses to changes in prices. Adjusted average yield growth rates for maize, rice and wheat in the main scenarios range from 0.2% to 1.9% per annum depending on economic development (developed, middle-income developing, low-income developing) and the production system used (rainfed, irrigated).		

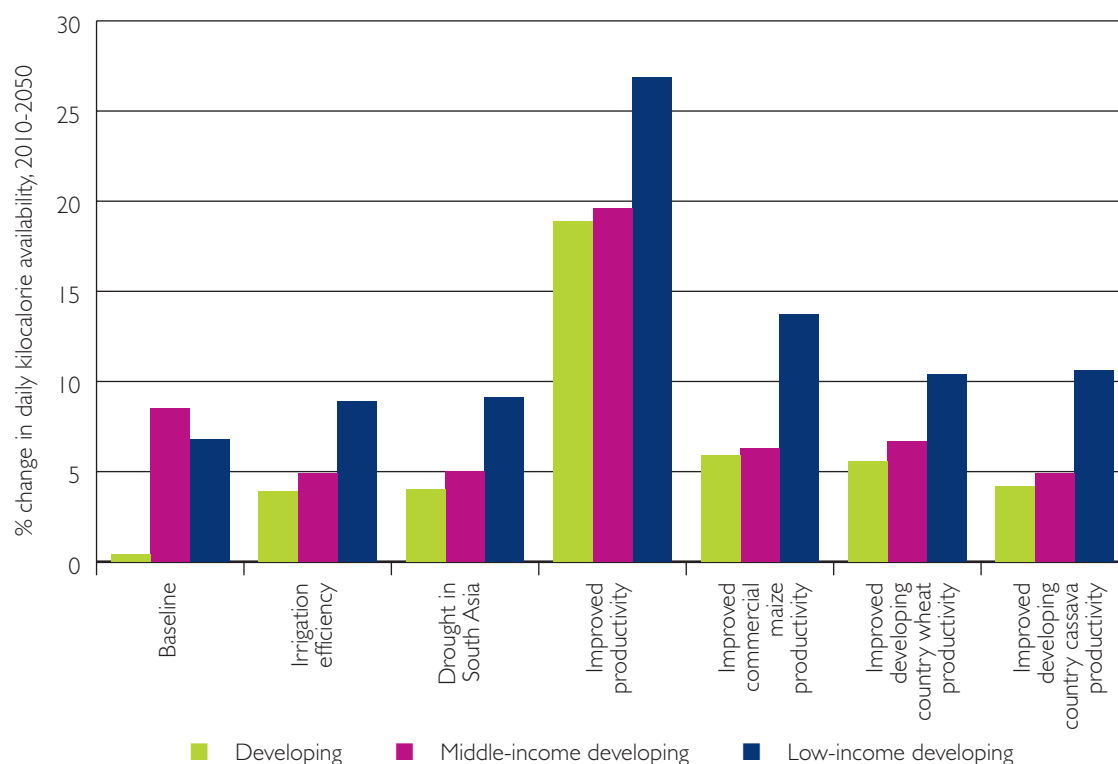
C4.5.2 Production: simulation results

The results for the IMPACT-based production simulations listed in Table C4.1 are summarised using the same indicators for food security outcomes as the main scenarios. There are results for changes in real food prices (Figure C4.11), changes in daily kilocalorie availability (Figure C4.12), and reductions in the number of malnourished children (Figure C4.13). These results are then compared with those of the baseline scenario in order to analyse the sensitivity of food security outcomes to the simulations.

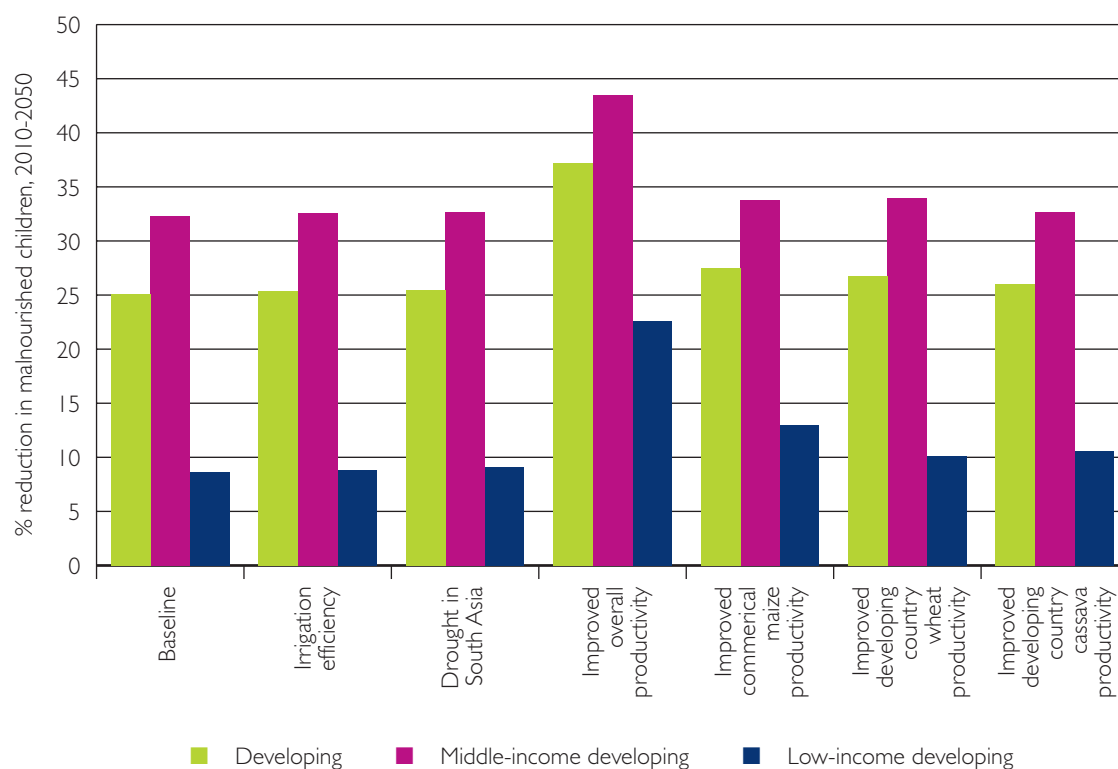
Figure C4.11: Real food price changes for the production simulations, 2010–50 (%)



Source: Nelson et al. (2010).

Figure C4.12: Impact of production simulations on daily kilocalorie availability, 2010–50 (%)

Source: Nelson et al. (2010).

Figure C4.13: Reductions in the number of malnourished children for simulation scenarios, 2010–50 (%)

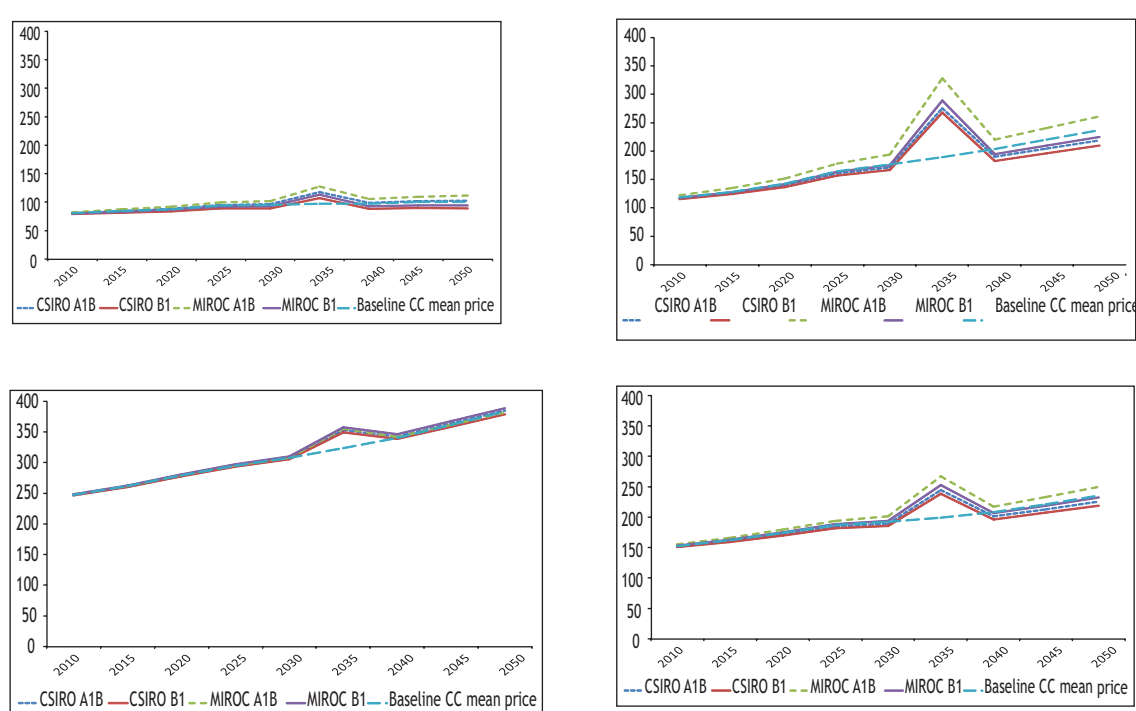
Source: Nelson et al. (2010).

Drought in South Asia, 2030–35

Change in future precipitation over India is uncertain partly because of the balance between the expected weakening of the dynamical monsoon circulation (decreasing the Indian monsoon precipitation) and the increase in atmospheric water content associated with warming (increasing the Indian monsoon precipitation)²⁶. An extended drought in South Asia (Bangladesh, India, Pakistan) was simulated using the IMPACT modelling framework beginning in 2030, continuing through 2035, and then with recovery to the previous path of the baseline scenario to 2050. It is assumed that only rainfed agriculture is affected and that sufficient water is available for irrigated agriculture.

The world prices of maize, rice and wheat all show a sharp increase during the drought (Figure C4.14) and, although they return to trend afterwards, these higher prices contribute to a 1% increase in the number of malnourished children in 2050 (Figure C4.13).

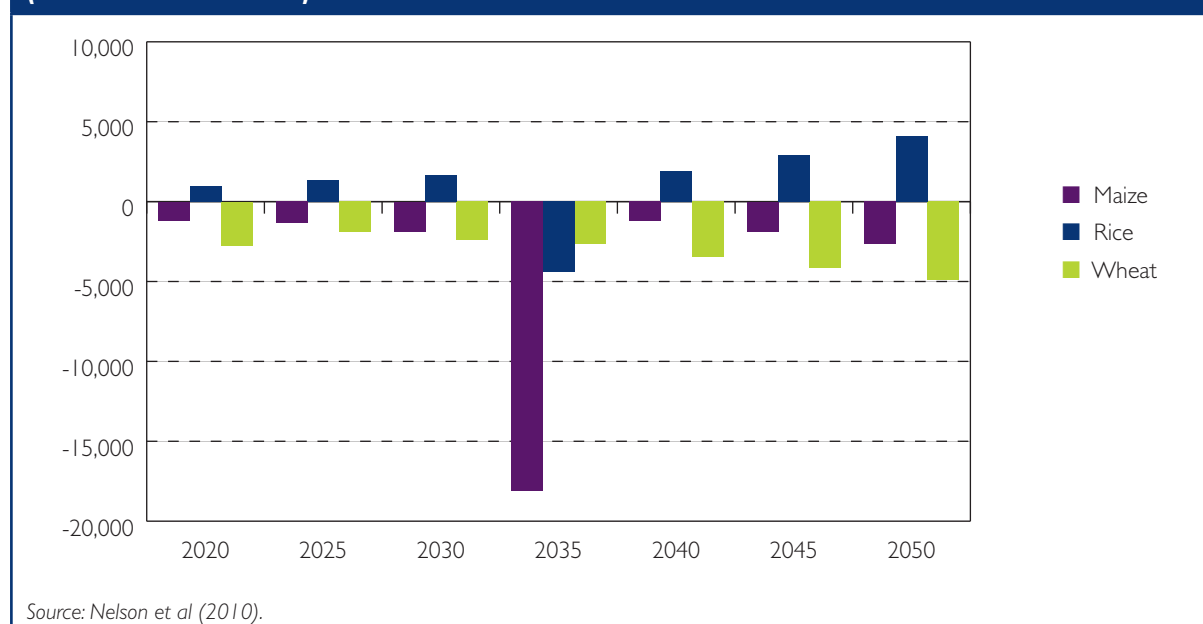
Figure C4.14: Price pathways for drought in South Asia, 2030–35 (2000 US\$/metric tonne). Results are provided for four climate scenarios (CSIRO A1B, CSIRO B1, MIROC A1B, MIROC B1) and for the baseline scenario.



Source: Nelson et al. (2010).

In the baseline scenario the rainfed area in South Asia declines as the irrigated area expands. With the simulated drought, however, producers respond to increasing prices by expanding the irrigated area more and more quickly, with irrigated rice showing the biggest increase. As the drought recedes, and prices fall, some of this additional area reverts to rainfed production but the irrigated area still remains higher than it would have been.

²⁶ Meehl et al. (2007)

Figure C4.15: Change in net cereals trade in South Asia under drought simulation, 2010–50 (million metric tonnes)

In this simulation, international trade plays an important role in lessening the drought-induced impact of the loss of rainfed production (Figure 4.15). Without the drought, South Asia is a growing rice exporter, and wheat and maize imports increase. During the drought, the region becomes a substantial rice importer and maize imports become much larger. Wheat imports reduce during the drought, most likely because of the larger increase in irrigated wheat area.

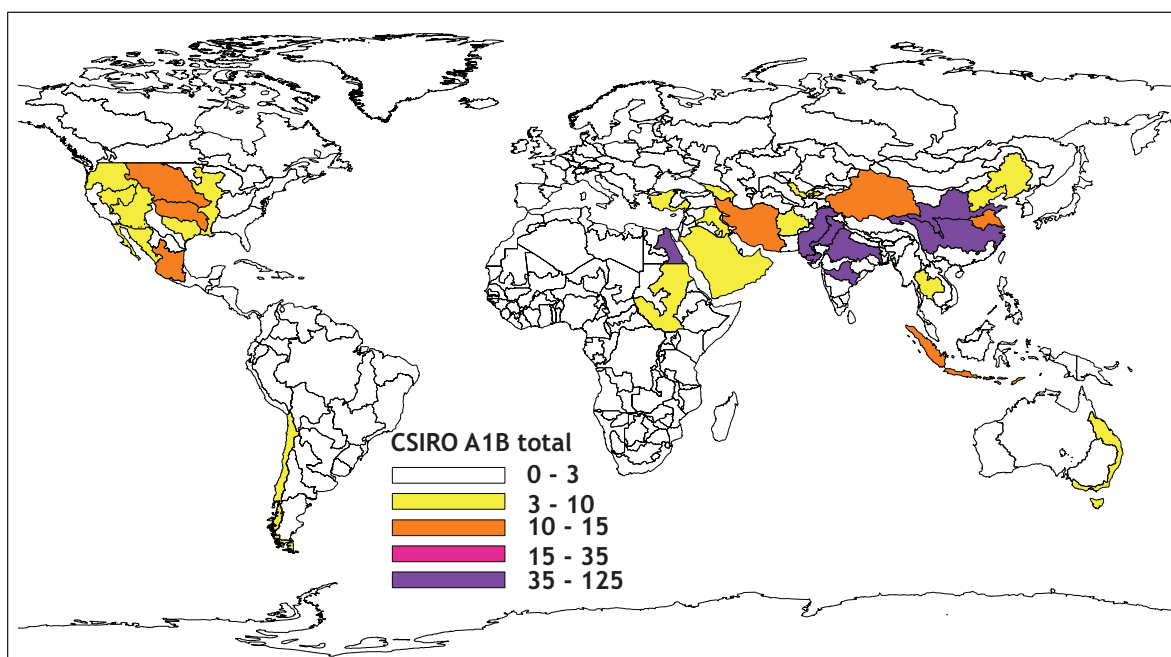
Improved irrigation efficiency

Increasing demands for water pose threats to food systems, and improving the irrigation efficiency of agriculture is considered to be a critical response²⁷. Of the major food crops, irrigation is currently most important for rice and accounts for around one-third of production in developed countries and around a half in developing countries. In contrast, roughly 15% of maize production is on irrigated land; in developed countries wheat production is almost exclusively rainfed, but in developing countries about 30% of production is from irrigated systems. The share of production from irrigated rice and maize already increases in the baseline scenario. For wheat, the irrigated share in developed countries is constant, but in developing countries the share increases.

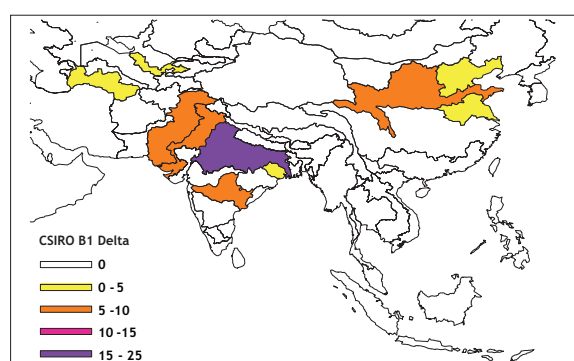
Improvements in irrigation efficiency in the developing world are modelled by increasing basin efficiency, which is the ratio of beneficial irrigation water consumption to total irrigation water consumption, by 15%²⁸. The improvements focus on production areas where irrigated yields are considered low because of water shortages. These improvements have relatively little effect on food security outcomes because the benefits of the efficiency gains are almost entirely in India, Pakistan and China where the predominant use of irrigation is for rice production. Figures C4.16–4.20 highlight the areas that benefit from efficiency gains under each climate scenario. Rice prices do decline by about 5% from 2010 to 2050 compared with the baseline scenario, but maize and wheat prices are relatively unchanged (Figure 4.11). There is a small reduction in the number of malnourished children, mostly in middle-income developing countries (Figure 4.13).

27 DR12 (Annex E refers); Postel (1998)

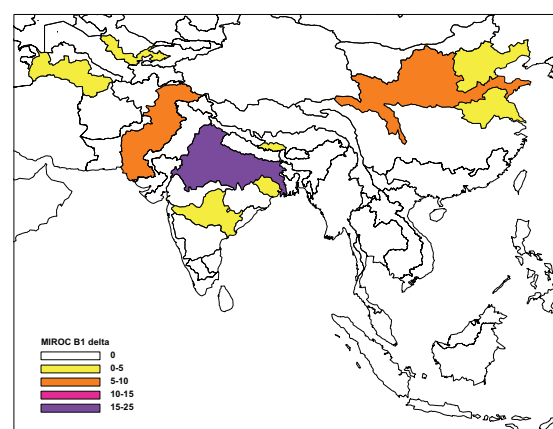
28 Haie and Keller (2008)

Figure C4.16: Irrigation water use in 2050, CSIRO A1B (km³)

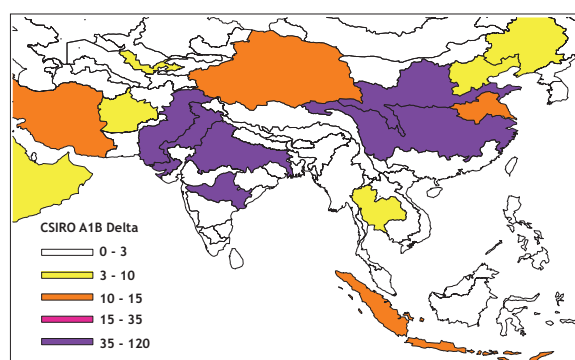
Source: Nelson et al. (2010).

Figure C4.17: Increase in agricultural water use in 2050, improved irrigation efficiency simulation CSIRO B1 (km³)

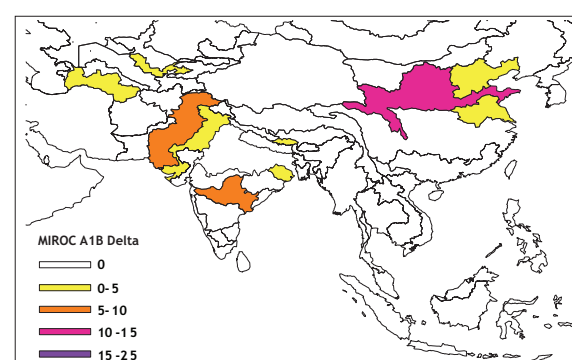
Source: Nelson et al. (2010).

Figure C4.18: Increase in agricultural water use in 2050, improved irrigation efficiency simulation MIROC B1 (km³)

Source: Nelson et al. (2010).

Figure C4.19: Increase in agricultural water use in 2050, improved irrigation efficiency simulation CSIRO A1B (km³)

Source: Nelson et al. (2010).

Figure C4.20: Increase in agricultural water use in 2050, improved irrigation efficiency simulation MIROC A1B (km³)

Source: Nelson et al. (2010).

Overall improvements in crop productivity

From 1961 to 2008, yield growth rates for grains in developed countries were on average 1.5% per annum and 2.1% in developing countries²⁹. Since 1985 there has been a reduction in these average growth rates. The IMPACT modelling framework assumes that growth rates increase slightly over the next 10–15 years and then decline gradually to 2050. Adjusted average productivity growth rates for maize, rice and wheat in the baseline scenario range from 0.2% to 1.9% per annum depending on economic development (developed, middle-income developing, low-income developing), crop and the production system used (rainfed, irrigated). In this simulation, intrinsic productivity growth rates in developing countries are increased by 40% from 2015 to 2050 compared with the baseline scenario³⁰.

Of all the variations of the baseline scenario that have been developed to test the sensitivity of food security, this change produces the most clearly advantageous outcomes. World prices increases for maize, rice and wheat are reduced by 41%, 24% and 34% respectively compared with the baseline scenario (Figure 4.11). As a result, there is a massive increase in the daily amount of kilocalories that is available to the average person in each country or region (Figure 4.12). The number of malnourished children falls by an additional 12% from 2010 to 2050 (Figure 4.13). According to this analysis, the most powerful driver in the food system to improve food security outcomes is yield growth.

²⁹ DR8 (Annex E refers)

³⁰ Intrinsic productivity growth rate assumptions are subsequently adjusted for the effects of climate change and producer responses to changes in prices.

Box C4.3: What are the food security outcomes in other quantitative scenarios to 2050?

The project reviewed several quantitative scenarios of the food system to 2050³¹. Some simulations that use modelling frameworks that differ from the IMPACT framework are highlighted here.

The impact of climate change on food security outcomes has been explored using emission scenarios (A1FI, A2, B1, B2) previously produced by the IPCC. An integrated assessment modelling framework, based on the International Institute for Applied Systems Analysis (IIASA) CGE basic linked system model, was created to estimate the response of cereal yields to simulated climate change, based on these scenarios, and then to quantify the implications for cereal production, prices and risk of hunger³². Climate scenarios were developed using the Hadley Centre HadCM3 model. Under a reference case with no climate change, world cereal prices rise by around 30–80% from 1990 to 2050. With climate change, results are reported with and without CO₂ fertilisation effects on the basis that true effects will fall somewhere between. Assuming CO₂ fertilisation effects, climate change increases prices roughly by 7–20% more than the reference case. Without these effects, climate change increases prices by around a further 50–100%. For the pessimistic A2 scenario with the highest population growth (11.3 million in 2050) and lowest GDP growth to 2050, price increases are highest. Although there is an increasing divergence in cereal yields between developed and developing countries in all the scenarios, the differences are greatest in this scenario. In particular, yields dramatically decrease in developing countries because of regional temperature increases and precipitation decreases. The impact on production up to 2050 in A2 is similar to other scenarios, but prices are higher and, with a larger and poorer population, the additional number of people at risk of hunger is much greater. Without CO₂ fertilisation effects, there are around 200 million additional people at risk of hunger by 2050, and there are almost 600 million by 2080.

Another integrated assessment of the impact of climate change on agriculture used a similar modelling framework but estimated the response of cereal yields using a different crop model and with climate simulations from five different climate models³³. The impact of climate change affects world cereal prices moderately: for HadCM3 the increase from 1990 to 2080 is 2–20%; for CSIRO the increase is 4–10%; and for the other climate models the changes are less. Without the impact of climate change, hunger is reduced substantially in all but the pessimistic A2 scenario where the number of people at risk of hunger in 2050 remains high at over 721 million. With climate change and assumed CO₂ fertilisation, numbers are increased slightly. Without CO₂ fertilisation effects, the numbers at risk are even higher.

Climate change is expected to increase prices, but population and economic growth are also likely to have a strong impact on food security³⁴. Real prices vary depending on the crop model and climate model used but are projected to be higher than current levels. Real incomes are generally expected to increase more rapidly than real food prices in most scenarios, but higher prices may still result in negative food security outcomes in vulnerable regions, and prices are expected to rise more substantially after 2050³⁵. The effects of CO₂ fertilisation are found to be significant yet uncertain.

31 DRI0A (Annex E refers)

32 Parry et al. (2004)

33 Fischer et al. (2005)

34 Easterling et al. (2007)

35 Schmidhuber and Tubiello (2007)

Simulations using the Global Trade Analysis Project (GTAP)³⁶ CGE model suggest that higher agricultural productivity could offset rising prices³⁷. Assuming a scenario in which total factor productivity³⁸ in agricultural productivity is equal to that in the rest of the economy, real prices for maize, wheat and rice increase by 127%, 110% and 68% respectively to 2050. This assumption implies a substantial reduction in the growth rate of agricultural productivity. If, on the other hand, total factor productivity in agriculture is 1% per annum higher than the rest of the economy, real price increases for these commodities are minimal. Limiting increases to the developing world results in real price increases of 31%, 26% and 16% respectively.

World Bank quantitative scenarios, using their Environmental Impact and Sustainability Applied General Equilibrium (ENVISAGE) model to 2030, also suggest that prices are particularly sensitive to assumptions of agricultural productivity growth³⁹. Global total factor productivity growth of 2.1% per annum results in a slight decrease in world agricultural prices in real terms. If productivity is halved, real prices rise by 35% in comparison. If only developing country agriculture is subjected to the lower productivity growth, the price increase is 16%. Scenario analysis using this model also finds that climate change could substantially reduce real incomes in South Asia and sub-Saharan Africa by 2030 despite economic growth.

Other medium-term projections suggest rises in real food prices. The most recent outlook for agriculture, published by the Organization for Economic Cooperation and Development (OECD), projects average wheat and coarse grain prices to be 15–40% higher in real terms in 2020 relative to the period from 1997 to 2006⁴⁰. Under 'low-productivity' and 'high-productivity' scenarios with the GTAP CGE model, world cereal prices rise on average by 32% and decline by 16% respectively from 2000 to 2030⁴¹. Prices for coarse grains under the 'low-productivity' scenario rise on average by as much as 63%.

Selective improvements in crop productivity

The impact of improvements in the productivity of commercial maize, wheat and cassava in different areas of production were also simulated. In each instance the increase in the world price is tempered but there is little or no effect on the prices of the other main commodities (Figure C4.11), based on model assumptions of relatively low cross-price substitutability in demands. The world prices of maize and cassava are much reduced compared with the baseline scenario, but reductions are predicated on productivity improvements across larger areas of production than for wheat. Maize prices are 89% lower and wheat prices are 26% lower compared with the baseline scenario; cassava prices are actually reduced by 10% from 2010 to 2050 compared with a 25% increase in the baseline scenario (Figure C4.11; cassava prices are not illustrated). Food security outcomes improve modestly in developing countries and especially in the regions where consumption is important. For example, improving cassava productivity results in a greater decrease in the number of malnourished children in low-income developing countries compared with the baseline scenario (Figure C4.13).

Significant increase in energy prices

Modern agriculture is dependent on fossil fuel resources, although there are opportunities for innovation and renewable energies to reduce this reliance⁴². The impact of an unexpected scarcity of fossil fuel resources is simulated using the multi-country GLOBE CGE model. Global fossil fuel resources are reduced by 20%, and, as a result, global crude oil and refined fuel prices increase by around 60% compared with the baseline scenario. Countries that are net fuel importers lose out to net fuel exporters, which experience strong improvements in their terms of trade and real income (Figure C4.21 highlights the change in real absorption or expenditure on real goods and services). Households in the former experience income reductions and need to spend a higher proportion of their disposable income on energy-intensive goods. As a result, their consumption of other goods including food decreases.

36 Hertel (1997)

37 Hertel (1997); Ivanic and Martin (2010)

38 See Box 4.5

39 van der Mensbrugghe et al. (2010)

40 OECD/FAO (2010)

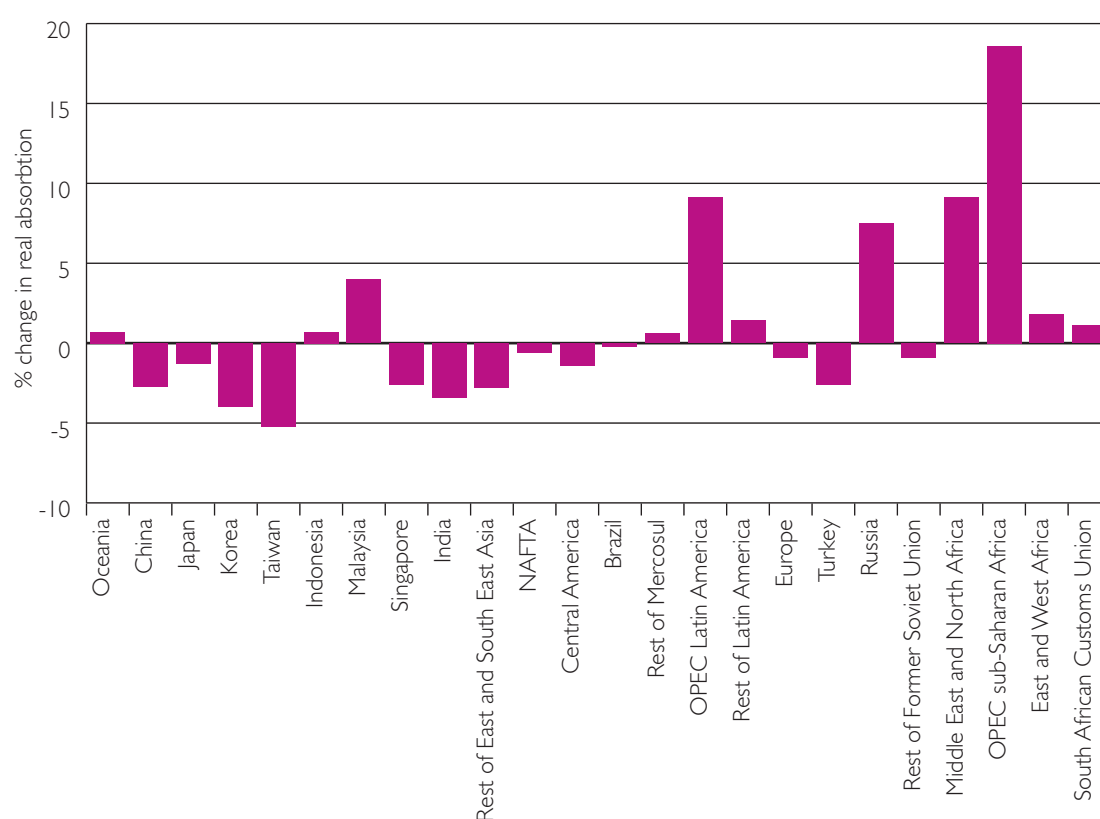
41 Hertel et al. (2010)

42 DR4 (Annex E refers)

This is a reminder that the accessibility of food is a function of disposable incomes as well as of food prices. The significant increases in food consumption in fuel-exporting regions are based on the assumption that the windfall gains from the fuel price increase translate into income gains across all household groups in these regions.

From an economy-wide perspective, agriculture is not a relatively energy-intensive sector compared with non-agricultural sectors. Therefore, the simulated fuel price increase does not lead to an increase in global food crop prices relative to non-agricultural goods, and the effect on global crop prices is modest. However, a permanent fuel price increase of this magnitude may increase the profitability of biofuel production and provide an incentive to farmers to switch from food to biofuel crops. The model does not incorporate this effect.

Figure C4.21: Regional change in welfare under fossil fuel scarcity scenario (% change in real absorption). Real absorption is the total of expenditure on real goods and services. FSU, former Soviet Union; LA, Latin America; MENA, Middle East and North Africa; NAFTA, North American Free Trade Agreement; OPEC, Organization of Petroleum Exporting Countries; SA, South Africa; SSA, sub-Saharan Africa



Source: GLOBE results.

Box C4.4: What could be the impact of biofuel production on future food prices?

The demand for feedstocks used in biofuel production has increased markedly in the last decade and many scenarios of the future project an increase in the land used for biofuel production⁴³. It is challenging to project future biofuel production because it will depend on uncertainties such as energy prices, policy choices and technological change.

Four quantitative scenarios of future biofuel production were created using a modelling framework based on the IIASA CGE World Food System model⁴⁴. Energy demand for transport throughout is based on the International Energy Agency World Energy Outlook (WEO) 2008 reference scenario⁴⁵. These results show that the development and deployment of second-generation conversion technologies has a significant impact on food prices. Further sensitivity analyses confirm that the aggregate share of first-generation biofuels mandated to contribute to consumption of transport fuel has a considerable impact on food prices. Real cereal prices increase by 10–27% owing to biofuel production, depending on the biofuel production scenario. The harvested area increases by 26–59 million hectares. The impact of biofuel production in the scenarios on land use is substantial, especially if biofuel targets are ambitious and development of second-generation conversion technologies is inhibited.

Scenarios exploring the impact of future biofuel production have also been created using the IFPRI partial equilibrium IMPACT model⁴⁶. In order to offset the negative impacts on food security outcomes of the target set by the Energy Independence and Security Act of 15 billion gallons of first-generation biofuel by 2022, growth in cereal productivity based on yields would have to increase further from a baseline average annual rate of 1.3–1.8%. Enhanced agricultural knowledge, science and technology (AKST) can reduce competition for land by increasing the availability of land for non-agricultural use. Under scenarios of enhanced AKST the impact of increased biofuel production on food prices is ameliorated but not eliminated.

Recent policy in the USA and EU on biofuel production has been partly driven by perceived opportunities to reduce CO₂ emissions, although such benefits have been contested⁴⁷. Further research from IFPRI uses a modified version of the global CGE model MIRAGE to explore the future impacts of mandatory provisions of ethanol to 2020⁴⁸. Real oil prices are kept stable at US\$60 a barrel. Resulting ethanol production is increased by 48 million tonnes of oil equivalent (MTOE) in the USA and 16 MTOE in Europe. Increased demand for feedstocks leads to an increase in world prices. The price of maize increases by 11% and wheat by 3%. A further scenario with liberalisation of ethanol trading is found to encourage the production of feedstocks in more efficient regions such as Brazil. In this case the price increases are 9% and 1% for maize and wheat respectively. Brazil and food-exporting countries in Latin America emerge as beneficiaries under the trade liberalisation scenario, but food-importing Caribbean countries suffer. More generally, results suggest that ethanol mandates represent a welfare transfer from consumers to farmers. There is increased competition for land, and biofuel crops displace other crops and impinge on pastures and managed forests. Finally, the direct emissions savings from biofuels are outweighed by the indirect emissions from land use change. However, with a carbon budget in place, it is calculated that by around 2030, the indirect emissions from land use change would be 'paid back'⁴⁹.

43 DR7B (Annex E refers); HMG (2009)

44 Fischer (2009)

45 IEA (2008)

46 Msangi and Rosegrant (2009)

47 Searchinger et al. (2008)

48 Bouet et al. (2010)

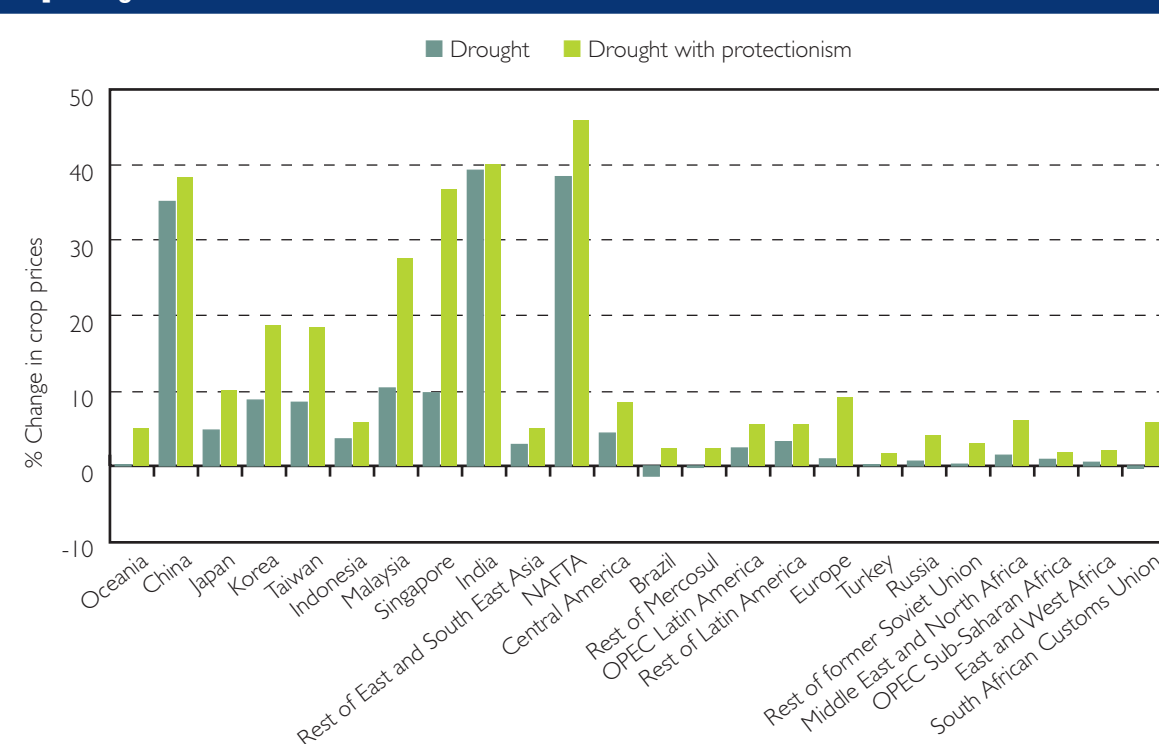
49 This calculation does not consider the effect of fertiliser emissions from intensified production.

C4.5.3 Governance: simulation results

Drought in the North American Free Trade Agreement (NAFTA) area, China and India and a protectionist response

The recent food price spike for rice and wheat in 2008 has been partly attributed to export restrictions⁵⁰. To investigate further the potential impacts of drought, a reduction in crop yields in the USA, Canada, Mexico, China and India, followed by the imposition of a 25% export tax by all crop-exporting regions, is simulated. This is an extreme simulation designed to illustrate the impact of a general protectionist response. There are high crop price rises in the domestic markets of the regions directly affected by the drought (Figure C4.22). Net importers in East Asia also face significant rises in crop prices because drought-affected regions export less to them and compete more for imports. Increased incentives to produce in regions not directly affected by the drought and international trade both limit the fall in global crop production to less than 2%. If food exporting regions impose a protectionist response, however, crop prices are significantly higher in all regions and trade is harshly impeded (Figures C4.22 and C4.23). Global crop production does not fall under this scenario, as high crop prices provide an incentive to produce more but often in areas with a comparative disadvantage. Restrictions on exports thus lead to inefficient, high-cost production.

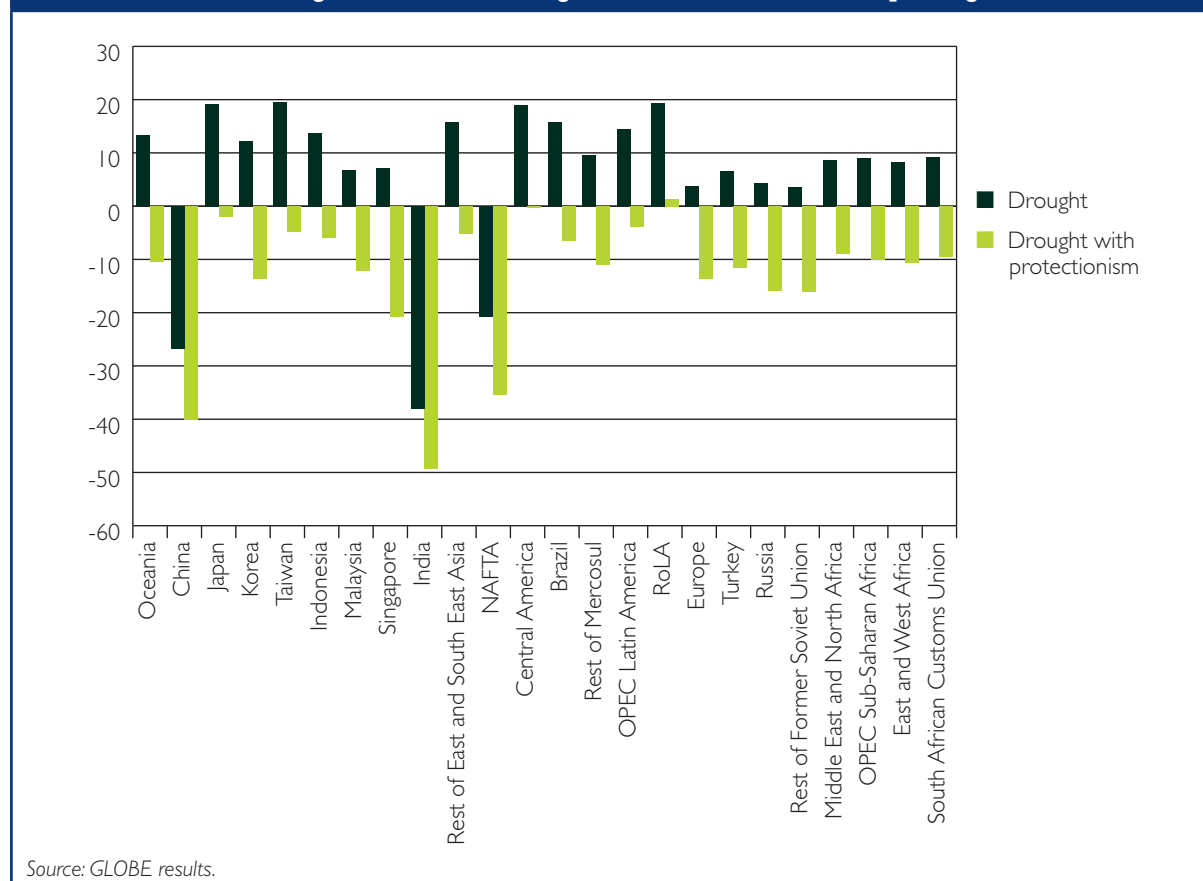
Figure C4.22: Real domestic food price changes under a drought scenario with and without export restrictions (% change in crop prices relative to each region's overall consumer price index). NAFTA, North American Free Trade Agreement; OPEC, Organization of Petroleum Exporting Countries



Source: GLOBE results.

50 HM Government (2009)

Figure C4.23: Change in net food crop trade (% change in export volume). NAFTA, North American Free Trade Agreement; OPEC, Organization of Petroleum Exporting Countries

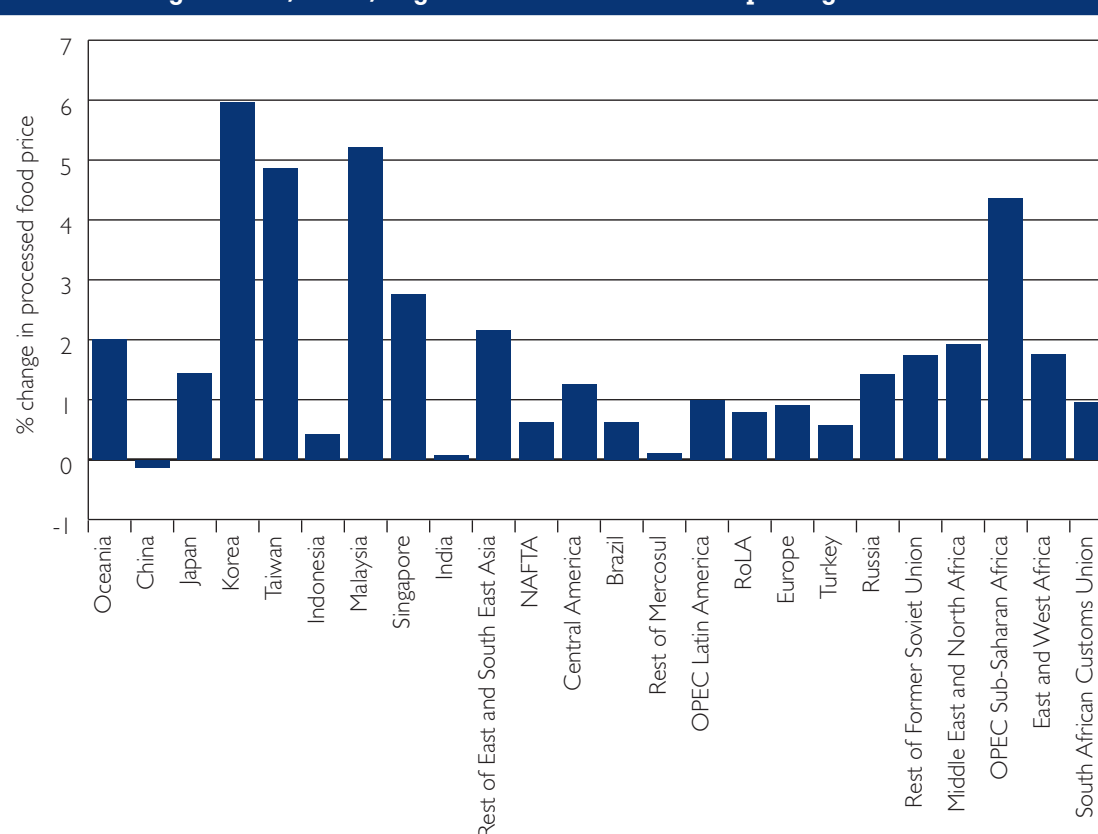


Major increase in protectionism

In this scenario, import duties are doubled from 2005 rates across all regions. Existing free trade areas such as NAFTA remain intact. This scenario does not imply that the World Trade Organization (WTO) effectively dissolves, but instead assumes that the current Doha Round of multilateral trade negotiations breaks down. Applied tariffs are often well below the maximum bound tariffs allowed under the current WTO regime, and increases of the order of magnitude considered here are mostly consistent with current WTO regulations⁵¹. Increased protectionism leads to notable increases in prices for processed foods and especially for net importers (Figure C4.24). International trade flows between regions halt.

⁵¹ Bouet and Laborde (2010); Willenbockel (2009)

Figure C4.24: Real price changes in processed food under a major increase in protectionism (% change relative to each region's overall consumer price index). NAFTA, North American Free Trade Agreement; OPEC, Organization of Petroleum Exporting Countries



Source: GLOBE results

C4.5.4 Demand: simulation results

Additional increase in demand for meat in China and India

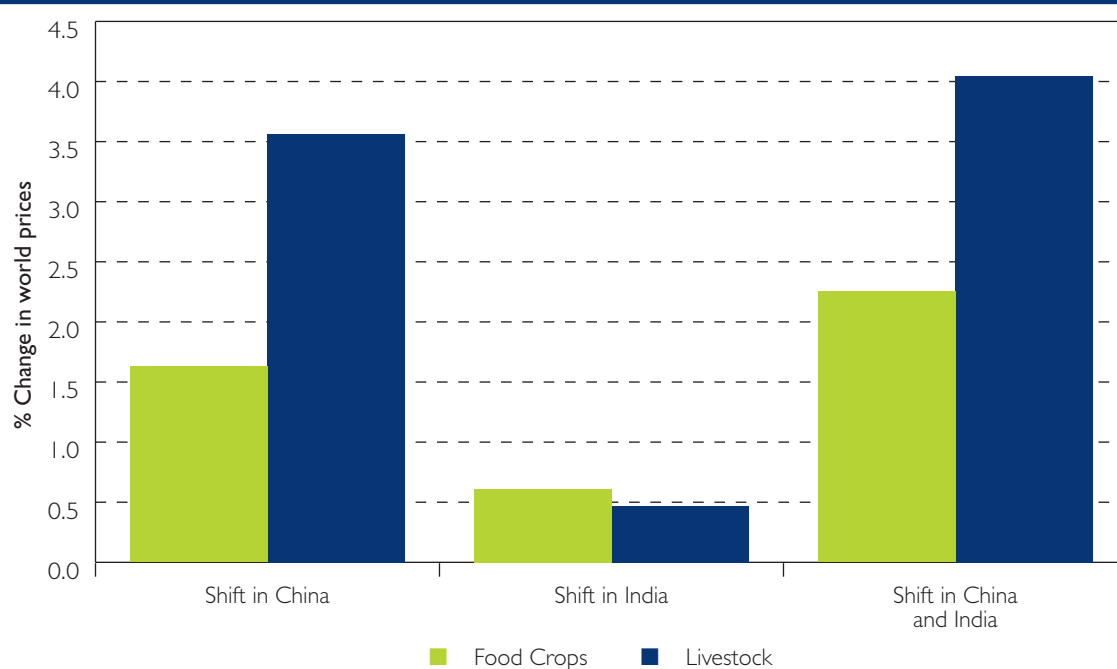
In recent years there has been a substantive shift in China to a diet with more livestock products and a lower consumption of traditional foods⁵². Although meat consumption is not expected to increase in India at the same rate as in China, a rise in consumption is plausible⁵³. The impact of changes in the demand for meat in China and India is simulated using the GLOBE model. In this simulation, the share of total consumer spending on livestock products is increased by 10%, whereas the share spent on services decreases by the same amount⁵⁴.

The impact on domestic prices in both countries of livestock and food crops is significant, which induces increased production within the countries and more imports. This in turn affects world markets and leads to increased world prices and significant growth in the global production of livestock, and increased trade (Figures C4.25 and C4.26). A rise in Chinese demand has a larger impact on world markets because China is more dependent on imports than India.

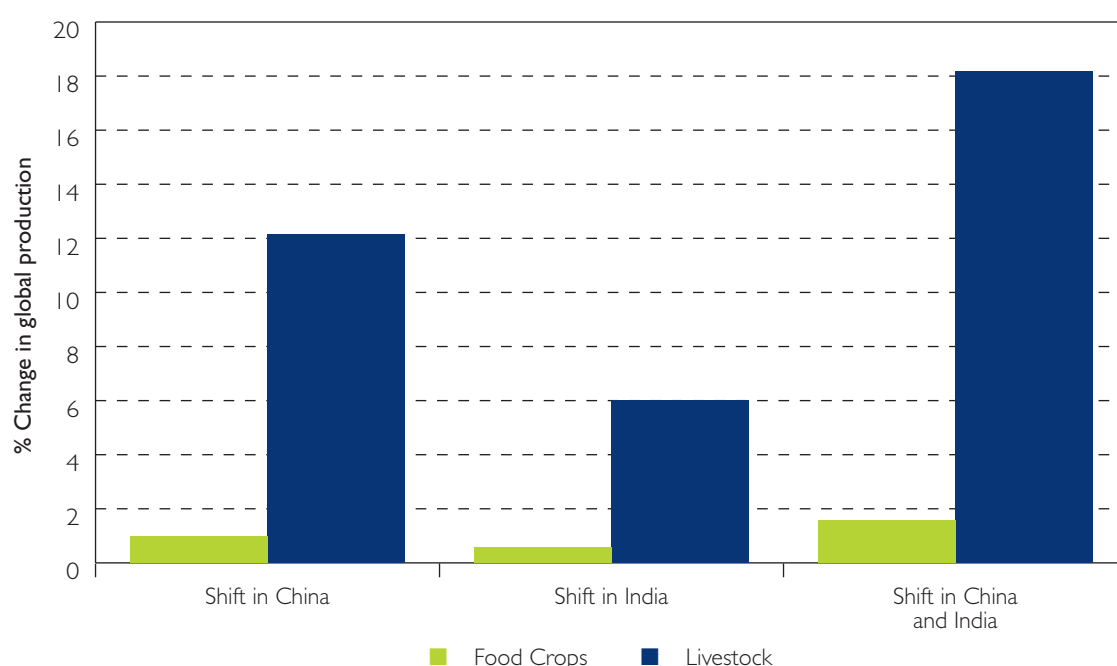
⁵² Du et al. (2004)

⁵³ DR3

⁵⁴ In high-income countries, much of the demand for meat is in the form of processed food and food purchased in restaurants – the latter shows up in the data as demand for services. The data for China and India reflect high levels of on-farm consumption of meat, so it is convenient to increase livestock demand directly in these scenarios.

Figure C4.25: Real world food price changes under increased meat demand in China and India (% change in world prices)

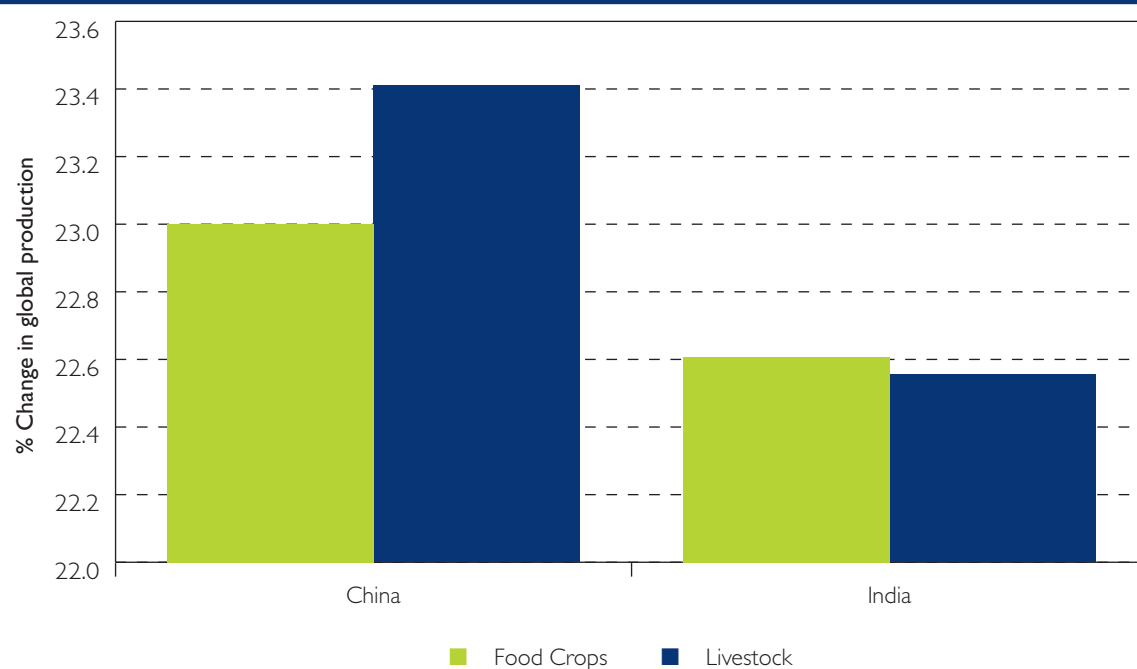
Source: GLOBE results.

Figure C4.26: Change in global food production under increased meat demand in China and India (% change in global production)

Source: GLOBE results.

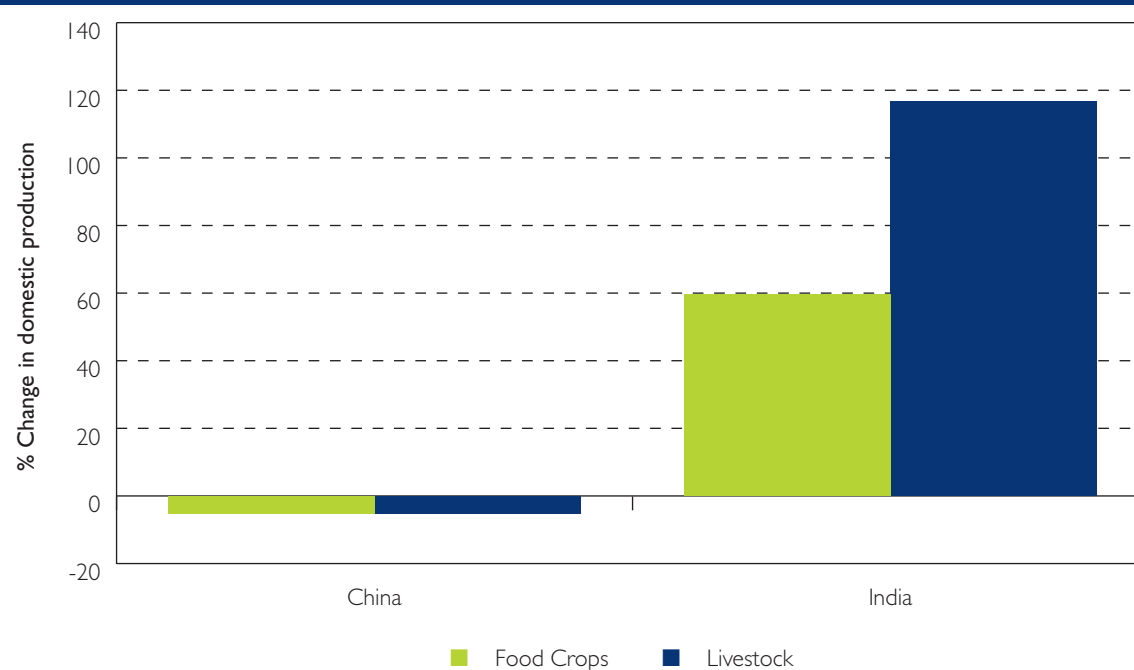
If demand is increased in both countries, household consumption of livestock is roughly double, and household demand for food grains increases by about 20%. Domestic prices of both livestock and food grains go up dramatically in both countries (Figure C4.27), and both countries respond by increasing livestock production (Figure C4.28). Competition for land limits the ability of food crop production to increase. Imports of both livestock and food grains also go up (Figure C4.29), although from a much lower base in India than in China.

Figure C4.27: Real domestic food prices under increased meat demand in both China and India (% change in domestic prices)

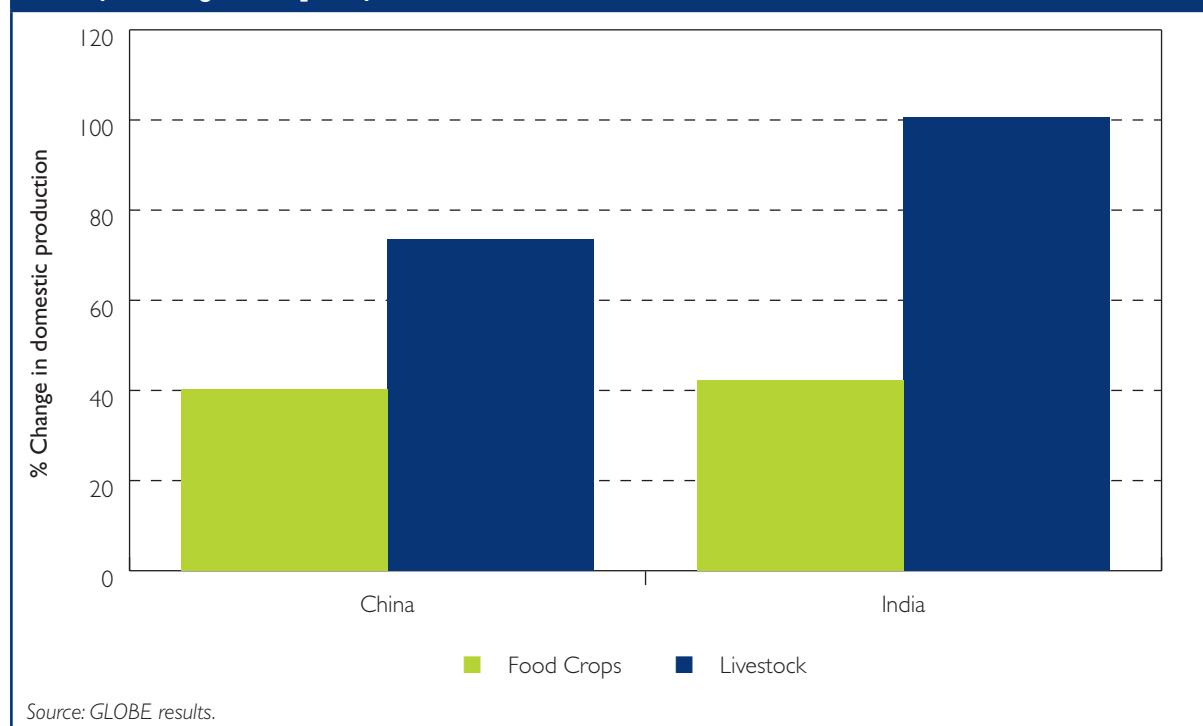


Source: GLOBE results.

Figure C4.28: Change in domestic food production under increased meat demand in both China and India (% change in domestic production)



Source: GLOBE results.

Figure C4.29: Change in domestic imports under increased meat demand in both China and India (% change in imports)

There is a strong indirect link to food grain prices and global imports from increased livestock demand. However, there is little indirect effect on global production of food grains, because there is competition for land from increased livestock production, which limits the ability of food crop production to increase. In the longer run, one might expect there to be a larger indirect effect on food grain production, if livestock production can move to less land-intensive methods.

Shifts in demand for livestock in large countries such as China and India do have global impacts in this analysis. The magnitudes indicate that world markets should be able to respond to such demand changes, but the impacts on markets within the two countries is much more dramatic. Over time, in response to the large price changes within China and India, further changes in technology and trade, especially in livestock products, would be expected, with further indirect impacts on other countries. However, as in the drought scenarios, if international markets are not able to respond, the impacts on China and India will be more severe. If countries respond to increased foreign demand by limiting trade, then there is a weaker supply response from outside of India and China, and much stronger effects on world prices. In fact, additional model runs with different assumptions on trade policy suggest that the impact is two to three times greater on livestock and grain prices within India and China and correspondingly on world markets.

C4.6 Uncertainties in the analysis

Using a quantitative model to simulate a complex food system is hugely challenging, and this analysis is necessarily qualified by the underlying data and methods that have been used to produce these results⁵⁵.

Both partial equilibrium and multi-country CGE models have a limited domain of applicability (Box C4.1). More generally, the availability, coverage, quality and accessibility of spatially explicit data sets for global production and trade, land use and hydrology, which provide the basis for model calibration and validation, require improvement⁵⁶. IMPACT uses the Food and Agriculture Organization (FAO) FAOSTAT data for 2000 as a base year to project from, but this data set is not complete and some data have to be manually constructed. Data are aggregated and disaggregated so that they can be used at spatial and temporal scales different from those at which they were collected; but the methods used to do this

⁵⁵ Rotmans and van Asselt (2001)

⁵⁶ DRI0A (Annex E refers)

require improvement⁵⁷. Input assumptions for crucial drivers such as population and income growth are exogenous to the models and are themselves subject to uncertainty. The assumptions made for future agricultural productivity and growth in crop area in the main scenarios are based partly on expert judgement (see Box C4.5). Recent analysis suggests that many models could be exaggerating food price rises by underestimating the responsiveness of the long-term supply of new land for food production as prices increase⁵⁸. More work is also required in modelling the future impact on agriculture of demand for biofuels.

Box C4.5: Is agricultural productivity growth improving or deteriorating?

From 1961 to 2008, growth rates of yields (output per hectare) for grains in developed countries were on average 1.5% per annum and 2.1% in developing countries. Since 1985, there has been a reduction in these average growth rates⁵⁹. Projections of food prices are very sensitive to assumptions about growth in supply, and hence to changes in yields.

Growth in agricultural output can result from growth in either area planted or yields, or both. Yield growth can arise from intensification of inputs (more inputs used with the same amount of land) or from productivity growth (changes that yield more output for the same level of inputs). Total factor productivity (TFP) growth is a measure of increases in output per unit of all inputs, including land, and is used as a summary measure of increases in output that are not due to increases in inputs. While intensification (e.g. greater use of machinery, labour or chemicals with the same amount of land) is an important source of growth in agriculture in developing countries, productivity growth is generally more important. Identifying the nature and sources of productivity growth is crucial for policy: what mix of policies should be emphasised to develop better machinery, better seeds, better chemicals, better farm management practices and improvements in land and irrigation.

Research suggests that global TFP growth has improved in recent decades and accounts for an increasing share of the growth in agricultural output⁶⁰. In fact, there has been a slowing down in the growth of inputs for production, with variation across different regions.

Growth in TFP is important to the concept of sustainable intensification⁶¹ because it will ease constraints on land, labour and other resources: 1% growth in TFP means 1% fewer resources are needed to produce the same amount of output. Research and development is key to increasing productivity, but there may be long lead times before benefits are fully realised. In summary, productivity growth has offset the deceleration of input growth to keep global agriculture growing at an average of 2% per annum since the 1960s⁶². There has, however, been a slowing down in recent years in public research and development expenditure on agriculture, particularly on productivity-enhancing research⁶³.

There are both optimistic and pessimistic views on the future of agricultural productivity⁶⁴. In the base scenario, the IMPACT modelling framework assumes that growth rates of yields increase slightly over the next 10–15 years and then decline gradually to 2050. These assumed trends incorporate assumptions about intensification and productivity growth, assuming 'business as usual' levels of resources applied to research and development.

Biophysical effects of CO₂ fertilisation in the field are uncertain⁶⁵. Four different plausible temperature and precipitation outcomes have been chosen because of the uncertainties surrounding climate modelling. The results assume that climate variables change linearly between their values in 2000 and 2050. This assumption eliminates any random extreme events such as droughts and floods, which are

57 Ewert et al. (2009)

58 Hertel (2010)

59 DR8 (Annex E refers)

60 Fuglie (2008); Fuglie (2010)

61 Sustainable intensification produces more food from the same amount of land in a renewable way; see The Royal Society of London (2009).

62 Fuglie (2010)

63 DR8 (Annex E refers)

64 DR8 (Annex E refers)

65 DR2 (Annex E refers)

expected to increase in frequency⁶⁶. The effect of this assumption is to underestimate negative effects from climate variability. Direct effects on livestock are not included.

To project food demand it is important that models possess Engel flexibility: that is, they accurately reflect the changes over time in the budgetary share for food and in the composition of the budget as income grows. In particular, marginal budget shares should vary non-linearly with income. The current generation of models do not have enough Engel flexibility to accurately capture decreasing marginal budget shares⁶⁷.

There are drivers that are not explored in this scenario analysis. Many of these drivers are difficult either to quantify or to model, and in some instances knowledge about them is currently inadequate⁶⁸. The evolution of pests, parasites, diseases and weeds, especially in a changing climate, may have an impact on crop production⁶⁹. In addition, rising ozone concentrations are likely to have adverse impacts⁷⁰. On the other hand, future food production may actually be underestimated by these results. While the loss of crop areas owing to climate change is simulated by the IMPACT modelling framework, gains from new areas where production is subsequently possible are not. Examination is required of a wider range of climate change adaptation strategies and costs⁷¹. For example, the possibility of varietal substitution is not included. The adoption of new emerging technologies from areas such as nanotechnology, biotechnology, robotics and information and communications technology (ICT) could plausibly induce substantial changes in agricultural productivity, but there is a lack of relevant historical precedents to help simulate their future impact. Human behaviour and values are subject to unpredictable change. High-impact, high-uncertainty 'black swan' events may all be unknowable (Table C4.2)⁷².

Table C4.2: Selected sources of uncertainties in this analysis

Type of uncertainty ⁷³	Source of uncertainty
Technical	Data to calibrate and validate models Exogenous assumptions for population and income growth Partly exogenous assumptions for agricultural productivity and crop area growth Elasticity of land supply with respect to price
Methodological	Upscaling and downscaling of data Modelling demand for biofuels Lack of Engel flexibility in demand systems Modelling climate change Modelling gains from new areas of production Biophysical effects of CO ₂ fertilisation in the field
Epistemological	Climate variability Impact of pests, parasites, diseases and weeds Impact of rising ozone concentrations TFP growth Farmer adaptation to climate change Human behaviour and values Technological change High-impact, high-uncertainty 'black swan' events

66 DR2 (Annex E refers)

67 DR11 (Annex E refers)

68 DR10A (Annex E refers)

69 DR5A (Annex E refers)

70 DR2 (Annex E refers)

71 Easterling et al. (2007)

72 Taleb (2007)

73 Uncertainty types are based on Funtowicz and Ravetz (1990); see DR10A (Annex E refers).

Scenarios are a limited yet valuable tool to help decision-makers prepare strategies that are more robust to future uncertainty⁷⁴. These uncertainties do mean that probabilities cannot be credibly assigned to the absolute results of the scenarios and simulations. Nevertheless, this analysis does allow exploration of a range of plausible futures.

C4.7 Key conclusions

- According to the main scenarios, economic development has a large positive impact on food security outcomes for developing countries⁷⁵.
- World food prices increase in the main scenarios in a reversal of the trend in the 20th century; they are driven on the demand side by drivers such as population and income growth and on the supply side by assumptions on yield growth and reduced productivity because of climate change.
- An increase in productivity-enhancing research will be needed if the significant price rises reported here are to be prevented.
- Growth in TFP is important to attaining sustainable intensification.
- Other models have projected price rises in the future but prices appear particularly sensitive to assumptions about growth in agricultural productivity.
- Climate change overall has a negative effect on crop productivity, but there are large regional differences in its impact: results differ depending on the climate model used and demonstrate the uncertainty surrounding the impact of climate change on agriculture.
- Results from these models and others suggest that international trade is important in ameliorating the impact of both the unequal distribution of climate change effects and idiosyncratic supply-side shocks such as droughts.
- Increases in protectionism amplify stresses on the food system by increasing prices and encouraging production in less suitable areas.
- In other simulations it is changes in the growth in crop productivity that have the greatest effects on food prices and food security outcomes.
- An increase in energy prices decreases food security outcomes indirectly by diverting household resources away from food consumption in countries that are dependent on fuel imports; this impact dominates any effects from higher input prices for agriculture.
- The impact of future biofuel production will depend on uncertainties such as energy prices, energy policies and technological change; recent research has found that increased biofuel production results in food price rises but that this impact is reduced if second-generation technology is available or if international trade encourages production in more suitable regions.
- More modelling research is needed so that decision-makers can better comprehend the complex interconnections between the energy system and the food system.
- A rise in demand for livestock products in large countries such as China and India increases global demand for food and leads to increases in world food prices; global markets can lessen the impact if trade flows freely, otherwise the effects may be more severe.
- Systematic comparison of the many food system models that produce long-term projections is needed so that decision-makers can understand better the various uncertainties that surround the future of the food system.
- The data sets that provide the basis for model calibration and validation urgently require improvement to enhance the utility of scenarios and models to decision-makers.

⁷⁴ Lempert et al. (2006)

⁷⁵ Developing countries include low-income and middle-income developing countries.

References

- BOUET, A. AND LABORDE, D. 2010. Assessing the Potential Cost of a Failed Doha Round. *World Trade Review* 9(2), 319–51.
- BOUET, A., DIMRANAN, B.V. AND VALIN, H. 2010. Modelling the global trade and environmental impacts of trade policies. IFPRI Discussion Paper 01018.
- CARPENTER, S.R., PINGALI, P.L., BENNETT, E.M. AND ZUREK, M.B. 2005 Ecosystems and human well-being: findings of the scenarios working group of the millennium ecosystem assessment. In *Millennium ecosystem assessment series, vol. 2*. Washington, DC: Island Press. (eds).
- DEVARAJAN, S., LEWIS, J.D. AND ROBINSON, S. 1990. Policy Lessons from Trade-Focused, Two-Sector Models. *Journal of Policy Modeling* 12, 625–657.
- DEVARAJAN, S. AND ROBINSON, S. 2002. The influence of computable general equilibrium models on policy. In *Trade and macroeconomics division discussion paper 98*. Washington, DC: International Food Policy Research Institute.
- DU, S., MROZ, T.A., ZHAI, F. AND POPKIN, B. M. 2004. Rapid income growth adversely affects diet quality in China – particularly for the poor! *Social Science and Medicine* 59, 1505–1515.
- EASTERLING, W. E. et al. 2007. Food, fibre and forest products. In *Climate change 2007: impacts, adaptation and vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (eds M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E. Hanson), pp. 273–313. Cambridge, UK: Cambridge University Press.
- ERICKSEN, P.J. 2008. Conceptualizing food systems for global environmental change research. *Global Environmental Change* 18, 234–245.
- EWERT, F., VAN ITTERSUM, M. K., BEZLEPKINA, I., THEROND, O., ANDERSEN, E., BELHOUCLETTE, H., BOCKSTALLER, C., BROUWER, F., HECKELEI, T., JANSSEN, S., KNAPEN, R., KUIPER, M., LOUHICHI, K., OLSSON, J. A., TURPIN, N., WERY, J., WIEN, J. E. & WOLF, J. 2009. A methodology for enhanced flexibility of integrated assessment in agriculture. *Environmental Science & Policy*, 12, 546–561.
- FAOSTAT. 2010. FAOSTAT. www.faostat.fao.org
- FISCHER, G., SHAH, M., TUBIELLO, F.N. AND VAN VELHUIZEN, H. 2005. Socio-economic and climate change impacts on agriculture: an integrated assessment, 1990–2080. *Philosophical Transactions of the Royal Society B* 360, 2067–2083.
- FISCHER, G. 2009. World Food and Agriculture to 2030/50: How do climate change and bioenergy alter the long-term outlook for food, agriculture and resource availability? *FAO Expert Meeting on How to Feed the World in 2050*. June 24–26. Rome: FAO.
- DE FRAITURE, C., WICHELNS, D., ROCKSTRÖM, J., KEMP-BENEDICT, E., ERIYAGAMA, N., GORDON, L., HANJRA, M., HOOGVEEN, J., HUBER-LEE, A. & KARLBERG, L. 2007. Looking ahead to 2050: scenarios of alternative investment approaches. In: *MOLDEN, D. (ed.) Water for food, water for life: a comprehensive assessment of water management in agriculture*. London: Earthscan.
- FUGLIE, K.O. 2008. Is a slowdown in agricultural productivity growth contributing to the rise in commodity prices? *Agricultural Economics* 39, 431–441.
- FUGLIE, K.O. 2010. Accelerated productivity growth offsets decline in resource expansion in global agriculture. *Amber waves*. Washington, DC: United States Department of Agriculture Economic Research Service.
- FUNTOWICZ, S. O. AND RAVETZ, J. R. 1990. *Uncertainty and quality in science for policy*. Dordrecht, Netherlands: Kluwer.

- HAIE, N. AND KELLER, A.A. 2008. Effective Efficiency as a Tool for Sustainable Water Resources Management. *Journal of the American Water Resources Association* 44, 961–968.
- HAZELL, P. AND WOOD, S. 2008. Drivers of change in global agriculture. *Philosophical Transactions of the Royal Society B* 363, 495–515.
- HERTEL, T. Ed. 1997. *Global Trade Analysis: Modeling and Applications*. Cambridge: Cambridge University Press.
- HERTEL, T. 2010. The Global Supply and Demand for Agricultural Land in 2050: A Perfect Storm in the Making? GTAP Working Paper No 63. West Lafayette, IN: Purdue University.
- HERTEL, T.W., BURKE, M. B. & LOBELL, D. B. 2010. The poverty implications of climate-induced crop yield changes by 2030. *Global Environmental Change-Human and Policy Dimensions*, 20, 577–585.
- HM GOVERNMENT. 2009. *The 2007/08 Agricultural Price Spikes: Causes and Policy Implications*. London: HM Government.
- INTERNATIONAL ENERGY AGENCY. 2008. *World Energy Outlook*. Paris, France: OECD/IEA.
- IVANIC, M. AND MARTIN, W. 2010. *Promoting global agricultural growth and poverty reduction*. Washington, DC: World Bank.
- LONG, S.P., AINSWORTH, E.A., LEAKEY, A.D.B., NOSBERGER, J. AND ORT, D.R. 2006. Food for thought: lower-than expected crop yield stimulation with rising CO₂ concentrations. *Science* 312, 1918–1921.
- MCCALLA, A. F. AND REVOREDO, C. L. 2001. Prospects for global food security: a critical appraisal of past projections and predictions. Food, agriculture, and the environment discussion paper 35. Washington, DC: International Food Policy Research Institute.
- MCDONALD, S. AND THIERFELDER, K. 2004. Deriving a Global Social Accounting Matrix from GTAP version 5 Data', GTAP Technical Paper 23. Global Trade Analysis Project. Lafayette, IN: Purdue University.
- MCDONALD, S., THIERFELDER, K. AND ROBINSON, S. 2007. *Globe: A SAM Based Global CGE Model using GTAP Data*. USNA Working Paper No. 14. Annapolis, MD: US Naval Academy.
- MARGULIS, S. et al. 2010. *Cost to Developing Countries of Adapting to Climate Change: New Methods and Estimates*. Washington, DC: World Bank.
- MEEHL, G.A., STOCKER, T.F., COLLINS, W.D., FRIEDLINGSTEIN, P., GAYE, A.T., GREGORY, J.M., KITOH, A., KNUTTI, R., MURPHY, J.M., NODA, A., RAPER, S.C.B., WATTERSON, I.G., WEAVER, A.J. AND ZHAO, Z.-C. 2007. Global Climate Projections. In *The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (eds. S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller). Cambridge, UK and New York, NY, US: Cambridge University Press.
- VAN DER MENSBRUGGHE, D., OSORIO-RODARTE, I., BURNS, A. AND BAFFES, J. 2009. Macroeconomic environment, commodity markets: a longer term outlook. FAO Expert Meeting on How to Feed the World in 2050.. June 24–26. Rome: FAO.
- MSANGI, S. AND ROSEGRANT, M. 2009. World agriculture in a dynamically-changing environment: IFPRI's long-term outlook for food and agriculture under additional demand and constraints. FAO Expert Meeting on How to Feed the World in 2050. June 24–26. Rome: FAO.
- NAKICENOVIC, N., ALCAMO, J., DAVIS, G., DEVRIES, B., FENHANN, J., GAFFIN, S., GREGORY, K., GRÜBLER, A. et al. 2000. *Special Report on Emissions Scenarios (SRES)*. Intergovernmental Panel on Climate Change (IPCC). Cambridge, UK: Cambridge University Press.
- NELSON, G.C. et al. 2009. *Climate change impact on agriculture and costs of adaptation*. Washington, DC: International Food Policy Research Institute.

NELSON, G.C., ROSEGRANT, M.W., PALAZZO, A., GRAY, I., INGERSOLL, C., ROBERTSON, R., TOKGOZ, S., ZHU, T., SULSER, T.B., RINGLER, C., MSANGI, S. AND YOU, L. 2010. Food security, farming, and climate change to 2050: Scenarios, results, policy options. Washington, DC: International Food Policy Research Institute.

OECD/FAO. 2010. Agricultural Outlook 2010–2019. Organization for Economic Co-operation and Development and Food and Agriculture Organization.

PARRY, M.L., ROSENZWEIG, C., IGLESIAS, A., LIVERMORE, M. AND FISCHER, G. 2004. Effects of climate change on global food production under SRES emissions and socioeconomic scenarios. *Global Environmental Change* 14, 53–67.

PARSON, E.A., BURKETT, V., FISHER-VANDEN, K., KEITH, D., MEARN, L., PITCHER, H., ROSENZWEIG, C. AND WEBSTER, M. 2007. Global-change scenarios: their development and use. Washington, DC: US Climate Change Science Program.

POSTEL, S.L. 1998 Water for Food Production: Will There Be Enough in 2025? *BioScience* 48(8), 629–637.

ROBINSON, S. (1989). Multisectoral Models. In H.B. Chenery and T.N. Srinivasan, eds. *Handbook of Development Economics*. Amsterdam, Netherlands: North-Holland.

ROSEGRANT, M.W., MSANGI, S., RINGLER, C., SULSER, T., ZHU, T. & CLINE, S.A. 2008. International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT). Washington, DC: IFPRI

ROTMANS, J. AND VAN ASSELT, M.B.A. 2001. Uncertainty in integrated assessment modelling: a labyrinthic path. *Integrated Assessment* 2, 43–55.

ROYAL SOCIETY OF LONDON. 2009. Reaping the benefits: science and the sustainable intensification of agriculture. London, UK: Royal Society.

SCHMIDHUBER, J. AND TUBIELLO, F.N. 2007. Global food security under climate change. *Proceedings of the National Academy of Sciences* 104, 19703–19708.

SEARCHINGER, T. et al. 2008. Use of US Croplands for Biofuels Increases Greenhouse Gases Through Emissions from Land-Use Change. *Science* 319, 1238–1240.

TALEB, N.N. 2007. *The black swan: the impact of the highly improbable*. London, UK: Penguin.

WACK, P. 1985. Scenarios: uncharted waters ahead. *Harvard Business Review* 63, 72–89.

WILLENBOCKEL, D. 2009. From Overhang to Hangover: Consequences of Protectionist Responses to the Global Crisis for Low-Income Countries. MPRA Discussion Paper No. 16100, University of Munich.

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