Global Food Security Modelling:
A Review of Approaches and Results

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Executive Summary

Context and Aims

The global food system will face an unprecedented confluence of pressures over the next decades arising from the combination of population growth, rising per-capita incomes and climate change. Deciding how to address the challenges of securing access to affordable nutritious food for a growing world population in a sustainable manner is a major task facing policy makers today.

Rational forward-looking decision making requires informed projections of the likely consequences of alternative policy strategies to address the challenges to food security and sustainable development over the coming decades. Given the complex dynamic interactions among the socio-economic drivers and bio-physical processes that co-determine food security outcomes and the numerous uncertainties surrounding these drivers, the provision of long-run projections for the global food and farming system is a difficult task that requires advanced modelling tools.

The present report provides a concise overview of the current state of the art in long-term global food system modelling with a focus on contemporary modelling efforts that integrate climate change factors with projections for agricultural production and international food security towards the middle of the 21st century. It (i) provides a brief synopsis of key results from applications of these models in major recent scenario studies from a food security perspective, (ii) compares and contrasts different modelling approaches presently in use, (iii) identifies reasons for major differences in projections across models and studies, and (iv) points out major knowledge gaps and priority areas for future model development aimed at improving the usefulness of these models for the generation of policy-relevant insights.

Global Food Security Projections towards 2050 in Major Recent Scenario Studies

The review of long-run scenario projections for global food security in major recent international assessments covers studies published since 2005 that address the links between global environmental change and the food system. The comparison across scenarios highlights the sensitivity of results to alternative assumptions about the uncertain drivers of change that enter the modelling systems exogenously – such as projections for population, per-capita income and agricultural trend productivity growth.

While the more optimistic scenarios suggest improvements in food security outcomes for all of today's developing regions relative to the present, other scenarios indicate that in sub-Saharan Africa and parts of South Asia a combination of continued high population growth with adverse climate change impacts and low investments in yield growth in the absence of effective international development cooperation may lead to dramatic deteriorations in food security in these regions towards the middle of the century.

Modelling Approaches

Contemporary models in use for long-run projections of agriculture and the food system can be classified into two broad categories – economy-wide computable general equilibrium (CGE) models and partial equilibrium (PE) multi-market models that focus only on agricultural sectors. CGE models consider all production sectors in an economy simultaneously and take full account of macroeconomic constraints and intersectoral linkages. With respect to the representation of the food system, their strength is that they include the entire value chain from agricultural production to food processing and distribution and finally to food consumption by households. In contrast, PE models focus on just one aspect of the value chain – unprocessed or first-stage processed agricultural products – and ignore macroeconomic constraints and linkages between agricultural production and aggregate income. This limits the domain of applicability of these partial-analytic models to scenarios in which the feedback effects of shocks to agriculture on aggregate income are small. On the other hand, PE models support a more detailed commodity disaggregation than CGE models and a finer spatial resolution on the supply side.

In contrast to the CGE models as a group, the PE models are far more heterogeneous in terms of their specifications of the supply side. Some PE models incorporate very detailed spatially explicit grid- or pixel based representation of bio-physical agricultural production conditions, while others feature a more aggregated level of spatial resolution on the supply side.

Why Do Long-Run Projections of Global Food Security Outcomes Differ?

A pioneering global agricultural model comparison initiative currently addresses the crucial question to which extent the large variation in existing long-run projections is attributable to methodological differences across models as opposed to differences in exogenous driver assumptions about population, income and agricultural productivity trends. Initial results from this ongoing project involving the leading modelling teams around the globe show that substantial cross-model differences in long-run projections persist even under harmonized assumptions about these main drivers of change.

From a conceptual perspective, the differences in projections across models under these harmonized assumptions can be traced back to differences in the explicit or implicit assumptions about the effective size orders of four sets of elasticities: the effective price and income elasticities of demand for agricultural commodities, the effective land supply elasticities, and the effective price elasticities of agricultural productivity growth. Thus, for the simulation behaviour of the models at broad regional scales, the choice of numerical values for the parameters that co-determine these elasticities are ultimately more important than the prior choice of methodological framework.

Priorities for Future Research

This review points to a number of priority areas for future research in global long-run agricultural and food system modelling. To a large extent, future model improvements are necessarily contingent on parallel progress in empirical research across a range of disciplines including, inter alia, climate science, crop and livestock science and economics to advance the state of scientific knowledge on which modellers must rely in the course of the numerical parameterization of the model components. More dialogue across modelling teams – in particular about best practice in incorporating the existing empirical evidence regarding the key parameters that determine simulation results – is essential to narrow down the variance in projections. The satisfactory integration of water availability and use in global long-run simulation models as well as model validation remain further major challenges for future research.

1. Introduction

The global food system will face an unprecedented confluence of pressures over the next decades[1]. The combination of population growth and rising per-capita incomes that will be accompanied by a shift towards more livestock-intense diets in parts of the world will translate into a substantial increase in the demand for agricultural output between now and the middle of the century. These demand-side drivers are bound to intensify the competition for land and water, particularly in low-income regions with high population growth and a high present incidence of undernutrition.

A further set of threats to future food security emerge from climate change. Long-run agricultural productivity trends as well as short-run yield variability are directly affected by climate change and the associated expected increases in extreme weather events, and a growing number of studies suggest that climate change may well reduce the productivity of farming in precisely those regions of the world where malnutrition is most prevalent.[2]

At the same time the global food system and its impact on land use contribute significantly to global greenhouse gas emissions – a fact which severely complicates the challenge of securing access to affordable nutritious food for a growing world population in a sustainable manner. Moreover, climate change mitigation policies aimed at the energy sector that raise fossil fuel prices affect bioenergy demand and further intensify the competition for land.

Deciding how to balance the multiple pressures and competing demands on the global food system is a major task facing policy makers today. Rational forward-looking decision making requires information about the likely consequences of alternative policy strategies to address the challenges to food security over the coming decades.

Given the complex dynamic interactions among the socio-economic drivers and bio-physical processes that co-determine food security outcomes and the numerous uncertainties surrounding these drivers, the provision of long-run projections for the global food and farming system is a difficult task. Despite substantial progress in food

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[1] Government Office for Science (2011a)

[2] Hertel (2011)

system modelling, there is significant scope for the development of improved modelling capabilities. As the recent UK Government Office for Science (2011) report on the future of food and farming puts it,

> "Food system modelling in particular will continue to be an invaluable tool for informing policy-makers. Modelling is very far from a panacea and faces huge challenges – yet it is the only tool available for trying to understand the complex non-linear interactions of the numerous drivers affecting the food system" (Government Office for Science 2011:159).

The present report aims to provide a concise overview of the current state of the art in long-term global food system modelling with a focus on contemporary modelling efforts that integrate climate change factors with projections for agricultural production and international food security towards the middle of the 21st century. The objectives are to compare and contrast different modelling approaches presently in use, to provide a synopsis of key results from applications of these models in major recent scenario studies from a food security perspective, and to identify reasons for differences in these results across models and studies.

Key questions addressed in this review include:

- Which models are currently in use and what kind of modelling approaches have been taken in terms of spatial, commodity and environmental coverage?
- How do models account for the impact of climate change?
- What are the key differences across models in terms of structure, assumptions, spatial coverage and outputs?
- Where are the main evidence gaps and how are these being addressed?
- Given the current state of modelling technology, what are the emerging results on long-run food security outcomes from these models? How sensitive are these results to underlying assumptions?

The following section sets the stage by reviewing the long-run scenario projections for global food security in major recent international assessments published since 2005 that address the links between global environmental change and the food system. This comparison across scenarios highlights the sensitivity of results to different assumptions about the drivers of change that enter the modelling systems exogenously – such as projections for population, per-capita income and autonomous agricultural trend productivity growth.

Section 3 provides an overview of the types of modelling tools used in these international assessments and in other recently published studies with a global outlook that provide quantitative projections for food security variables in a changing climate up to 2050. While the comparison of projections across scenario studies offered in section 2 provides insights about the degree to which long-run food security projections depend on exogenous assumptions about the uncertain evolution of the main socio-economic drivers of change, it gives little indication of the extent to which differences in projections are attributable to methodological differences across models used in the various assessments. This important question is addressed in section 4, which draws primarily on new insights from the first phases of the Agricultural Model Intercomparison and Improvement Project (AgMIP) hosted by Columbia University and co-funded by the UK government. The global modelling track of this ongoing project is a pioneering effort to engage leading modelling teams in the area of long-run global agricultural and food system modelling in a systematic comparison of projections for a standardized set of exogenous driver assumptions.

Finally, section 5 identifies major knowledge gaps and priority areas for future research and cross-disciplinary dialogue and collaboration aimed at overcoming the limitations of contemporary models in this area to further improve their usefulness for the generation of policy-relevant insights.

2. Recent Global Assessments of Long-Run Food Security in the Context of Environmental Change

2.1. Overview

This section reviews recent model-based long-run scenarios for the potential evolution of the global food system over the coming decades. It characterizes the assumed prospective trends for the main drivers of change that will shape future patterns of food production and trade at global and broad regional scales and provides a selective synopsis of existing scenario projections from a food security perspective.

The review covers six major studies concerned with the future of the global food system published since 2005 that provide a quantified outlook up to 2050. It includes the long-run scenarios developed as part of four international assessments – the Millennium Ecosystem Assessment (Carpenter et al (eds), 2005 –henceforth *MA*), the International Assessment of Agricultural Science and Technology for Development (Rosegrant et al, 2009 – *IAASTD*), the Comprehensive Assessment of Water Management in Agriculturestudy (de Freiture et al, 2007 – *CAWMA*) and the Global Environmental Outlook 4 (Rothman et al, 2007 – *GEO4*) – as well as the scenarios reported in the International Food Policy Research Institute's 'Food Security, Farming, and Climate Change to 2050' Report (Nelson et al, 2010 – *IFPRI*) and finally the 2012 revision of the Food and Agriculture Organization's global long-run projections (Alexandratos and Bruinsma, 2012 - *FAO*).

2.2. A Perspective on Scope, Objectives and Scenario Design

Scope and Objectives of the Scenario Studies

The six studies differ in terms of their focus and objectives, and these differences influence the choice of scenario design. The broad remit of the MA Scenarios Working Group was to assess future changes in world ecosystems and the consequences of these changes for human well-being, and to inform decisions-makers at various scales about possible response strategies. The MA is primarily geared towards the information requirements of the various United Nations (UN) conventions on biodiversity, desertification, wetlands and migratory species. The United Nations Environment Programme's (UNEP) GEO4 assessment is likewise broadly concerned with environmentally sustainable development, and in both studies food provision is conceptualized as one among other ecosystem services.

In contrast, in the other four studies under review agriculture and food security take the center stage. The objective of IAASTD is to assess the impacts of past, present and future agricultural knowledge, science and technology (AKST) on the reduction of hunger and poverty, improvement of rural livelihoods and human health, and equitable, socially, environmentally and economically sustainable development. IAASTD was initiated in 2002 by the World Bank and the FAO as an intergovernmental consultative process cosponsored by other United Nation bodies including the Global Environment Facility (GEF), UN Development Programme, UNEP, UN Educational, Scientific and Cultural Organization, and World Health Organization.

CAWMA aims to assess the current state of knowledge on how to manage water resources to meet the growing needs for agricultural products, to help reduce poverty and food insecurity, and to contribute to environmental sustainability in order to enable better investment and management decisions in water and agriculture in the future. CAWMA was coordinated by the International Water Management Institute and cosponsored by the Consultative Group on International Agricultural Research (CGIAR), the FAO and the UN biodiversity and wetlands conventions.

The objective of the IFPRI study is to provide an end-of-decade assessment of the challenges to global food security up to 2050 with a particular emphasis on the nexus between climate change, climate change adaptation and agricultural yields. The study has been co-sponsored via the UK Government Office for Science Foresight Programme and early results from the IFPRI study served as an input to the influential Foresight Global Food and Farming Futures Report (Government Office for Science, 2011a,b).

The FAO 2012 projections provide an update of earlier 2006 FAO long-run projections based on revised and more recent data.

Scenario Design

With respect to the approach to scenario design adopted in the various studies, it is helpful to distinguish between “business-as-usual” trend projections without major shifts in policy orientations or step changes in human behaviour, and exploratory scenario studies that consider a broader range of alternative conceivable futures (Reilly and Willenbockel, 2010).

Examples of the former are the FAO projections, the IAASTD reference world scenario, and the IFPRI and CAWMA baseline scenarios. Exploratory scenarios contrast different possible trajectories for the main drivers of change in the global agri-food system including population growth, aggregate real income growth, policies towards agricultural productivity growth, trade and international development policy orientations, attitudes towards ecological sustainability, and climate change impacts on yields. Among the studies in this category, the MA and GEO4 scenarios try to underpin the different assumptions for the driver paths with more (MA) or less elaborate (GEO4) qualitative narratives that outline envisaged major shifts in institutional and socio-political frameworks as well as in value systems. The four MA scenarios are framed in terms of contrasting evolutions of governance patterns for international cooperation and trade (globalized versus regionalized) and opposite approaches towards ecosystem management (pro-active versus reactive). Similarly, in GEO4 the scenarios are defined by different policy approaches and societal choices, “with their nature and names characterized by the theme that dominates the particular future envisioned, such as what comes *first*”[3] (Table 1).

Other scenarios in this category – including the IAASTD AKST scenarios, the IFPRI productivity improvement simulation runs, and the CAWMA water management investment scenarios – focus on an exploration of alternate investment strategy options for the agricultural sector while adopting *ceteris paribus* assumptions for other drivers of system change. Table 1 provides a brief overview of the distinguishing key features of the scenarios reviewed here in terms of their assumptions about policy shifts affecting the food system.

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[3] Rothman, Agard and Alcamo (2007: 451), italics in original.

Table 1: Policy Orientations in the Scenarios

Study	Scenario	Key Characteristics
FAO		Projection without major shifts in policy orientations
MA	Global Orchestration - GO	Global cooperation and a reactive approach towards ecosystem management
	Techno Garden - TG	Proactive technology- and market-based approach to ecosystems and high levels of international cooperation
	Adapting Mosaic - AM	Emphasis on local approaches and local learning to the improvement of ecosystem services with low levels of international cooperation
	Order from Strength - OS	Reactive approach to ecosystem stresses, high trade barriers and low levels of global cooperation
GEO4	Markets First	Emphasis on market-based solutions, increased role of the private sector in previously government-led areas, liberalised trade, and "commoditization of nature"
	Policy First	Centralized policy-led approach to balancing strong economic growth with "a lessening of the potential environmental and social impacts". Similar to MA GO
	Security First	Government and private sector compete for control in efforts to improve human well-being for "mainly the rich and powerful in society". Similar to MA OS
	Sustainability First	Actors at all levels follow through on pledges made to date to address environmental and social concerns
CAWMA	Baseline Scenario	Projection without major shifts in policy orientations
	Rainfed High Yield	Investments in rainfed areas: water harvesting, supplemental irrigation
	Rainfed Low Yield	Pessimistic case: upgrading rainfed agriculture is not successful
	Irrigation Area Expansion	Expansion of irrigated areas
	Irrigation Yield Improv.	Improvements in the performance of existing irrigated areas
	Trade Scenario	Increased agricultural trade from water-abundant to water-scarce countries
	Comprehensive Scenario	Optimal region-specific combination of rainfed, irrigation and trade strategies
IFPRI	Baseline	Projection without major shifts in policy orientations
	Optimistic	Lower population growth and higher per-capita GDP growth than baseline
	Pessimistic	Higher population growth and lower per-capita GDP growth than baseline
	Productivity improvement	Various measures to raise agricultural productivity
	Perfect Mitigation	Baseline without climate change impacts on crop yields
IAASTD	Reference Run	Current policy pathways are expected to continue out to 2050
	AKST_high_pos	High levels of agricultural R&D investment with high growth of complementary investments
	AKST_low_neg	Low levels of agricultural R&D investment with decelerating growth of complementary investments

The Use of Simulation Models in the Scenario Studies

The MA, GEO4 and IAASTD employ various ensembles of 'soft-linked'[4] simulation models with a common core that consists of the global integrated assessment model IMAGE (Integrated Model to Assess the Global Environment) developed at the Dutch

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[4] In soft-linked model ensembles, output variables from one model are used to inform the selection of values for the input variables or parameters of another model, but the different models are not formally merged—or hard-wired—into a single consistent simultaneous-equation system. The scientific basis for linking models across disciplines and scales is still weak and requires specific attention in future research as further discussed in section 5.

National Institute for Public Health and the Environment and the global multi-market partial equilibrium model IMPACT (International Model for Policy Analysis of Agricultural Commodities and Trade) maintained at IFPRI. IMAGE is designed to capture interactions between economic activity, land use, greenhouse gas (GHG) emissions, climate, crop yields and other environmental variables. It includes (optionally) a stylised multi-region computable general equilibrium model of global trade and production, a carbon-cycle module to calculate GHG emissions resulting from economic activity including energy and land use, a land-use module and an atmosphere–ocean climate module that translates GHG emissions into climate outcomes. The model-determined temperature and precipitation outcomes in turn feed back into the performance of the economic system via agricultural productivity impacts. The global agricultural market model IMPACT is designed to provide disaggregated projections for production, demand for food, feed and other uses, prices, trade, crop area and yields across over 30 food commodity groups and also derives impacts on and childhood malnutrition from these projections.

To exemplify the use of soft linkages between models, in the MA study, for instance, the changes in crop yields due to climate change predicted by IMAGE have been used to adjust the agricultural productivity parameters of IMPACT, the IMPACT agricultural production data have served as input to the IMAGE land cover model, and the changes in irrigation within IMPACT as well as the climate projections of IMAGE have been used as inputs for the WaterGAP simulations.

In the three scenario studies this common core of models is further soft-linked to a varying range of further simulation models to arrive at projections for other variables of interest and to downscale[5] results for particular regions. Thus, for instance both the MA and GEO4 use WaterGAP hydrology and water-use model simulations to assess water stress and the EcoPath/EcoSim modelling suite to project marine ecosystems. Both MA and IAASTD employ the GLOBIO model to simulate biodiversity impacts.

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[5] Downscaling refers to the process of disaggregating variables towards a more detailed spatial or commodity classification scale.

Furthermore, the MA employs a second integrated assessment model, AIM, to compare emissions projections with those of IMAGE, and IAASTD uses the computable general equilibrium model GTEM for additional trade liberalisation scenarios.

In contrast to these three studies, the projections of the IFPRI and CAWMA scenarios are each based on single partial-equilibrium models, namely the aforementioned IMPACT model and IWMI's WATERSIM model respectively. WATERSIM consists of a food production and demand module (which is identical to the IMPACT model) and a water supply and demand module based on a water balance and water accounting framework.

The quantitative FAO projections are not based on the simulation of a formal documented behavioural model but are derived by combining simple demand projections from Engel demand functions and exogenous assumptions on population and GDP growth with an iterative process of adjustments to yield and area change projections by commodity and region involving expert judgements. The FAO supply utilization account framework is used to establish consistency between source and use projections (Alexandratos and Bruinsma, 2012:137-139). This approach does not generate projections for the evolution of food prices over time.

The characteristics and limitations of the models mentioned here are further discussed and compared with a wider set of contemporary global food system models in sections 3 and 4 respectively.

2.3. Assumptions for Key Drivers of Change in the Global Food System

Population and Income Growth

Table 2 reports the assumptions about global population and per-capita real income growth – the two main drivers of food demand – underlying the various scenarios. In the MA, the predicted world population in 2050 ranges from 8.1 billion in the GO to 9.6 billion in the OS scenario. The main reason for the divergence is that GO assumes higher economic growth and higher human capital investments in education and health than OS and hence a faster transition towards lower fertility and mortality rates in developing regions. Trade liberalization, international economic cooperation, and technology exchange foster economic performance in the two MA scenarios with globalized governance (GO and TG), while trade barriers and inward-oriented policies are assumed to contribute to lower growth rates in the OS and AM scenarios. Growth rates are higher in GO compared to TG, because in the latter investments in environmental technologies are favoured at the expense of human capital investments.

The differences in population growth across the four GEO4 scenarios are based on a similar reasoning. In the IFPRI study, the assumed differences in population and income per capita are simply the defining characteristic that differentiates the three scenarios, but in contrast to the MA and GEO studies these differences are not underpinned by an elaboration of the socio-political developments that co-determine demographic trends and economic performance.

From a food security perspective, it is worth emphasizing that the major portion of the projected global population growth will be located in the least-developed countries of sub-Saharan Africa and South Asia.

Table 2: Population 2050, Per-Capita Income Growth and Calorie Intake

Study	Scenario	Population 2050 *million*	Average per-cap. GDP growth Base year to 2050 *% p.a. (Base Year)*	Calorie Intake 2050 World *kcal/capita/day*	Calorie Intake 2050 SSA *kcal/capita/day*
		2005: 6900		2005/07: 2770	2005/07: ~2300
FAO		9150	1.3 (2005)	3070	~2700
MA	Global Orchestration	8100	2.7 (1997)	3521	>3000
	Techno Garden	8800	2.2 (1997)	3210	<3000
	Adapting Mosaic	9500	1.7 (1997)	2920	<2500
	Order from Strength	9600	1.28 (1997)	2953	<2500
GEO4	Markets First	9200	~ 2.6 (2005)	~4000	~3500
	Policy First	8600	~ 2.8 (2005)	~4200	~3700
	Security First	9700	~ 1.4 (2005)	~3200	~2400
	Sustainability First	8000	~ 2.5 (2005)	~4400	~4000
CAWMA	All Scenarios	8900	2.2 (2000)	2970	na
IFPRI	Baseline	9096	2.5 (2010)	↑	↑
	Optimistic	7913	3.2 (2010)	↑	↑
	Pessimistic	10399	0.7 (2010)	↓	↓
IAASTD	Reference Run	8200	~ 2.0 (2000)	~ 3000	2738
	AKST_high_pos	8200	na	> 3000	4700
	AKST_low_neg	8200	na	< 3000	1600

Agricultural Productivity Growth

On the supply side, a key direct driver of change in food system performance is agricultural productivity growth. The last column of Table 3 displays the average annualized growth rates of cereal yields between the study-specific base year (third column) and 2050 as a rough aggregate indicator of differences in agricultural productivity growth across the various scenarios. As the base years range from 1997 to 2010 across the scenario studies, comparisons across different scenarios within the same study are more straightforward than cross-study comparisons.

Climate Change

With the exception of FAO and presumably CAWMA[6], all scenario projections take account of climate change impacts on agricultural productivity. In the MA scenarios, global mean temperature increases for 2050 range from +1.6 °C (TG) to +2.0 °C (GO) over pre-industrial levels. Yield impacts are based on IMAGE model projections that suggest positive effects for the USA and the former Soviet Union but negative for other regions, including in particular South Asia with strong adverse impacts on rice and temperate cereal yields. In GEO4, global mean temperature increases range from +1.7 °C (Sustainability First) to +2.2 °C (Markets First) by 2050 relative to the pre-industrial mean. Yield impacts relative to a reference case without climate change are not reported for this study. IAASTD assumes a mean global rise of +1.7 °C over pre-industrial level by 2050. Agricultural impacts are projected to be negative for dryland areas in Africa, Asia and the Mediterranean area. Yield impacts of climate change by 2050 are characterized as "still relatively small, apart from some crucial regions like South Asia".[7]

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[6] In an appendix note, Alexandratos and Bruinsma (2012: 92-93) concede that the FAO projections make no attempt to incorporate climate change impacts and end with the remarkable admission that "(i)n principle, a scenario that assumes no climate change has no place in the array of scenarios to be examined". The CAWMA study points out that climate change adds to the complexity of water resources planning and management and includes a selective review of the literature on climate change and agricultural performance, but there is no indication how climate change impacts have been incorporated in the quantitative projections.

[7] Rosegrant, Fernandez and Sinha (2009:327). The unsharp nature of the cited statement is typical for the descriptions of the assumed influence of climate change in most of the scenario studies under review.

In the IFPRI scenarios, which consider climate projections arising from the combination of two IPCC emission scenarios (A1B, B1) with two global circulation models (CSIRO, MIROC), mean global surface temperature changes by 2050 range from +1.0 to +3.0 ^{o}C relative to the late 20th century mean (i.e. about +1.6 to+3.6 ^{o}C compared to pre-industrial levels). The global average yield changes compared to the counterfactual Perfect Mitigation (i.e. zero climate change) scenario for 2050 – obtained by linking the climate projections with the DSAT crop model suite – range from -2.0 to -12.0 per cent for maize, from 0 to -12.1 per cent for rice and from -4.1 to -13.2 per cent for wheat.

Table 3: Assumed Cereal Yield Growth and Projections for Staple Crop Prices

Study	**Scenario**	**Base Year**	**World Market Price Change** *Base to 2050 %*			**Cereal yield growth** *Base to 2050 % p.a.*
			Rice	**Wheat**	**Maize**	
FAO		2005/07	na	na	na	0.66
MA	Global Orchestration	1997	-31.6	6.3	38.8	~1.00
	Techno Garden	1997	-25.6	-12.7	-11.7	~0.82
	Adapting Mosaic	1997	56.1	41.3	53.4	~0.57
	Order from Strength	1997	46.0	14.7	19.4	~0.41
CAWMA	Rainfed High Yield	2000	na	na	na	rf 1.09 irr 0.61
	Rainfed Low Yield	2000	na	na	na	rf 0.37 irr 0.58
	Irrigation Area Expansion	2000	na	na	na	rf 0.36 irr 1.00
	Irrigation Yield Improvement	2000	na	na	na	rf 0.38 irr 1.15
	Trade Scenario	2000	na	na	na	rf 0.93 irr 0.58
	CAWMA	2000	na	na	na	rf 0.92 irr 0.88
IFPRI	Baseline	2010	54.8	54.2	100.7	na
	Optimistic	2010	31.2	43.5	87.3	na
	Pessimistic	2010	78.1	58.8	106.3	na
	Productivity Improvement	2010	31.2	20.0	59.8	na
	Perfect Mitigation	2010	19.8	23.2	32.2	na
IAASTD	Reference Run	2000	21.5	61.6	41.7	1.02
	AKST_high_pos	2000	-53.8	-48.2	-73.1	1.63
	AKST_low_neg	2000	303.3	780.8	1291.5	0.41

Notes: rf: rainfed cereal yields;irr: irrigated cereal yields; na: not available; p.a.: per annum. GEO4 reports neither of the indicators tabulated here.

With the exception of the IFPRI study, none of the scenario reports provides a systematic quantitative comparison relative to a hypothetical reference case without climate change.

All studies under review emphasize the high degree of uncertainty surrounding projections of climate change impacts on agricultural productivity, which arises inter alia from the high variance in projections of future precipitation patterns across climate models and from the current lack of scientific consensus about the potential magnitude of benign carbon fertilization effects on crop yields.

The IPPC Fourth Assessment Report anticipates with high confidence that “projected changes in the frequency and severity of extreme climate events will have more serious consequences for food and forestry production, and food insecurity, than will changes in projected means of temperature and precipitation” (Easterling et al, 2007), and the more recent IPCC Special Report on Managing the Risks from Extreme Events (IPCC, 2012) lends further support to this conclusion. While most of the scenario studies under review mention that an increased frequency of droughts and floods in a changing climate will affect food security outcomes, the quantitative projections do not take account of this additional climate change impact channel.[8]

In view of the current deadlock in global mitigation negotiations, it is worth pointing out that the global temperature projections for 2050 at the lower end of the spectrum in the reviewed scenarios appear now already highly overoptimistic, if not obsolete. Climate science is adamant that annual global CO_2 emissions would have to peak by 2020 at the latest and need to drop steadily in subsequent decades in order to maintain a reasonable chance to achieve the aim of limiting the average global temperature rise to +2 ^{o}C above pre-industrial levels. It is now clear that even under optimistic assumptions about further progress in post-Durban climate diplomacy, no binding global deal covering the major greenhouse gas emitters will be in force prior to 2020 – hence the +2^{o} C limit is now

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[8] A partial exception is the IFPRI study, which explores the price implications of a prolonged drought in South Asia in a separate scenario. For a brief selective review of the current state of science concerning projections of changes in the frequency of extreme events due to anthropogenic climate change and a set of explorative simulation scenarios examining the potential food price impacts of extreme weather events using a global general equilibrium model see Willenbockel (2012). This study also examines the contribution of weather extremes to the recent observed food price hikes. For an example of recent progress in model-based economic climate change impact analysis for individual countries incorporating projections of extreme weather shocks see Robinson, Willenbockel and Strzepek (2012).

likely to be exceeded[9] and scientists are getting serious about contemplating human development prospects in a +4^o C world.[10]

2.4. A Brief Synopsis of Projections Towards 2050

This section provides a concise selective synopsis of scenario projections for the middle of the 21st century with a focus on food security outcomes, international trade in food commodities and envisaged shifts in the modes of food production and distribution systems.

Food Security

Table 2 displays the simulated results for average calorie intake per capita per day in 2050 at a global scale. None of the studies envisages a plain world-wide Malthusian doom scenario. However, the global averages mask considerable variations in food security outcomes towards the middle of the century at sub-global scales across the simulations, as illustrated in the last column of Table 2 for the case of sub-Saharan Africa (SSA).[11]

While most of the scenarios suggest improvements in food security along with reductions in malnutrition for all developing sub-regions relative to the base year, the MA Order from Strength scenario as well as the IFPRI pessimistic case, the GEO4 Security First and the IAASTD AKST_low_neg scenario suggest that a combination of continued high population growth, adverse climate change impacts and low investments in yield growth

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[9] This is confirmed by the new IPCC (2013) AR5 Report, which states with high confidence that global warming is likely to exceed +2 ^{o}C under two of the four IPCC emission scenarios (RPC8.5 and RCP6.5) and more likely than not to exceed +2 ^{o}C under the optimistic RCP4.5 scenario. The exception is the (for practical realistic planning purposes largely irrelevant) RCP2.6 scenario, which counterfactually assumes that drastic global mitigation measures are already under way or imminent on a global scale.

[10] See e.g. New et al (2011) and Thornton et al (2011). The latter study envisages a bleak future for agriculture in sub-Saharan Africa in a +4^o C world.

[11] Since the composite sub-regions for which scenario results are reported differ across the various studies, it is not possible to provide a systematic and concise tabular synopsis of food security outcomes or other scenario results at sub-global scales. However, the following overview highlights scenario projections for regional food insecurity hotspots – which are predominantly located in sub-Saharan Africa and South Asia – as far as these are reported in the scenario narratives.

in the absence of effective international development cooperation may lead to opposite outcomes for SSA – and similar conclusions apply to low-income South Asia, the other hotspot of persisting or worsening food security problems in these pessimistic scenarios.

In stark contrast, the reported calorie consumption figures for the IAASTD AKST-high_pos and GEO4 Sustainability First scenarios, taken at face value, would seem to imply that by 2050 nutrition problems in SSA will take the form of obesity problems.

Three of the MA scenarios project absolute decreases in the absolute number of malnourished children in 2050 relative to 1997 baseline numbers, while in the MA OS this number increases by 18 million in SSA and by 6 million in South Asia as a result of depressed food supplies, high food prices, and low investments in maternal and child care as well as health and sanitation services. Under the AM scenario, the number of malnourished children increases by 6 million children in sub-Saharan Africa, but declines by 14 million in South Asia.

In the FAO projection the incidence of undernourishment in today's developing countries as a group drops from 15.9 per cent of the total developing country population in the 2005/07 baseline to 7.1 per cent in 2050 (that is an absolute decline by 509 million people). In SSA, undernourishment drops from 27.6 to 7.1 per cent (- 82 million), in South Asia from 21.8 to 4.2 per cent (- 238 million), in East Asia from 11.0 to 2.8 per cent (-217 million), in Latin America and the Caribbean from 8.5 to 2.5 per cent (-29 million) and in the MENA region from 7.4 to 3.4 per cent (-7 million).

With respect to the projected remaining levels of undernourishment in 2050 (318 million people – 119 million in SSA, 93 million in South Asia and 62 million in East Asia), the FAO study points out that despite the assumptions about positive per-capita income growth across all regions, 15 developing countries will still show a per-capita income below $1,000 in 2050 according to the projections[12] and the persistence of undernourishment in 2050 is a reflection of this prospect. While the FAO study robustly dismisses the notion of an emerging *global* food availability problem as a result of population growth, the persistence of undernourishment is *not* reduced to a mere problem of access that is unrelated to supply side constraints:

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[12] Down from 45 countries in the 2005/07 baseline.

> “production constraints are and will continue to be important determinants of food security; however, they operate and can cause Malthusian situations to prevail, at the local level and often because in many such situations production constraints affect negatively not only the possibility of increasing food supplies but can be veritable constraints to overall development and prime causes of the emergence of poverty traps” (Alexandratos and Bruinsma, 2012:10).

In the IAASTD reference run, the global childhood malnutrition headcount is projected to decline by 50 million children relative to the 2000 baseline to 99 million children by 2050. However, in sub-Saharan Africa child malnutrition rises by 11 per cent to 33 million in this scenario. Average per-capita calorie availability for South Asia in 2050 is with 2746 kcal / day very close to the projection for SSA in the reference scenario. Under the High_AKST_high scenario, food security outcomes improve significantly.

In the IFPRI study, daily calorie availability in low-income developing countries as a group rises by 6.8 per cent in the baseline, by 9.7 per cent in the optimistic scenario and by up to 26.9 per cent in the productivity improvement scenarios while dropping by 6.2 per cent in the pessimistic scenario between 2010 and 2050. The corresponding figures for the projected percentage change in the number of malnourished children are – 8.6 (baseline), -36.6 (optimistic), -22.6 (productivity improvement) and +18.1 (pessimistic) respectively.

Staple Crop Prices

Table 3 reports world market price projections for the main traded staple crops between the base year and 2050 as a key indicator of the extent to which global supply keeps up with rising demand, as far as price results are presented in the scenario reports. Due to the differences in base years across the scenarios, comparisons of the price results across the different scenarios are far from straightforward. It is not obvious that rebasing to a common base year using observed prices for a particular recent year would resolve this problem, given that prices in the long-run simulation models should appropriately be interpreted as long-run trend prices that do not reflect short-run deviations from the underlying long-run trend due to temporary shocks. However, it is clear from the figures in Table 3 that long-run price projections vary widely across scenarios, and that – unsurprisingly – differences in the assumptions about long-run agricultural productivity growth are one of the main explanatory factors for these variations.

How Sensitive are Projections to the Choice of Model?

This cursory synoptic glimpse at recent long-run food system scenarios highlights the wide range in assumptions about the main drivers of change within and across the studies. For the exploratory scenarios this is as it should be – it is after all precisely the high degree of uncertainty about the future pathways for the main drivers of change and the need to explore alternative policy options that motivates the adoption of a multi-scenario approach in the first place (Reilly and Willenbockel, 2010). But even in the various baseline scenarios that aim to employ "middle-of-the-road" trend projections and envisage no major policy shifts, the exogenous driver assumptions about population, GDP and agricultural productivity growth differ substantially.

Therefore, this synopsis does not indicate to which extent the differences in outcomes are plainly attributable to the fact that different scenario studies use different quantitative simulation models or model ensembles. This crucial question will be explored in section 4 below.

3. A Typology of Modelling Approaches

3.1. Overview

This section provides an overview of the types of models used to generate long-run projections for the global food system in the scenario studies reviewed above and in other recently published peer-reviewed studies with a global outlook that provide quantitative projections for food security variables in a changing climate up to 2050.

These models can be classified into two broad categories – economy-wide computable general equilibrium (CGE) models and partial equilibrium (PE) multi-market models that focus only on agricultural sectors. CGE models consider all production sectors in an economy simultaneously and take full account of macroeconomic constraints (including factor market constraints, household budget constraints and balance-of payments constraints) and intersectoral linkages. CGE models take consistent account of the circular flow of income in an economy from (i) income generation through productive activity, to (ii) the primary distribution of that income to workers, owners of productive capital, and recipients of the proceeds from land and other natural resource endowments, to (iii) the redistribution of that income through taxes and transfers, and to (iv) the use of that income for consumption and investment. With respect to the representation of the food system, their strength is that they include the entire value chain from agricultural production to food processing and distribution and finally to food consumption by households.

In contrast, PE models focus on just one aspect of the value chain – unprocessed or first-stage processed agricultural products – and ignore macroeconomic constraints and linkages between agricultural production and aggregate income. This limits the domain of applicability of these partial-analytic models to scenarios in which the feedback effects of shocks to agriculture on aggregate income are small. On the other hand, PE models support a more detailed commodity disaggregation than CGE models and a finer spatial resolution on the supply side.

Table 4 lists the main contemporary models in these two categories and Table 5 gives an overview of their spatial and sectoral resolution with respect to agriculture and food.

Table 4: Model Synopsis 1: Overview

Model	**Affiliation**	**Locus**	**Documentation Link**	**Recent Applications**
General Equilibrium Models				
AIM	National Institute of Environmental Studies	Japan	http://www-iam.nies.go.jp/aim/infomation.htm	MA
ENVISAGE	Food and Agriculture Organization	Italy	http://siteresources.worldbank.org/INTPROSPECTS/../Envisage7b.pdf	van der Mensbrugghe et al (2011)
EPPA	Massachussetts Institute of Technology	USA	http://globalchange.mit.edu/igsm/eppa.html	Paltsev et al (2005)
FARM	US Department of Agriculture	USA		Sands et al (2013)
GTEM	Australian Bureau of Agricultural and Resource Economics and Sciences	Australia	http://www.daff.gov.au/abares/models	IAASTD
MAGNET	LEI - Wageningen University	Netherlands		Overmars et al (2012)
Partial Equilibrium Models				
CAPRI	University Bonn	Germany	http://www.capri-model.org/dokuwiki/doku.php	Shrestha et al (2013)
GCAM	Pacific Northwest National Laboratory	USA	http://wiki.umd.edu/gcam/index.php?title=Main_Page	Wise et al (2009)
GLOBIOM	International Institute for Applied Systems Analysis	Austria	http://www.iiasa.ac.at/Research/FOR/globiom.html	Havlik et al (2011)
IMPACT	International Food Policy Research Institute	USA	http://www.ifpri.org/book-751/ourwork/program/impact-model	MA, GEO4, IAASTD, Nelson et al (2010), Government Office for Science (2011b)
MAgPIE	Potsdam Institute for Climate Impact Research	Germany	http://www.pik-potsdam.de/research/sustainable-solutions/groups/landuse-group	Dietrich et al (2013)

Table 5: Model Synopsis 2: Spatial and Sectoral Dimensions

Model	Agricultural Commodities	Processed Food Commodities	Regions	Spatial Resolution of Land Use	Trade
General Equilibrium Models					
AIM	8	1	116	same	non-spatial
ENVISAGE	10	5	20	same	spatial
EPPA	2		16	same	spatial
FARM	12	8	13	same	spatial
GTEM	7	7	13	same	spatial
MAGNET	10	9	45	same	spatial
Partial Equilibrium Models					
CAPRI	45	2	63	Europe: 280 regions	spatial
GCAM	18	0	16	151 regions	non-spatial
GLOBIOM	31	6	30	0.5 by 0.5 degree grid	non-spatial
IMPACT	32	14	115	285 regions	non-spatial
MAgPIE	21	0	10	0.5 by 0.5 degree grid	non-spatial

3.2. CGE Models

The CGE models share essentially a common approach to the specification of agricultural supply, demand and trade. Production decisions and the resulting allocation of land across activities in each region are based on profit maximizing behaviour by price-taking producers subject to technology constraints. These technology constraints enter the model in the form of sectoral production functions that allow for imperfect substitutability between primary factors (land, labour, capital) and include an explicit disaggregated representation of intermediate input requirements. The share parameters of these production functions are in all cases calibrated to the empirical input-output tables in the regional blocs of the Global Trade Analysis Project (GTAP) database maintained at Purdue University. Final demand for food by households in each region is derived jointly with demand for all other consumer goods as the result of utility maximizing behaviour subject to their budget constraints. All CGE models except AIM[13] adopt a nested

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[13] AIM uses a single-nest Armington specification, which treats domestic output and aggregate imports in each commodity group as imperfect substitutes in each region’s demand system but does not further disaggregate imports by region of origin.

Armington specification for trade flows which treats agricultural and processed food products of different regional origin as imperfect substitutes, and thus allows the determination of bilateral trade flows among all model regions.

Within this basic common structure, differences across the CGE models arise primarily from the choices of sectoral and regional aggregation levels, functional form for the utility functions (Table 1), nesting structure of the production functions (Appendix Table A2), and elasticity parameters, as well as from differences in the specification of aggregate land supply and land substitutability across agricultural activities.

With respect to land use, the CGE models typically impose limited "mobility" of land between agricultural sectors, using flat or nested constant-elasticity-of-transformation (CET) specifications of varying complexity. In all CGE models, land supply for agricultural use is effectively a function of returns to land. In ENVISAGE and MAGNET total land supply is modeled using a logistic or rational function with a maximum asymptote, while in AIM natural forest and pasture area can be transformed to anthropogenic land using a logistic function. In FARM, land is allocated among crops, pasture, and forest within six land classes for each world region using a CET formulation.[14] In the market module of CAPRI aggregate agricultural land supply is likewise linked to the returns to land by specifying regional land supplies simply as iso-elastic functions of the land price.

3.3. PE Models

Supply-Side Specifications

In contrast to the CGE models as a group, the PE models are far more heterogeneous in terms of their specifications of the supply side. In particular, GLOBIOM and MAgPIE incorporate very detailed spatially explicit grid or pixel based representation of bio-physical agricultural production conditions.

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[14] The treatment of land use in contemporary global long-run CGE and PE models is described in further detail in Schmitz et al (2013).

In GLOBIOM, the spatial resolution of the supply side relies on the concept of Simulation Units, which are aggregates of 5 to 30 arcmin pixels belonging to the same altitude, slope, and soil class, and also the same country. For crops, grass, and forest products, Leontief production functions covering alternative production systems are calibrated based on biophysical models. For the AgMIP study, the supply side spatial resolution was aggregated to 120 arcmin (about 200 x 200 km at the equator). Six land cover types are distinguished in GLOBIOM: cropland, grassland, short rotation tree plantations, managed forest, unmanaged forest and other natural vegetation. Depending on the relative profitability of the individual activities and on the recursivity constraints, the model can switch from one land cover type to another.[15]

MAgPIE is a nonlinear recursive dynamic optimization model that links regional economic information with grid-based biophysical constraints. The biophysical supply side of the model is simulated spatially explicit using 0.5 degree data aggregated to 1000 clusters. The biophysical inputs and yields are derived from the grid-based dynamic global vegetation model with managed land LPJmL. LPJmL is a process-based model which considers soil, water, and climatic conditions in an endogenous way In MAgPIE, agricultural production for all commodities and spatial cells at each time step is determined simultaneously as the optimal solution to a global cost minimization problem. The endogenous choice variables are crop areas, yield growth rates, and livestock production quantities. Global costs including production costs, land conversion costs and the costs of obtaining yield growth are minimized subject to land constraints, water constraints, crop rotation constraints, trade constraints and global demand constraints. Data on factor cost per unit of output and biophysical constraints as well as food demand enter the cost-minimization problem as exogenous parameters along with a range of other extraneous data – see Dietrich et al (2012), for a complete technical description. Thus, agricultural output prices in MAgPIE are the shadow prices associated with the cost minimisation problem.

In contrast, IMPACT and GCAM adopt a more aggregated level of resolution on the supply side. IMPACT distinguishes 285 Food Production Units formed by the spatial intersection of 115 countries / regions with 126 river basins. Domestic crop production is

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[15] See Havlik et al (2011 and 2013) for further details and recent applications.

determined by area and yield response functions. Harvested area is specified as a response to the crop's own price, the prices of other competing crops, the projected rate of exogenous (non-price) growth trends in harvested area, and water. Yield is a function of the commodity price, the prices of labor and capital, water, and a projected nonprice exogenous trend factor.

In GCAM, the model data for the agriculture and land use parts of the model is comprised of 151 subregions in terms of land use, based on a division of agro-ecological zones within each of GCAM’s 14 global geo-political regions. Within each of these 151 subregions, land is categorized into approximately a dozen types based on cover and use. An economic land sharing approach is used to allocate land between alternative uses based on expected profitability, which in turn depends on productivity, product price, and non-land costs of production (labor, fertilizer, etc.). The allocation of land types takes place in the model through global and regional markets for agricultural products.

A distinguishing feature of the CAPRI modelling framework in comparison with these four PE model is the combination of a very detailed and data-intensive representation of the supply side for the European focus region with a relatively parsimonious treatment of agricultural production decisions in the rest of the world. While the parameters of the nonlinear programming models for each of the 280 European NUTS 2 regions in the CAPRI supply module are calibrated to a rich set of physical and monetary input at output data at national and regional level, the quadratic cost function approach applied for all other regions – which leads to simple linear supply functions and which is combined with an iso-elastic land supply function for a single type of land – is far more stylized and less data-intensive than the supply-side specifications in GLOBIOM and MAgPIE.

In contrast to all other PE models, the assumption of regional product differentiation in CAPRI enables the determination of bilateral trade in agricultural commodities among all world regions as in five of the CGE models.

Demand Side Specifications

On the demand side, MAgPIE imposes demand quantities exogenously and thus demand is completely price-inelastic, while IMPACT, GLOBIOM and GCAM all work with simple ad-hoc regional demand functions for each commodity that are iso-elastic in per-capita income, population (with elasticity 1) and prices. Only IMPACT allows for non-zero cross-price effects, i.e. both GLOBIOM and GCAM rule out substitution effects in response to relative price changes altogether. In comparison, CAPRI features a more sophisticated treatment of the demand side based on rigorous theoretical micro-foundations by deriving the regional final demand functions – akin to the CGE approach to household demand - from the maximization of an indirect utility function subject to a budget constraint. As a result, the CAPRI demand functions obey the standard regularity properties postulated by microeconomic theory including the absence of money illusion and the non-violation of adding-up and symmetry constraints.

3.4. Treatment of Climate Change Impacts on Agriculture

In all models under consideration, climate change impacts on agriculture enter as shocks to the sectoral productivity parameters on the supply side. The determination of these shocks is application-specific. As further outlined in the appendix, some of the models, such as GCAM and AIM, are normally linked to – or are part of – a wider in-house integrated assessment modelling framework that translates emissions into climate outcomes and climate impacts, but can also be simulated in a stand-alone mode by taking impact projections from other extraneous sources. Similarly, ENVISAGE incorporates optionally a stylized climate model linked to sectoral damage functions that determine productivity impacts. As noted in section 2, for the MA scenarios, IMPACT has received estimates of climate change effects from the integrated assessment model IMAGE.

For the AgMIP global model comparison study, temperature and precipitation projections for a given emission scenario from two global circulation models have been passed on to two distinct crop model suites to generate four different agricultural climate change impact scenarios. The crop- and region-specific time series of yield impacts determined by the crop models have then been passed on to the ten participating global economic models for the simulation of food security outcomes.

4. Why Do Long-Run Projections of Global Food Security Outcomes Differ?

While the comparison of projections across scenario studies in section 2 illustrates the sensitivity of long-run food security projections to exogenous assumptions about the uncertain evolution of the main socio-economic drivers of change, it gives little indication to which extent differences in projections are attributable to methodological differences across models as outlined in section 3.

Thus, a prime reason for the large spread in global and regional food demand projections for 2050 across the scenario exercises reviewed in section 2 are differences in the assumptions about population and per-capita income growth. However, from a model comparison perspective, the key question is to which extent projections differ across models when the *same* harmonized assumptions about population and income growth are used.

To address this crucial question for further progress in model-based food system scenario analysis, the Agricultural Model Intercomparison and Improvement Project (AgMIP) hosted by Columbia University includes an ongoing study in which ten different global partial and general equilibrium models with a detailed representation of the food sector are subjected to a harmonized set of driver pathways up to 2050 and report simulation results for a standardized set of geographical regions and variables. Von Lampe, Willenbockel and Nelson (2013) report results from the first phases of this pioneering model comparison.[16]

The study suggests that once general assumptions are harmonized, the variation in projections across models declines, and several common conclusions emerge. However substantial cross-model differences in the long-run projections remain. This is illustrated by Figure 1 which shows the reference scenario projections for the price index over all agricultural commodities as well as for the three main traded staple crops – coarse grains, wheat and rice – and for ruminant meat. This reference scenario assumes "middle-of-the-

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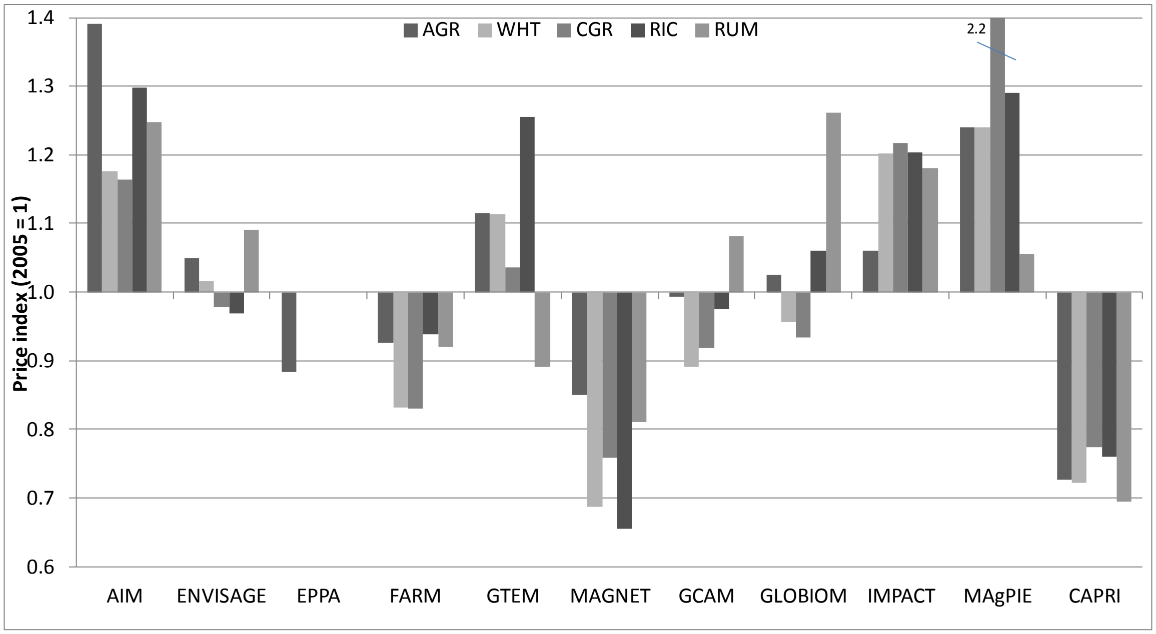
[16] See also Nelson et al (2014) and von Lampe et al (2014).

road" population and income growth and no climate change. The producer price indices can be seen as summary indicators of future tightness in agricultural markets. Evidently, the models do not even agree on the direction of the projected price changes.

Figure 1: AgMIP Reference Scenario S1 - Average Global Producer Price Index 2050 *(2005 = 1)*



(S1 –XPRP – WLD – 2050). AGR: All Agriculture, WHT: Wheat, CGR: Coarse Grains, RIC: Rice, RUM: Ruminant Meat

Source: Willenbockel (2013)

A closer analysis of the AgMIP results shows that both specification differences on the demand side and specification differences on the supply side play a role in explaining the cross-model variations in projections. We briefly discuss each of these aspects in turn.

4.1 The Role of Differences in Demand-Side Specifications

The results from the AgMIP project reported in Valin et al (2014) – see Appendix Table A-1 and Figure A-1 below – show a wide variation in demand projections across the ten participating global models under common population and income driver assumptions. The underlying reason is a considerable variation in the effective commodity- and region-specific income and price elasticities of demand across models.

It is noteworthy that the dialogue among modelling teams about the existing empirical evidence regarding these elasticity parameters in the course of the AgMIP process already led to a certain reduction in the cross-model variances for the demand function parameters.[17] However, there are gaps in the respective empirical evidence, and the fact that the crucial demand elasticity parameters are not time-invariant constants but vary with per-capita income poses intricate unresolved questions for the appropriate specification of food demand in long-run models. The implications for future research are detailed further in section 5.1.

4.2. The Role of Differences in Supply-Side Specifications

Differences in the Representation of Land Use

As Schmitz et al (2014) point out, global land use modelling is still in a state of infancy. Existing long-run projections of land use change towards 2050 show a high sensitivity of results to assumptions about the key driver paths, which – besides population and per-capita income growth and the associated dietary shifts – include agricultural productivity growth and the evolution of biofuel demand. A review of scenario studies in the IPCC AR4 finds simulation results for global cropland area change by 2050 relative to 2000 that range from -18 to +69 per cent (-123 mill. ha to 1158 mill ha) and global forest area changes from -18 to +3 per cent. (Fisher et al, 2007). The more recent survey by Smith et al (2010) likewise reveals a wide spectrum of results.

But to which extent is the large variation in land use change results attributable to specification differences across models as opposed to differences in exogenous driver assumptions? The results from the AgMIP project reported by Schmitz et al (2014) reveal that differences in global and regional land use projections remain considerable under harmonized assumptions about population, income and exogenous trend yield growth. For example, under the aforementioned reference scenario, seven out of ten models project an increase in global cropland of around 10 to 25 per cent by 2050 compared to 2005, but one model projects a decrease.

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[17] Without this convergence process, the spread in the demand projections shown in Table A-1 and Figure A-1 would have been considerably larger.

Hertel (2011) shows that for a given shift in the demand functions for agricultural output, a given autonomous rate of agricultural productivity growth and given shifts in non-agricultural demands for land, the resulting change in agricultural land use depends essentially on three sets of elasticities: the effective price elasticities of demand for agricultural commodities, the effective land supply elasticities, and the effective price elasticities of agricultural yield growth. Thus, from a conceptual perspective, the reasons for differences in land use projections across models under a common set of exogenous driver assumptions can be boiled down to differences in the explicit or implicit assumptions about the effective size orders of these elasticities.

This conclusion is in line with the findings of Schmitz et al (2014), who conclude that the strongest differences in model results are related to differences in the assumed costs of land expansion, the assumptions about potential cropland (i.e. factors that determine the effective supply elasticities of land) and the endogenous productivity responses to price changes (which determine the elasticities of yield growth). As further detailed in section 5.2, future research must aim to extend and consolidate the empirical knowledge base for informed judgements about plausible ranges for these elasticities.

Differences in the Representation of Endogenous Technical Change

As emphasized in the preceding paragraph, a key factor in the co-determination of price and land use projections is obviously the evolution of crop yields. While harmonized common assumptions about agricultural trend productivity growth are part of the exogenous drivers specification for the AgMIP scenarios, in all models the actual equilibrium yields depend to some extent endogenously on other variables such as output prices and input prices including land rents. Therefore the actual projected equilibrium yield growth rates can deviate substantially from the given autonomous growth rates. As a result, there is considerable cross-model variation in the crop yield projections for 2050 (See Appendix Figure A-2). This indicates that the effective elasticities of yield growth differ indeed substantially across the AgMIP models.

4.3. Differences in Methodological Approach versus Differences in Parameter Choices at the Calibration Stage

The preceding discussion of initial results from the AgMIP model comparison points towards an important insight. For the simulation behaviour of the model at broad regional scales, the modellers’ choice of numerical values for the parameters that co-determine the key elasticities enumerated above are ultimately more important than the prior choice of methodological framework. While the overview of different model types in section 3 has highlighted strong differences in the methodological approaches between PE and CGE models and in the level of spatial detail of PE models, an eyeball test of Figure 1 does not suggest that the tenor of model results is systematically linked to the choice of model type – e.g. both CGE and PE models are among the models that project the strongest price increases (decreases).

This finding is in line with Robinson et al (2014) who demonstrate within a highly stylized generic theoretical supply-side framework that the responsiveness of supply to changes in prices can be similar across CGE and PE models, depending on parameter choices that define the behavior of implicit supply functions.

5. Knowledge Gaps and Priorities for Further Research

The preceding review points to a number of priority areas for future research in global long-run agricultural and food system modelling. To a large extent, future model improvements are necessarily contingent on parallel progress to advance the state of scientific knowledge used by modellers in the course of the numerical parameterization of the model components.

5.1. Demand-Side Specification Issues

As noted in section 4.1, more econometric research is required to narrow down the plausible ranges for the long-run income elasticities of demand by commodity group and region and their evolution over time with rising per-capita income. In long-run projections, seemingly moderate differences in the chosen model parameter values that govern these elasticities compound to substantial differences in projected food consumption across models even under harmonised assumptions about per-capita income growth (von Lampe et al, 2014).

A related problem is that the demand systems typically employed in current-generation models possess insufficient "Engel flexibility"[18] (Cirera and Masset, 2010; Government Office for Science, 2011; Valin et al, 2014), that is, they do not adequately reflect the known stylized facts about changes over time in the budgetary share for food and in the commodity composition of food demand as income grows. In particular, marginal budget shares should vary non-linearly with income. In view of this problem, some modellers resort to ad hoc shifts in demand system parameters over time, but this pragmatic approach affects model transparency, and at present there is no consensus about best practice in this respect. AgMIP has identified this issue as a priority area for further research and cross-team dialogue in the next phase of the AgMIP process.

The treatment of future demand for first- and second-generation biofuel feedstocks is another demand-side issue requiring further attention in long-run global model development. As a case in point, only five of the ten models participating in AgMIP have

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[18] Engel curves describe the relationship between demand for a commodity and income.

so far been able to implement a harmonized second-generation bioenergy expansion scenario, and the simulated global land use impacts differ substantially across the five models (Lotze-Campen et al, 2014).

5.2. Supply Side Specification Issues

Endogenous Technical Progress and Land Use Change

Further research is required to reduce the degree of model uncertainty in long-run projections of land use change. As argued in section 4.2 above, improvements in the empirical knowledge about the factors that determine the effective elasticities of land supply and endogenous yield growth are needed in order to narrow down the large cross-model differences in land use projections under common exogenous driver assumptions. As Schmitz et al (2014) put it, too little is known about the costs of converting one land type into the other and about the biophysical and socio-economic availability of pasture for cropland conversion. Another challenge is the interaction between cropland and managed forest area. As emphasized by von Lampe et al (2014), further work is required to incorporate the location-specific environmental and other social costs of land conversion.

Lotze-Campen (2011) and Schmitz et al (2014) point out that the uncertainty and lack of data with respect to land availability and land quality remains a serious constraint on improving the robustness of agricultural scenario studies – a point further addressed in section 5.3 below.

Modelling future technological change is decisive due to its direct link with land expansion. Contemporary models employ various reduced-form specifications to capture endogenous agricultural productivity responses to price changes, but at present there is no consensus and little guidance from the related empirical literature (Piesse and Thirtle, 2010) about the plausible numerical range for the corresponding elasticity parameters. Only one of the models reviewed earlier (MAgPIE) attempts to incorporate the costs of achieving yield growth explicitly.

Incorporating Water Scarcity Constraints

Most of the models reviewed here do not take explicit account of water as a factor of production and do not incorporate competition for water between agricultural and non-agricultural uses, and the potential impacts of changes in precipitation patterns in a changing climate on water availability and crop productivity are only captured to the extent to which extraneous crop model estimates of yield changes used in model simulation take account of these impacts. As a matter of course, the large degree of present uncertainty about future regional precipitation patterns is a major factor constraining the reliability of long-run climate change impact projections. The satisfactory integration of water availability and use in global long-run simulation models remains a major challenge for future research.

Climate Change Impacts

More generally, the skill of the global long-run models in representing climate change impacts on agricultural productivity is necessarily constrained by the state of the art in climate science and crop science, where gaping holes in knowledge – not only with respect to future regional precipitation patterns but also with respect to extreme weather event frequencies, the evolution of pests and plant diseases, or the strength of CO_2 fertilization effects in a changing climate – persist.

The IPCC Fourth Assessment Report identifies a long list of knowledge gaps and associated research priorities related to climate change impacts on agricultural production (Easterling et al, 2007), which includes inter alia the need for (i) further free air CO_2 enrichment (FACE) experiments on an expanded range of crops, pastures, forests and locations, especially crops of importance for the rural poor in developing countries; (ii) basic knowledge of pest, disease and weed response to elevated CO_2 and climate change; (iii) a better representation of climate variability including extreme events at different temporal scales in crop models; (iv) new global simulation studies that incorporate new crop, forestry and livestock knowledge in models; (v) more research to identify highly vulnerable microenvironments and to provide economic coping strategies for the affected populations, since relatively moderate impacts of climate change on overall agro-ecological conditions are likely to mask much more severe climatic and economic vulnerability at the local level; and (vi) examination of a wider range of adaptation strategies and adaptation costs in modelling frameworks.

These are currently very active areas of research and the IPCC Working Group II contribution to the Fifth Assessment Report will report on progress in this areas in Mid-2014.

Incorporating Impacts of Agricultural Production on Environmental Sustainability

As Nelson and van der Mensbrugghe (2013) put it, although virtually everyone agrees that sustainable food security is very important there is little agreement on which of the many potential dimensions of sustainability are most important to assess. Currently available global models can already assess some dimensions of sustainability – land use change, use of water, nutrient use, greenhouse gas emissions – but there has been no systematic effort to review these metrics, how the models implement them, and what key aspects of sustainability are missing.

5.3. Data Issues

A recurrent theme in assessments of the state of long run food system modelling is data availability and data quality as a major factor constraining progress. 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 improvement. Most of the partial equilibrium models use FAOSTAT data is the main source for the base year calibration, but this data set is not complete and a significant proportion of the data is synthetically constructed rather than based on direct empirical observation. One of the problems is that the reporting standards and practices– particularly in Africa – have actually declined since the 1980s. In recognition of this problem, a "Global Strategy for Improving Statistics for Food Security, Sustainable Agriculture and Rural Development" has been formulated and initiated at UN level.[19]

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[19] World Bank / FAO (2011).

Based on extensive consultations with the global food system scenario modelling community through various Foresight workshops, the Government Office for Science (2011) Report concludes in this respect that

> "although extensive information is already collected on some aspects of the food system, data are poor in other areas, and data resources are often scattered and inaccessible. Investment in a better and more accessible database and the development of indicators and management tools to improve monitoring and evaluation should be a high priority for policy makers and research funders".

A concrete recent effort in this direction is the GEOSHARE initiative at Purdue University, which is currently in its initial pilot phase co-funded by the UK government. The aim is to compile a spatially-explicit, open-source database for analysis of agriculture, forestry and the environment. The plan is to (i) gather national and sub-national statistics from various statistical agencies around the world to put together a consistent global data set, along with regional companion data sets, on agriculture and land use, (ii) employ spatial disaggregation methods, including the use of satellite remote sensing technology and spatial statistics to develop geographically-explicit gridded data on a global scale, and (iii) develop a data portal, including new tools for providing data in a variety of convenient formats to the global research community.

5.4. Challenges in Working with Linked Model Ensembles

Several of the scenario studies reviewed in section 2 employ soft-linked ensembles of models that focus on different aspects of the food system in order to exploit the embodied specialized knowledge from different disciplines. However, owing to the heterogeneity of scales, accounting methods and conceptual frameworks across different models, the soft-linking approach is associated with substantial problems in achieving consistency and is susceptible to error propagation. The scientific basis for linking models across disciplines and scales is still weak and requires specific attention in future research (Ewert et al 2009, 2011). In particular, there is a need for the further development of protocol-based scaling methods that ensure conceptual consistency and transparency of the data flow between model components that operate at different spatial, sectoral and temporal scales. Various up- and downscaling methods exist but knowledge about scaling in integrated assessment is still in a state of infancy and often lacks scientific rigour (Ewert et al, 2009).

5.5. Dialogue across Modelling Groups and Disciplines

Long-run food system modelling requires assumptions to be made over a large number of subjects, encompassing both the natural and social sciences. This creates enormous challenges for individual researchers and modelling teams. As Conforti and Sarris (2011) emphasize,

> "(c)ommunication, networking and exchange of data and analytical tools among concerned institutions, working groups and individual analysts are among the most promising ways of addressing such complexity and the need to integrate several subject areas, and of improving the transparency and comparability of results."

The AgMIP project referred to extensively in this report is a pioneering effort to organize such a cross-model dialogue and comparison in a systematic and structured way through the design of harmonized scenarios, the development of protocols and common metrics for the comparison of assumptions and projections, and in-depth analysis and discussion of the reasons for differences in results across models. Given the success of the initial phases of this project, continued funding for this initiative deserves a high priority.

5.6. Model Validation

Finally, it is widely acknowledged that more work on the validation of model components used in integrated assessment studies is required, but the validation of long-run forward looking models that aim to make projections for several decades into the future poses formidable conceptual and operational problems. A detailed discussion of these problems and proposed solutions offered in the literature[20] (often by non-modellers) would deserve a separate report on its own. Given that ex-post validations of projections towards 2050 in a strictly literal sense must obviously be left to future generations, backcasting or hindcasting methods have been proposed. However, leaving problems of historical data availability apart, there is a risk of over-calibrating models to past processes that might not necessarily be the processes driving future developments (Uthes

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[20] See e.g. Schwanitz (2013, 2012).

et al, 2010). As climate change and the per-capita income growth assumed in global long-run projections examined take the models outside of the bounds of past experience, the ability of a model to track historical observed time series more closely than another does not necessarily ensure its superiority in projecting the distant future, given that the nature of the “data-generating process” changes.

Despite these principal difficulties, there are signs that long-run modeller are beginning to take calls for model validation work more seriously. Initial results from ongoing efforts in this direction are reported e.g. in Hertel and Baldos (2013) and Bonsch et al (2013).

Appendices

Table A-1: Projected Change in Global Food Demand 2005-2050 under SSP2 Population and Income Growth Scenario (*in percent, except world price index (2005 = 1)*)

Model	All	Crops					Livestock				
	Total food change (1)	Total food change (2a)	Food per cap change (3a)	World price index (4a)	Price effect (5a)	Income effect (6a)	Total food change (2b)	Food per cap change (3b)	World price index (4b)	Price effect (5b)	Income effect (6b)
AIM	66	62	13	1.21	-7	22	88	32	1.12	-17	59
ENVISAGE	70	65	15	0.93	6	9	94	36	0.90	15	19
EPPA	79	82	28	0.80	14	12	62	14	0.86	18	-3
FARM	98	97	38	0.85	0	38	102	41	0.97	0	41
GCAM	59	55	8	0.93	0	8	79	25	1.04	0	25
GLOBIOM	62	57	10	1.00	0	11	84	29	1.06	-2	31
GTEM	94	84	29	1.04	0	29	144	71	0.80	1	69
IMPACT	65	63	14	1.31	-7	23	78	25	1.03	-5	31
MAGPIE	83	55	8	1.54	0	8	242	140	1.04	0	140
MAGNET	65	66	16	0.93	1	15	61	12	0.85	5	7
AT2050[a]	54	50	8				76	27			

[a] "Agriculture Towards 2050" (Alexandratos and Bruinsma, 2012)

Calculation method:

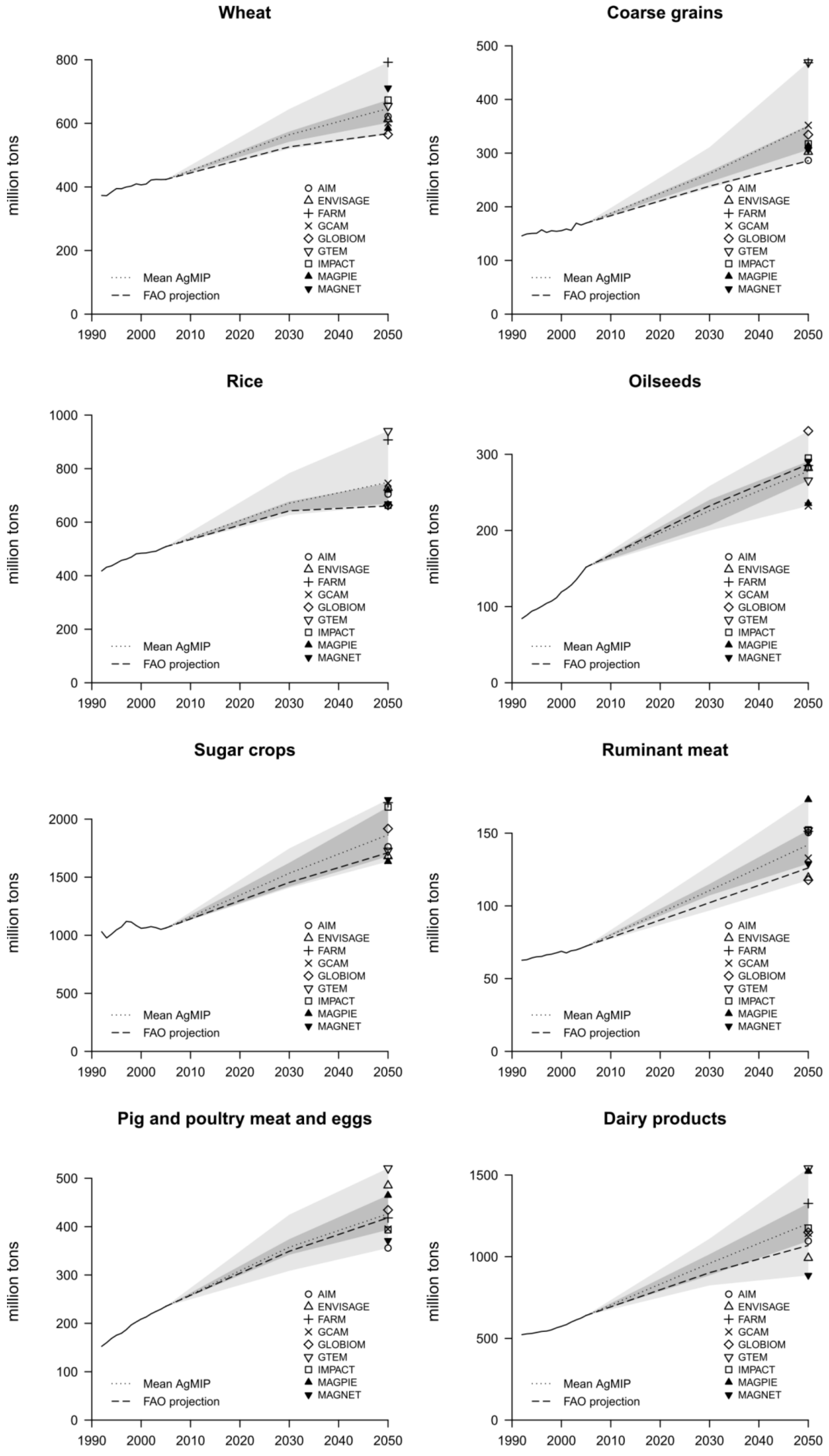
(1), (2a), (3a), (2b), (3b): Aggregated on a calorie basis for the 5 crop categories considered or the 3 livestock products.

(4a), (4b): Based on model reported values. For CGEs, the world price index is deflated by the world consumer price index.

(5a), (5b): Calculated at the product level using the price index and the price elasticities reported by models.

(6a), (6b): Obtained by subtracting the price effect from (5a) and (5b) from the change per capita (3a) and (3b).

Figure A-1: World Food Demand Projections for SSP2 Scenario by Commodity Group



Wheat

Coarse grains

Rice

Oilseeds

Sugar crops

Ruminant meat

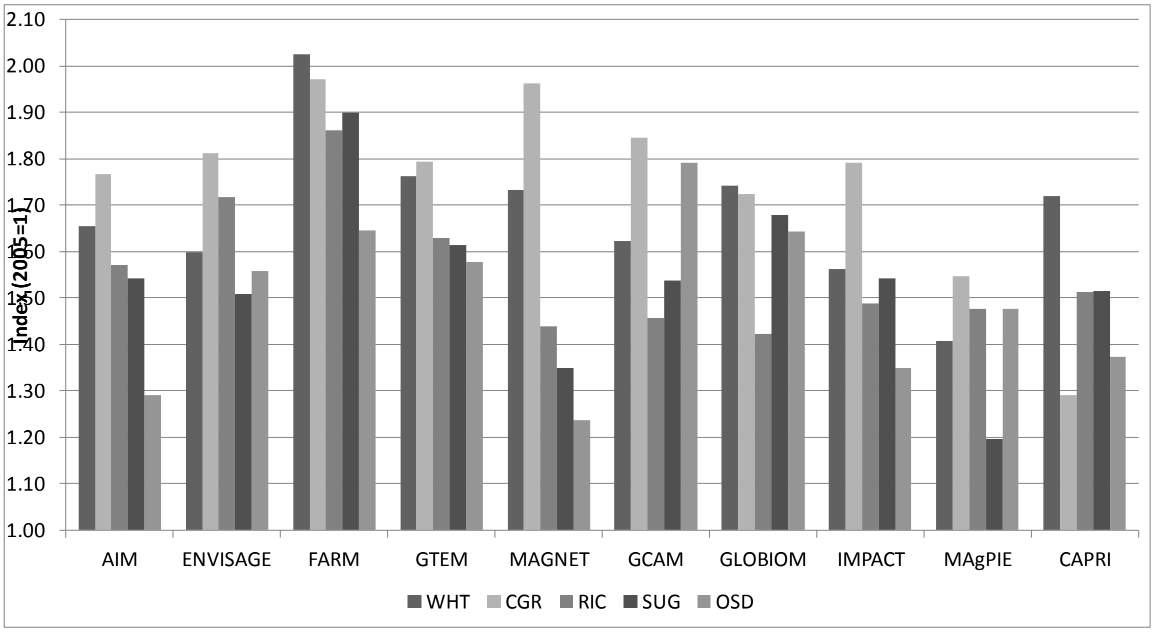
Pig and poultry meat and eggs

Dairy products

Explanatory notes for Figure A-1: Black plain line corresponds to historical data in FAOSTAT. Dashed line corresponds to FAO projections (Alexandratos and Bruisma, 2012). Dotted line corresponds to mean of AgMIP model results. Light grey indicates the span of results and dark grey the 1st-3rd quartile range.

Source: Valin et al (2013).

Figure A-2: AgMIP Reference Scenario S1 – Global Average Crop Yield Indices 2050 *(2005 = 1)*



(S1–WLD–YILD–2050). WHT: Wheat, CGR: Coarse grains, RIC: Rice, SUG: Sugar crops, OSD: Oilseeds.

Source: Willenbockel (2013)

Brief Self-Characterizations of the AgMIP Models

Computable General Equilibrium Models

ENVISAGE **Env**ironmental **I**mpact and **S**ustainability **A**pplied **G**eneral **E**quilibrium Model

The ENVISAGE model‘s core is a standard recursive dynamic global general equilibrium model. Incorporated with the core CGE model is a greenhouse gas emissions module that is connected to a simple climate module that converts emissions into atmospheric concentrations, radiative forcing and changes in mean global temperature. The climate module has feedback on the economic model through damage functions, affecting a number of parameters in the model. The combination of the socio-economic CGE model with the climate module turns the model into an integrated assessment model.

AIM (**A**sia-Pacific **I**ntegrated **M**odel)

AIM is a large-scale computer simulation model developed by the National Institute for Environmental Studies in collaboration with Kyoto University and several research institutes in the Asian-Pacific region. AIM assesses policy options for stabilizing the global climate, particularly in the Asian-Pacific region, with the objectives of reducing greenhouse gas emissions and avoiding the impacts of climate change.

The AIM comprises three main models – the greenhouse gas emission model (AIM/emission), the global climate change model (AIM/climate), and the climate change impact model (AIM/impact). The AIM/emission model estimates greenhouse gas emissions and assesses policy options to reduce them. The AIM/climate model forecasts concentrations of greenhouse gases in the atmosphere and estimates the global mean temperature increase. The AIM/impact model estimates climate change impacts on natural environment and socio-economy of the Asian-Pacific region.

FARM (**F**uture **A**gricultural **R**esources **M**odel)

FARM is an integrated global CGE modelling framework designed to analyze global changes related to agriculture and the environment. The model captures feedbacks between the agriculture and energy sectors in the production of renewable energy. The core model is the GTAP model. Dynamic elements that have been added include an intertemporal forestry model that competes with agriculture for land, and an aggregated stock of physical capital. Extensions to the economic database include a further disaggregation of sectors for biofuels analysis and electricity generation. To capture competition across land of heterogeneous quality, FARM includes an environmental database linked to the production of agricultural and forestry commodities according to agro-ecological zones characterized by length of growing seasons, temperature regime, and plant hardiness zones. Underlying data include GTAP social accounts and global land use; energy balances from the International Energy Agency; and FAO crop, livestock, and forestry production. Production sectors in FARM can be configured as any combination of the 57 production sectors in the GTAP data set. The model incorporates mitigation pricing and accounting for carbon dioxide, methane and nitrous oxide for the energy and agricultural/forestry sectors.

GTEM (**G**lobal **T**rade and **E**nvironment **M**odel)

GTEM is ABARES' dynamic, multi region, multi sector, general equilibrium model of the world economy. The model has been developed to address policy issues with long term global dimensions. GTEM has been used to analyse issues such as the climate change response policies including the Kyoto Protocol, trade reform under the World Trade Organisation, and trends and issues in international commodity and energy markets. The core economic database of GTEM is derived from the GTAP database. Agriculture in GTEM is comprised of 12 crop and livestock sectors, which can be identified separately or aggregated for different applications**.** GTEM has a single homogenous land type within each region that is assumed to be imperfectly mobile across various agricultural uses–crop and livestock, and forestry activities. Representative landowners in GTEM are therefore able to reallocate land to alternative agricultural and forestry activities in pursuit of higher rents, while limits on mobility prevent a uniform rental rate across the economy.

MAGNET (**M**odular **A**pplied **Gen**eral **E**quilibrium **T**oolbox)

MAGNET is based on the general equilibrium model GTAP. It uses the carbon market and the rough characteristics of the production structure of GTAP-E and the international capital flow accounting system of the dynamic GTAP model GTAP-DYN, and also includes parts of the agricultural variant of GTAP, GTAP-AGR. Various extensions of the model can be switched on or off through a simple change in coefficients or through closure swaps. An integrated production structure, with energy nesting (including biofuels) and feed and fertilizer nesting is included. EU energy policies including first and second pillar measures are implemented and can be switched on. Land supply is modeled, based on biophysical model outcomes from IMAGE. Substitution between different types of land is included.

3. Partial Equilibrium Models

CAPRI (**C**ommon **A**gricultural **P**olicy **R**egionalised **I**mpact Analysis)

CAPRI is a global partial equilibrium multi-market model with focus on the EU27, Norway, Turkey and the Western Balkans. It iteratively links a “supply module” that disaggregates these focus countries into 280 regions at NUTS 2 level with a spatial global “market module” that distinguishes 47 agricultural products and 63 countries / regions clustered in 40 trade blocks. A nested Armington specification is used to determine bilateral trade flows among these 40 trade blocks. The supply module consists of a set of non-linear programming models which maximize regional agricultural income for given prices (determined in the market module) subject to land, policy, feed and plant nutrient requirement constraints. In the market module, supply as well as feed and processing demand are derived from a normalized quadratic profit function. Land supply and yields are endogenous functions of prices. Human consumption demand is derived from a generalized Leontief expenditure function. In order to establish consistency between the two modules, the behavioural parameters for supply and feed demand in the market module for the countries covered by the supply part are sequentially updated to the results of the supply module.[21]

GCAM (**G**lobal **C**hange **A**ssessment **M**odel)

GCAM is a partial equilibrium model of the world with 14 regions. GCAM operates in five-year time steps from 1990 to 2095 and is designed to examine long-term changes in

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[21] For a detailed documentation of CAPRI see http://www.capri-model.org/dokuwiki/doku.php .

the coupled energy, agriculture/land use, and climate system. GCAM includes a 151-region agriculture land-use module and a reduced form carbon cycle and climate module in addition to its incorporation of demographics, resources, energy production and consumption. The model has been used extensively in a number of assessment and modelling activities such as the Energy Modeling Forum, the U.S. Climate Change Technology Program, and the U.S. Climate Change Science Program and IPCC assessment reports.

The agriculture-land-use model (AgLU) endogenously determines land use, land cover, and the stocks and flows of carbon from terrestrial reservoirs. AgLU is fully integrated with the GCAM energy and economy modules. In GCAM 3.0, the model data for the agriculture and land use parts of the model is comprised of 151 subregions in terms of land use, based on a division of the extant agro-ecological zones within each of GCAM's 14 global geo-political regions. Within each of these 151 subregions, land is categorized into approximately a dozen types based on cover and use. Some of these types, such as tundra and desert, are not considered arable. Among arable land types, further divisions are made for lands historically in non-commercial uses such as forests and grasslands as well as commercial forestlands and croplands. Production of approximately twenty crops is currently modeled, with yields of each specific to each of the 151 subregions. The model is designed to allow specification of different options for future crop management for each crop in each subregion. Stocks and flows of terrestrial carbon and other greenhouse gases are determined by associated land use and land cover and land-use-land-cover changes.

GLOBIOM (**Glo**bal **Bio**sphere Management **M**odel)

GLOBIOM is a global recursively dynamic partial equilibrium model integrating the agricultural, bioenergy and forestry sectors with the aim to give policy advice on global issues concerning land use competition between the major land-based production sectors. GLOBIOM covers 18 major crops Four management systems are considered (irrigated, high input – rainfed, low input – rainfed and subsistence) corresponding to the IFPRI crop distribution data classification. Crop supply can enter one of three processing/demand channels: consumption, livestock feeding or biofuel production.

Consumption demand is modeled by constant elasticity functions. Biofuel options from crops include first generation technologies for ethanol from sugarcane, corn and wheat, and biodiesel from rapeseed, palm oil and soybeans. Production system based livestock representation has been recently developed in collaboration with the International Livestock Research Institute (ILRI). The model differentiates between 14 production systems consistent with the ILRI/FAO production system classification.

IMPACT (**I**nternational **M**odel for **P**olicy Analysis of **A**gricultural **C**ommodities and **T**rade)

The IMPACT model is designed to examine alternative futures for global food supply, demand, trade, prices, and food security. IMPACT covers 30 commodities, which account for virtually all of world food production and consumption, including all cereals, soybeans, roots and tubers, meats, milk, eggs, oils, meals, vegetables, fruits, sugar and sweeteners, and fish in a partial equilibrium framework. It is specified as a set of 115 country-level supply and demand equations where each country model is linked to the rest of the world through trade.

Domestic crop production is determined by area and yield response functions. Harvested area is specified as a response to the crop's own price, the prices of other competing crops, the projected rate of exogenous (non-price) growth trends in harvested area, and water. Yield is a function of the commodity price, the prices of labor and capital, water, and a projected nonprice exogenous trend factor. Domestic demand for a commodity is the sum of its demand for food, feed, and other uses. Food demand is a function of the price of the commodity and the prices of other competing commodities, per capita income, and total population Feed demand is a derived demand determined by the changes in livestock production, feed ratios, and own- and cross-price effects of feed crops. The demand for other uses is estimated as a proportion of food and feed demand.

MAgPIE (Model of **Ag**ricultural **P**roduction and its **I**mpact on the **E**nvironment)

The global land-use model MAgPIE is a recursive dynamic programming model with a cost minimization objective function The biophysical supply side of the model is simulated spatially explicit using 0.5 degree data aggregated to 1000 clusters. It distinguishes 16 food/feed crops, 3 bioenergy crops, 5 livestock types and 10 world regions. Demand for calories in each region is a function of exogenous population and per-capita income projections. The biophysical inputs and yields are derived from the grid-based dynamic global vegetation model with managed land LPJmL. LPJmL is a process-based model which considers soil, water, and climatic conditions in an endogenous way. Four categories of costs arise in the model: production costs for livestock and crop production, yield increasing technological change costs, land conversion costs and intraregional transport costs. The model solution is derived by minimizing these four cost components on a global scale for the current time step. In order to increase total agricultural production, MAgPIE can either invest in yield-increasing technological change or in land expansion.

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