CHAPTER 14

Modeling the Global Economy – Forward-Looking Scenarios for Agriculture

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Abstract

The development of global computable general equilibrium (CGE) models lagged behind development of national models as globally consistent datasets were not readily available and software and hardware were generally not up to the task. As the latter improved and data became more readily available – particularly through the efforts of the GTAP consortium – the use of global CGE models to examine critical economic policies of an international or a global nature exploded in the 1990s. The catalysts of the use of global CGE models were international trade negotiations in the form of the Uruguay Round and the rising concern over global warming. Over the last two decades global CGE models have expanded in size, complexity and the range of policy issues including bilateral and regional trade agreements, the role of trade preferences, trade in services, international migration, foreign direct investment, cross-border environmental issues, structural transformation, demographics and more. This chapter is focused on work largely undertaken at the World Bank over the last decade using the ENVISAGE model with a focus on long-run dynamics, impacts on agriculture and interactions with climate change.

Keywords

Economy-wide projections, agricultural projections, climate change

JEL classification codes

C68, D58, F47, O41, Q11, Q54

14.1 INTRODUCTION

Johansen (1960) is credited with being the father of computable general equilibrium (CGE) modeling, but it took many years with advances in data, computing and software before CGE modeling entered the arsenal of modern economic policy analysis. Country-based analysis took off in the late 1970s and throughout the 1980s with a focus on fiscal and trade issues. Shoven and Whalley (1984, 1992) provide excellent surveys of the earlier CGE policy studies. It took some time longer for global CGE models to appear – confronted with more serious issues of data and computation. Two critical

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international policy issues emerged in the 1980s that galvanized the efforts in global CGE modeling – the Uruguay Round of multilateral trade talks and climate change. Since then, the area has exploded abetted by the Global Trade Analysis Project (GTAP) and its cyclical release of a consistent global data set that now encompasses input–output tables for 112 regions, of which 95 are individual countries, 57 goods and services and a full accounting of bilateral trade flows.[1]

Since the 1970s, the World Bank has been at the forefront of CGE modeling both as a producer and a consumer. The economic development issues developed in this chapter represent efforts over the last 10 plus years of work at the World Bank using both the LINKAGE and ENVISAGE models whose inception can be traced back to work done at Stanford University in the 1980s and transiting through the University of Brussels and the Organization for Economic Cooperation and Development (OECD)[2]. Since 2000, World Bank analysis has touched upon international trade and the Doha Development Agenda (DDA), the growing role of developing countries, structural change and the dynamics of income distribution, forward looking scenarios of agriculture and energy, the global and regional implications of international migration, and more recently on climate change and its potential economic impacts.

The focus of this chapter is largely on forward-looking scenarios for agriculture – a topic that has piqued the interest of virtually the entire world with the sudden and sharp rise of food prices in 2007/08. However, whereas agriculture could have been studied in a more confined space in the past, in the current global economy it would be difficult to analyze agriculture without its linkages to energy markets – through biofuels and to climate change that could have a dramatic impact on agricultural productivity. The outline of the rest of the chapter is as follows. Section 14.2 provides a brief history of global CGE modeling at the World Bank dating back to the 1970s. Section 14.3 first describes the basic theoretical structure of a global CGE model focusing mostly on the international linkages component rather than on the domestic supply and demand components. It follows with a more detailed description of the World Bank's ENVISAGE CGE model. The following three sections focus on forward looking scenarios. Section 14.4 describes the basic macroeconomic dynamic framework through 2050 that includes a discussion on population and labor force growth, and assumptions on savings behavior and productivity. Section 14.5 delves more deeply into the evolution of global agriculture where the key issues are global food prices and the global allocation of food production. Section 14.6 develops the climate part of ENVISAGE and how future climate change may impact different regions of the world, including analysis of climate change and agricultural linkages. There is a final concluding section in Section 14.7.

1 The next release, slated for 2012, is expected to have 119 countries/regions and the same set of sectors.
2 See for example Burniaux (1987) and OECD (1990).

14.2 GLOBAL MODELING AT THE WORLD BANK

The World Bank was one of the key focal points at the onset of computable general equilibrium modeling. Internally, most of the efforts focused on single-country models that were derived from the structural analysis of Chenery and his colleagues (Chenery, 1971; Chenery *et al.*, 1986) and the early planning models based on linear analysis (Blitzer *et al.*, 1975). These efforts culminated in the still influential volume by Dervis *et al.* (1982), commonly referred to as DMR that provided a theoretical derivation of a standard single-country CGE model (with some offshoots) and a practical guide to CGE modeling. In parallel, the World Bank supported the development of data collection tools and methodology as evidenced by the publication of *Social Accounting Matrices: A Basis for Planning* by Pyatt and Round (1985), which set the standard for developing CGE-ready databases. The theoretical and data advances cited above were complemented by the development of vastly improved modeling software conceived and developed by World Bank staff (Brooke *et al.*, 1992). The General Algebraic Modeling System (GAMS) simplified the computer implementation of CGE models and facilitated economists' ability to turn theory into empirical policy analysis. Prior to the development of GAMS (and other similar systems such as GEMPACK), economists either had to have good programming skills in such languages as Fortran, Pascal or C, or else to rely on skilled programmers to implement their models.[3] Programming skills were not sufficient as solution algorithms also needed to be implemented to solve the models. CGE conferences of the 1970s and 1980s devoted significant time to solution methods, existence and uniqueness of model solutions. The design of GAMS is particularly elegant as it separates the specification of the model from its solution, i.e. GAMS is a model compiler. Any model can be coupled with a variety of different solution algorithms, some of which have specific design features such as mixed complementarity programming, integer/mixed integer, optimization, and so on.

Although global modeling is barely more difficult than single-country modeling in theory (see Section 14.3), the efforts to build a consistent global database, combined with the lack of analytical tools and inadequate hardware, proved to be a significant barrier to the earliest efforts. The Tokyo Round of multilateral trade negotiations provided the impetus to some of the earliest efforts. Evaluations of the Tokyo Round by Deardorff and Stern (1981) and Whalley (1982) set the initial standards. Some of the earlier World Bank *World Development Reports* also used global CGE modeling to highlight potential long-term structural changes based on early models developed at the Univesité Libre de Bruxelles by Ginsburgh and Waelbroeck among others. Much of this work was driven by studies on how to transform mainly agricultural based economies into industrial

[3] Horridge *et al*, Chapter 20 of this Handbook, for a more complete description of the evolution of modeling infrastructure.

economies using the agriculture development led-industrialization (ADLI) strategy promulgated by Adelman and Robinson (1978, 1989). Their single-country analysis was expanded to global models in studies by Burniaux (1987) and Fischer *et al.* (1988), which laid the foundation for models focused on agricultural support and international trade policies.

The field of global CGE modeling really took off with evaluations of the Uruguay Round in the late 1980s and early 1990s. A conference organized by the World Bank that brought together the most prominent global models of the day resulted in a volume *The Uruguay Round and the Developing Countries* by Martin and Winters (1996). On the heal of the 1992 UN Rio Conference on the Environment and Development and the publication of the Intergovernmental Panel on Climate Change (IPCC) *Second Assessment Report* (IPCC, 1995) climate change also emerged as a major international policy concern in the early 1990s. Much of the original work on the economics of climate change emanated from the existing energy models that had been developed during the 1970s to evaluate the consequences of the dual energy crises and thus had a strong focus on the energy sectors. Another Japanese city provided the overarching impetus for the economics of climate change work, with the signing of the Kyoto Protocol in 1997. The World Bank was less involved in the climate change work in the 1990s where much of the model inter-comparison was undertaken by the Paris-based OECD and by the Stanford-based Energy Modeling Forum (EMF). This may have been driven in part by the fact that, by and large, developing countries were perceived at being at the periphery of the climate change policy dialogue, even if they would be the most negatively impacted upon in the long run. The Kyoto Protocol itself required no constraint on emissions on the part of developing countries (with the exception of some countries in Europe and Central Asia).

The analytical tools and the hardware improved exponentially in the 1980s. Data development, at global level, lagged significantly. Each global modeling team developed its own global data based on an *ad hoc* collection of input-output tables and other satellite accounts such as national income and product accounts, tariff and world trade databases, amongst other things. These disparate global databases had different base years, different country and sector coverage and different institutional details. Model comparison proved difficult in this context.[4] The development of the GTAP database was a radical change – that was perhaps even more important than the hardware and software developments.[5] The earliest versions of the GTAP database – developed from the SALTER model[6] – had an agricultural and OECD bias. The latest release, version 7, has 57 sectors and 112 countries and regions, of which 95 are countries. Virtually all global CGE models are

4 The Martin and Winters (1996) volume on the Uruguay Round highlights this issue.

5 Hertel, Chapter 12 of this Handbook, describes the development of the GTAP database.

6 See Jomini *et al.* (1991).

based to a large extent on some version of GTAP using potentially satellite accounts to incorporate features that are not possible with the standard GTAP database. The World Bank was highly supportive of the GTAP initiative from its inception and was a founding consortium member. It has been a heavy consumer of the GTAP database as well as contributing to its development through sharing of its own data resources.

Global CGE modeling at the World Bank took off again in the early 2000s as the successor to the Uruguay Round, the DDA negotiations were initiated in 2001. Analysis of the DDA has been prolific, in part because of the duration of the negotiations, and in part because of the increasing sophistication of the analytical tools and the underlying databases. For example, most of the *ex ante* analysis of the Uruguay Round was based on formula cuts of the most favored nation (MFN) level of tariffs at the one- or two-digit level. *Ex post* analysis of the actual agreement showed that the global gains would be much lower, leading to significant criticisms of the analysis. Economists have been much more cautious with their analysis of the DDA, focusing on the specific details of the tabled proposals, including notably the exceptions. And the underlying databases have been vastly improved with much better representation of existing preferential agreements, non-tariff barriers and upstream analysis of the tabled offers done at the six-digit 200+ country level, rather than at the much more aggregate level of the global models.[7]

The World Bank has been active in this area on both the data side as well as on the modeling side. Several of the World Bank's *Global Economic Prospects* reports highlighted the potential gains from a successful conclusion to the DDA negotiations (World Bank 2001, 2002, 2004). Various aspects of the Doha tariff proposals have been analyzed including potential exemptions and special treatment (Laborde *et al*., 2011a). Another angle of analysis has been attempts to overcome the traditional aggregation bias of global CGE models. Recent work (Laborde *et al*., 2011b), based on theoretical work by Anderson and Neary (1996) and Anderson (2009), has led to a relatively simple modification in the specification of trade in global CGE models to overcome the aggregation bias. This has allowed analysts to use the full information available at the six-digit tariff line level and then to aggregate to a level typically deployed in global models.

Global CGE work at the World Bank has not been limited to assessing the economic impacts of changes to the world trading system. Based on a satellite account of bilateral stock of migrants (and remittances) that has been developed for the GTAP database, the *Global Economic Prospects* report of 2006 assessed the potential economic impacts of raising the stock of developing country migrants in high-income countries, extending the seminal work by Walmsley and Winters (2003). There were two distinct extensions

7 Boumellassa *et al*. (2009) provide a description of the development of the detailed six-digit level tariff database that is being used to construct the various reform scenarios for DDA analysis.

of the earlier work. The first allowed for differentiation of workers by region of origin. This dampened to some extent the negative wage impacts on native workers, with a greater impact on non-native workers – an area of still considerable dispute and econometric analysis. The second extension adjusted the welfare gains for the change in prices when migrants move from regions with relatively low prices to regions with higher prices (using a purchasing power parity adjustment factor). The adjustment lowers the gains for the new migrants, except for that part of their income remitted to their home country.

The use of global CGE models has also been instrumental in elucidating the changing structure of global production and trade. Assessing these global dynamic changes was one of the first applications of the global CGE modeling in the late 1970s and early 1980s and continues to be a focus today. The 2007 *Global Economic Prospects* report looked at changes in population, both in terms of absolute numbers as well as structural evolution, combined with changes in relative productivity and income growth, to assess changes in relative comparative advantage and the allocation of global production and trade. The analysis in the 2007 *Global Economic Prospects* report was supplemented by micro-simulation analysis that assessed the evolution of global income distribution and the rise of a middle class in emerging countries.

The more recent research has focused on natural resources and commodities. This has been due to the re-emergence of two critical issues for developing countries. On the one hand, the publication of the IPCC *Fourth Assessment Report* (AR4) in 2007 (IPCC, 2007) more or less simultaneously with the publication of the UK-sponsored *Stern Review* (Stern, 2007) and the screening of former Vice-President Gore's documentary entitled *An Inconvenient Truth* refocused global attention on climate change. In particular the two reports highlighted that the negative impacts on developing countries from climate change could be highly damaging and that the impacts are already being felt today and not in some distant future. This shifted attention much more towards the impact and adaptation dimensions of climate change from the somewhat greater traditional focus on the mitigation side. This shift in emphasis has also entailed a greater focus on developing countries that would be most negatively impacted and with fewer resources with which to adapt to a changing environment.

The second aspect, perhaps not unlinked to the first, was the commodity price spike of 2007/08, which has abated to some extent, but with prices still much higher than in the early 2000s. While the food price spike may have been the result of a perfect storm, i.e. the simultaneous occurrence of a series of negative shocks, there is sufficient evidence to suggest that some of these shocks may happen with greater frequency and amplitude than in the past due to a changing global climate. Moreover, climate mitigation policies are likely to lead to higher conventional fuel prices – at least for end-users. This will have two impacts on agricultural prices: (i) It will lead to a cost push effect as higher input prices (energy and fertilizers) are passed on to consumers, and (ii) it could lead to accelerated development of crop production for biofuel feedstock and thus a competition for land between "food and fuel." With limited land resources, the demand-pull factor would tend to promote higher food prices that adds to the cost-push factor of higher energy prices on food prices.

The 2008 *Global Economic Prospects* report focused on commodity prices — both in the medium and long term. On the food side, the report, supported by other studies (van der Mensbrugghe *et al.*, 2011), suggests that the world food system is sufficiently flexible to accommodate future demand that will grow from population and income growth, although at a decelerating pace. Another study (Timilsina *et al.*, 2010) analyzed the economic and environmental consequences of the current biofuels mandates that have been legislated in many countries. This study suggests, as well, only modest impacts on food prices from the biofuels mandates as long-term flexibility between factors of production and land use changes accommodates the modest increase in competition for land resources (at a global level). Some of the optimism is based on continued improvement in agricultural productivity, despite a slowdown in the last decade. There are still considerable gaps in yields across the globe. One recent estimate (Foley *et al.*, 2011) suggests that closing 95% of the yield gap globally could raise production of 16 major crops by 58% — more than likely enough to meet the growth in food demand through 2050. Land expansion potential is highly contested. UN Food and Agriculture Organization (FAO) data suggests that there is still significant land potential, particularly in Latin America, Sub-Saharan Africa, and parts of Europe and Central Asia, although the environmental impacts of land expansion require consideration. Section 14.5 of this chapter focuses on this strand of recent World Bank research. Be it though productivity and/or land expansion, efforts to feed a growing global population will require complementary investments by both the public and private sectors and a solid policy environment.

Global CGE models focused on the economics of climate have mostly concentrated on the mitigation side, i.e. various carbon price regimes — carbon taxes (with and without coordination), carbon trading, quota allocation, and so on. The impact literature has largely been undertaken at the micro level, for example, spatial or for specific sectors. As the impact literature has swelled in recent years and developing countries are becoming more alarmed at current events that appear to be climate-related, there has been a budding literature on integrating the micro-level impacts at the macro-level to understand the macroeconomic impacts of climate change as well as the potential feedbacks on trade. Nordhaus' DICE and RICE family of models represent some of the earliest global models of the economics of climate change (Nordhaus, 1977, 2008; Nordhaus and Boyer, 2000).[8] Nordhaus' models have been designed to undertake full dynamic cost—benefit analysis due to the models' integration of both climate and impact modules. These models allow for evaluating the level of an optimum carbon tax and its

8 See also Nordhaus, Chapter 16 of this Handbook.

time path under various constraints and with an objective function that maximizes expected discounted utility. Hope's PAGE model (Hope, 2006), which provided the core of the analytical results in the *Stern Review*, also has an integrated impacts module that includes as well non-economic impacts (such as biodiversity). One of the key features of the PAGE model is the incorporation of uncertainty and the possibility of extreme or threshold effects. The FUND model (Anthoff and Tol, 2008) decomposes the simple macroeconomic damage functions of DICE and PAGE to include more distinct impacts such as impacts from sea-level rise, health effects, amongst others. The World Bank, with its new ENVISAGE model, has further extended the FUND work to allow for greater regional and sectoral disaggregation of the economic impacts. This work is described in greater detail in Section 14.6.

The range of applications of global CGE modeling has expanded vastly over the last three decades — from a focus mostly on international trade policies, to include commodities, climate change, international migration, dynamic structural change, and population dynamics, and there are other critical issues that would benefit from the consistent type of analysis that can only be provided by CGE analysis. Even in the traditional spheres of focus there are some underexplored areas (e.g. market structure and other deviations from well functioning market mechanisms) that await further theoretical advances, data collection and/or empirical validation. Finally, particularly in the realm of climate change, much more systematic use of uncertainty techniques is needed to better quantify the range of confidence of the analysis.

14.3 MODEL SPECIFICATION

14.3.1 Single-country 1—2—3 model

The core of the global CGE model takes off from the oft-used and discussed 1—2—3 model.[9] The 1—2—3 model is a single-country model (hence the 1) with two producing sectors (a non-tradable and an export good) and three goods (the non-tradable and export goods and an import good). Equations (14.1)—(14.12) fully characterize the model where demand is represented by a single agent, there are no distortions in the economy, production is fixed (in the short-run) and the small country assumption holds whereby world prices are fixed.[10] The model captures the essence of trade modeling used in most CGE models — though abstracting from much of the recent empirical trade literature that focuses on increasing returns to scale, love of variety and trade-productivity linkages.

9 See, e.g. de Melo and Robinson (1989) and Devarajan *et al.* (1997).

10 All variables are indexed by *r*, a regional indicator, which is not needed for a single-country model, but is for the global model.

Fixed aggregate output, XP, is allocated between domestic and export markets assuming a constant elasticity of transformation (CET) function, where XD^s represents supply to the domestic market and XE^s (aggregate) export supply. Equations (14.1) and (14.2) represent the derived supply equations where the prices PP, PD and PE represent respectively the aggregate output price, the price of domestically produced goods sold domestically and the (aggregate) export price.[11] The CET share parameters are represented by γ^d and γ^e, respectively the domestic and export share parameters, and the elasticity of transformation is given by ω^x.[12] Intuitively these equations reflect that supply to the relevant market is a price sensitive share of aggregate supply, with supply responding positively to an increase in the relevant market price relative to the average price. The output price, PP, is the CET aggregation of the component prices, PD and PE and can be derived from the CET primal formulation, Equation (14.3):[13]

$$XD_r^s = \gamma_r^d \left(\frac{PD_r}{PP_r}\right)^{\omega_r^x} XP_r \tag{14.1}$$

$$XE_r^s = \gamma_r^e \left(\frac{PE_r}{PP_r}\right)^{\omega_r^x} XP_r \tag{14.2}$$

$$PP_r = \left[\gamma_r^d PD_r^{1+\omega_r^x} + \gamma_r^e PE_r^{1+\omega_r^x}\right]^{1/\left(1+\omega_r^x\right)}. \tag{14.3}$$

The fuller model of course relaxes the assumption of exogenous output that will be formed through a combination of capital, labor, other factors of production and material inputs. Following the circular flow logic of the CGE model, income, Y, is derived from production and in this simple model it is simply equal to the value of output — adjusted potentially by outside financial flows, either positive or negative, B, Equation (14.4). The latter is fixed in volume terms and it is assumed to be converted to nominal income via the numéraire, P. Income is then converted into demand for goods and services, XA, which in this model represents domestic absorption that has a price PA, Equation (14.5):[14]

11 The derivation of these formulas is described more fully in van der Mensbrugghe (2010).

12 The dual share parameters and the CET elasticity can be linked to the CET primal formula via the following transformation: $\gamma_i = g_i^{-\omega}$ and $\omega = 1/(\nu - 1)$, where g represents the primal share parameter and ν the primal exponent.

13 In the actual model formulation, perfect transformation is allowed where the transformation elasticity is equal to infinity. In this case Equations (14.1) and (14.2) are replaced by the law-of-one price, i.e. PD and PE are both set to PP and Equation (14.3) is replaced with a simple linear aggregation of the volumes.

14 In a multisector model, Equation (14.5) would be replaced by demand functions derived from a utility function.

$$Y_r = PP_r XP_r + P \cdot B_r \tag{14.4}$$

$$XA_r = Y_r / PA_r. \tag{14.5}$$

Domestic absorption is allocated between demand for domestically produced goods, XD^{d} and (aggregate) imports, XM^{d}. Typically, the ubiquitous Armington assumption is implemented where domestic and imported goods are assumed to be imperfect substitutes with a constant elasticity of substitution (CES) function used almost universally for the preference function.[15] Equations (14.6)–(14.8) summarize the Armington decomposition. The first two represent the standard Armington demand functions for respectively domestically produced goods and (aggregate) import demand. Intuitively demand for the relevant component declines as its component price rises relative to the aggregate price. The share parameters are represented by α^{d} and α^{m} and the CES substitution (or Armington) elasticity is given by σ^{m}.[16] Equation (14.8) determines the Armington price and is derived from the CES aggregation of the component prices:

$$XD_r^{\mathrm{d}} = \alpha_r^{\mathrm{d}} \left(\frac{PA_r}{PD_r} \right)^{\sigma_r^{\mathrm{m}}} XA_r \tag{14.6}$$

$$XM_r^{\mathrm{d}} = \alpha_r^{\mathrm{m}} \left(\frac{PA_r}{PM_r} \right)^{\sigma_r^{\mathrm{m}}} XA_r \tag{14.7}$$

$$PA_r = \left[\alpha_r^{\mathrm{d}} PD_r^{1-\sigma_r^{\mathrm{m}}} + \alpha_r^{\mathrm{m}} PE_r^{1-\sigma_r^{\mathrm{m}}} \right]^{1/\left(1-\sigma_r^{\mathrm{m}}\right)}. \tag{14.8}$$

In this model there is only one equilibrium condition, represented by Equation (14.9). It guarantees supply–demand equilibrium on the domestic goods market and determines the equilibrium price on this market, *PD*. With the small country assumption, the "foreign" price of exports and imports is given, respectively *PWE* and *PWM*.[17] These prices are converted to domestic prices using the numéraire, *P*:[18]

$$XD_r^{\mathrm{s}} = XD_r^{\mathrm{d}} \tag{14.9}$$

15 See Armington (1969).

16 Similar to the CET above, the CES dual parameters can be linked to their primal equivalent using the following transformations: $\alpha_i = a_i^{\sigma}$ and $\sigma = 1/(1-\rho)$, where a represents the primal share parameter and ρ the primal exponent. The convention used herein is that all equations are formulated assuming input elasticities are positive.

17 An easy extension to the model would be to include an export demand and an import supply curve that would make the trade prices endogenous (as well as the terms of trade).

18 In some single-country models the numéraire will be called the exchange rate. In effect, the numéraire represents a price index of traded goods, or international goods, whose price is fixed by the small country assumption.

$$PE_r = P \cdot PWE \tag{14.10}$$

$$PM_r = P \cdot PWM. \tag{14.11}$$

This simple single-country model has thus 11 equations with 11 unknowns: XD^s, XE^s, PP, Y, XA, XD^d, XM^d, PA, PD, PE and PM. There are five exogenous variables: P, PWE, PWM, XP and B. This single sector model has nonetheless seven prices in total with the CET and CES functions largely determining wedges across the various components. With PWE and PWM fixed, it is easy to demonstrate that the single-country model is homogeneous of degree 1 in all prices. Finally, Walras' law can be shown to be given by the balance of payments constraint that is not included as part of the model implementation, Equation (14.12) but can be verified postsimulation to verify accounting consistency:

$$B_r = WPM \cdot XM_r^d - WPE \cdot XE_r^s. \tag{14.12}$$

14.3.2 Global 1—2—3 model

Converting the single-country 1—2—3 model into a global model requires only the addition of a handful of equations and a discussion of the model numéraire and Walras' law. The global model has r distinct regions (which in many implementations will also include individual countries). Equations (14.1)—(14.9) hold as above, however now all variables and equations are truly indexed by r. The trade module incorporates a full accounting of bilateral trade (abstracting for the moment allowance for homogenous goods) and all trade prices are endogenous, i.e. each country/region potentially has some market power that will be a function of the trade elasticities and market share. Equations (14.11) and (14.12) are dropped and replaced by equations that determine export supply by market of destination and import demand by region of origin.

A second CET nest is specified that allocates aggregate export supply, XE^s, to the different export markets. The variable WTF represents the volume of bilateral trade and is a two dimensional matrix with exports along the row and imports down a column, i.e. $WTF_{r,r'}$ represents exports from region r to region r'. Equation (14.13) determines bilateral export supply where $PWTF$ is the bilateral trade price, γ^w represents the CET (dual) share parameters and ω^w is the CET transformation elasticity. The aggregate export price, PE, is the CET aggregation of the component prices, Equation (14.14):

$$WTF_{r,r'}^s = \gamma_{r,r'}^w \left(\frac{PWTF_{r,r'}}{PE_r} \right)^{\omega_r^w} XE_r \tag{14.13}$$

$$PE_r = \left[\sum_{r'} \gamma^{w}_{r,r'} PWTF_{r,r'}^{1+\omega^{w}_r} \right]^{1/\left(1+\omega^{w}_r\right)}. \tag{14.14}$$

Analogously, the Armington demand for aggregate imports is decomposed by region of origin using a second CES nest. Equation (14.15) determines imports into region r from region r' and Equation (14.16) determines the aggregate price of imports, PM, as implemented using the CES dual price aggregation function.[19] The CES share parameters are given by α^{w} and the second-level substitution elasticity is σ^{w}:

$$WTF^{d}_{r',r} = \alpha^{w}_{r',r} \left(\frac{PM_r}{PWTF_{r',r}} \right)^{\sigma^{w}_r} XM_r \tag{14.15}$$

$$PM_r = \left[\sum_{r'} \alpha^{w}_{r',r} PWTF_{r',r}^{1-\sigma^{w}_r} \right]^{1/\left(1-\sigma^{w}_r\right)}. \tag{14.16}$$

Fully endogenizing bilateral trade requires an additional set of equilibrium conditions that determines the equilibrium price of each bilateral trade node. Equation (14.17) represents this equilibrium condition and determines the matrix of bilateral trade prices, $PWTF$. Unlike the standard 1−2−3 single country, the terms of trade in the global model are endogenous:

$$WTF^{s}_{r,r'} = WTF^{d}_{r,r'}. \tag{14.17}$$

The nested CES structure for trade, as presented above, embeds potentially strong assumptions on the inter-substitutability of imports by region of origin. Any given pair of imports has the same substitution irrespective of the goods' origin. With the increasing globalization of production, this may not be a bad long-run assumption, but a priori one would assume, for example, that cars produced by high-income countries are more substitutable with each other, than cars produced by high-income countries and emerging markets.[20] Both the LINKAGE model (van der Mensbrugghe, 2011) and CEPII's MIRAGE model (Bchir *et al.*, 2002) have additional nests that allow for more substitution flexibility by region of origin. Empirical estimation and validation are potential weak points that are further addressed below. An alternative, that has rarely been used, is to use a top-level flexible functional form that would allow direct

[19] Note the change in the indices when comparing the bilateral export supply and import demand equations. In both sets of equations, the focus is on region r, and r' indices the trading partner.

[20] Incorporating dynamic Armington substitution elasticities was pioneered by work done at the Netherlands Bureau for Economic Policy Analysis (CPB) in their WorldScan model (CPB, 1999) and has been implemented in the LINKAGE model (van der Mensbrugghe, 2011), although rarely used.

implementation of variations in cross price elasticities across any pair of imported goods (see, e.g. Robinson *et al*., 1991). A potential drawback may be the domain of application of the flexible functional form. Robinson *et al.* used the Almost Ideal Demand System[21] (AIDS) that works well for small shocks, but can have demand shares that exceed the 0−1 range of applicability for large shocks. Like the estimation of Armington elasticities, estimating flexible functional forms for specifying import demand requires long time series of price and trade volumes that are only available in a handful of countries.

ENVISAGE, as some other global CGE models and many global partial equilibrium models of agriculture, also allows for homogeneous traded goods. Even if almost all goods exhibit some form of two-way trade, it is often a useful approximation to actual market developments (e.g. in the global market for crude oil). Under the assumption of homogeneous goods, imported goods are not identified by region of origin and only net trade is accounted for.

The notion of price transmission, i.e. the transmission of global price shocks to the domestic market, needs careful interpretation. Under the standard Armington assumption, there is perfect price transmission in the sense that changes to the world price, i.e. the c.i.f. (cost, insurance and freight) price of a good is perfectly reflected in the domestic agent's price of imports. However, that does not translate into a similar change in the price of the competitive domestic good − nor on the average absorption (or Armington) price. The price transmission from the world to the domestic market is simply a function of the initial import value share of total absorption, i.e. the elasticity of the Armington (or domestic absorption price) relative to the import price is s^{m}, irrespective of the elasticity, where s^{m} is the value share of imports in domestic absorption. It would be possible to isolate the domestic market from global market changes by having an endogenous tariff that would neutralize changes in the price of imported goods. This was one of the key mechanisms of the EU's earlier Common Agricultural Policy (CAP) program that in essence insulated the domestic market from world markets. Imperfect agricultural price transmission was one of the mechanisms of the RUNS model (see Burniaux, 1987; Burniaux and van der Mensbrugghe, 1991) that also assumed a homogeneous global market for agricultural goods.

There are various ways to handle the issue of the model numéraire. The ENVISAGE model, similar to the LINKAGE model uses a price index composed of a basket of goods as the numéraire and fixes the value of this basket to an initial value − typically 1.[22] The basket used is the manufactured exports of high-income countries. This is intuitively appealing as it represents on average what can be purchased with a given volume amount of foreign savings. Equation (14.18) implements this for the global 1−2−3 model, where

21 Extensively described in Deaton and Muellbauer (1980) in the context of consumer demand.

22 Some models have a country-specific numéraire, i.e. fix some national price index and use an exchange rate to convert prices across regions (see, e.g. McDonald *et al*., 2007). Any price can of course be fixed. For example, the Walras model fixed the price of labor in the US (see Burniaux *et al*., 1990).

P represents the model numéraire, HIC is a subset of the model's regions (often the subset of high-income countries) and φ represents base-year export shares.

$$P = \sum_{r \in \mathrm{HIC}} \sum_{r'} \varphi_{r,r'} PWTF_{r,r'}. \tag{14.18}$$

The global model has the same base set of equations as the single-country model — so this starts with 11 endogenous variables times the number of regions. In addition, there are three sets of bilateral equations. Thus the total number of equations is $(11 + 3 \cdot R)R$. There is however an additional equation — the numéraire definition. It is relatively easy to show that Walras' law at the global level can be derived by the income definition equation (14.4) and thus this equation can be dropped for one of the regions.[23] The endogenous variables are therefore XD^s, XE^s, PP, Y, XA, XD^d, XM^d, PA, PD, PE, PM, WTF^s, WTF^d and $PWTF$ — the first 11 of which multiplied by R and the last three by $R \times R$. There are three exogenous variables: P, XP and B — the first is the model numéraire and the latter two are multiplied by R. Note that the R components of B are not fully independent as they must sum to zero globally (one of the complications of creating a consistent global database).

14.3.3 Global 1—2—3 model extensions

A full global model extends the 1—2—3 model in a number of ways. One extension is to replace the assumption of fixed output with a true production structure that includes factors of production and other production inputs. A simple structure would have intermediate inputs in strict proportion to output (the Leontief specification) and a value-added bundle that would be composed of a CES combination of capital and labor. More elaborate specifications are typically used in larger models that have additional factors of production, e.g. land, skilled and unskilled labor, etc., and more realistic nesting structures; for example energy (perhaps combined with capital) as a substitutable input for labor. The addition of factors of production requires specifying equilibrium conditions and the mobility of factors across sectors.

A second extension is to increase the number of commodities being modeled. For most of the equations described earlier, this simply implies adding a sectoral index, e.g. i. Some would require modifications to incorporate the additional dimensionality such as the income and consumption equations, the balance of payments formula, and so on. While income and the balance of payments formula are identities by definition, the consumer demand specification typically relies on an explicit utility function such as a Cobb—Douglas, linear expenditure system or AIDADS.

[23] In the full global model it is the balance of global savings and investment that defines Walras' law and thus the investment equation is dropped for one of the regions from the model.

A third extension increases the number of domestic agents — including typically government and investment accounts, and potentially multiple representative households rather than a single nationally representative household. Model closure then requires explicit assumptions — government fiscal balance and investment savings balance.

Finally distortions in the form of taxes and subsidies form part of virtually all models — even if they are not one of the key driving factors for developing CGE models in the first place. These distortions can appear at all levels where market transactions take place.

14.3.4 ENVISAGE model

ENVISAGE is a recursive dynamic global CGE model. It is currently calibrated to GTAP's release 7.1 database that has a 2004 base year, 112 regions/countries and 57 sectors. ENVISAGE has been designed to have a flexible aggregation of the base data and thus there is no unique regional or sectoral aggregation of the model.

The description of the ENVISAGE model takes off from the basic framework described above of the global 1—2—3 model, but has a number of specific features that differentiates it from a simple global CGE model. This section describes its main features as regards its comparative static implementation. The next section will focus on the dynamic components.

Large scale CGE models have taken two basic approaches to modeling the multi-sector production structure. Both approaches use a cost minimization paradigm where producers aim to minimize costs subject to a production frontier that is a function of the various inputs of production — goods and services, labor, capital and potentially other factors of production such as land. One approach, pioneered in large part by Jorgenson and colleagues,[24] uses so-called flexible functional forms, that can be thought of as a close approximation of the true underlying production structure. Under standard regularity conditions and with appropriate datasets, flexible functional forms are suitable for estimation and can be readily implemented in large scale numeric models. These include the translog, generalized Leontief and normalized quadratic functional forms. As an example, the cost function of the translog production function is:

$$\ln(c) = \ln(b_0) + \sum_i b_i \ln(p_i) + \frac{1}{2}\sum_i \sum_j a_{ij} \ln(p_i) \ln(p_j),$$

where c is unit cost, p_i represents the prices of inputs, and b_0, b_i and a_{ij} are parameters of the production function. The derived input shares from this functional form are:

$$s_i = b_i + \sum_j a_{ij} \ln(p_j).$$

24 Christensen *et al.* (1973), Jorgenson (1984) and Jorgenson *et al.*, Chapter 7 of this Handbook.

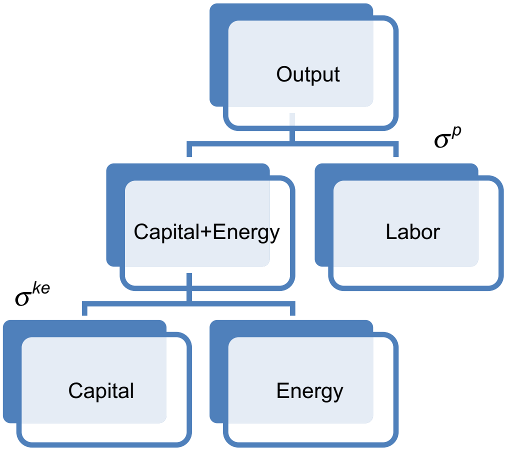

Figure 14.1 Hierarchical production nesting.

One can readily see that the cost function allows for a rich set of own- and cross-price effects and the share equation lends itself readily to econometric estimation given the availability of time series on input shares and prices, and subject to the consistency conditions on the parameters to satisfy the regularity conditions of cost functions.

The second approach, that has tended to dominate the empirical implementation of CGE models, is the so-called nested CES approach.[25] Rather than capturing the complex interactions of inputs with a single top-level functional form such as the translog, the nested CES structure attempts to reproduce these interactions by specifying a nested structure for the inputs. For example, assume we have a production function that has labor, capital and energy as inputs, and we have econometric estimates of the cross-substitution elasticities that indicate that capital and labor are substitutes, but that capital and energy are complements. In the flexible functional form, the parameters of the a_{ij} matrix would capture these substitution and complementary relations. In the nested CES approach, production might have two nests. The top-level nest would combine labor with a composite input of capital and energy, with a CES substitution elasticity of σ^{p}. The second level nest would combine capital with energy to "produce" the capital and energy bundle for the top level nest using a substitution elasticity of σ^{ke}. This is depicted in Figure 14.1.

Use of a single nested CES function for the three inputs, would impose strong assumptions about the pair-wise cross elasticities that would most likely be ruled out through econometric estimation. For example, the matrix of elasticities in the translog function is given by:

25 The MONASH model (Dixon *et al.*, 2002) uses a hybrid approach that includes some production nesting that also includes the CRESH flexible functional form (Hanoch, 1971).

$$\varepsilon_{ij} = \frac{\partial x_i}{\partial p_j}\frac{p_j}{x_i} = s_j + \frac{a_{ij}}{s_i} - \delta_{ij}.$$

The relevant matrix for a single nested CES would be:

$$\varepsilon_{ij} = \sigma\left(s_j - \delta_{ij}\right),$$

where σ is the substitution elasticity. Unlike in the translog function, where the a_{ij} matrix captures pair-wise specific effects, in the single nested CES the pair-wise elasticities are uniform for each input, i.e. the substitution between capital and labor is the same as between capital and energy.

Perroni and Rutherford 1995 and 1998 argue that nested functional forms can be made to replicate specific sets of initial conditions — similar to flexible functional forms. They also suggest that the nested CES structure may have better behavior over a wider domain than flexible functional forms, which can help with numerical convergence. Given the potentially close approximation of either approach, the final choice will be left with the model developer. Validation of the specification choice and parameterization is often lacking, with some notable exceptions. It has proven easier to validate model results at the single-country level, although even there, it requires long-time series of detailed production data. Dixon and Jorgenson and their respective colleagues have set the standards for respectively Australia and the US, but there has been little replication in other countries.[26] The econometric advantage of flexible functional forms is less an advantage in the global CGE models where the availability of good time series cross-country data is sorely lacking. The Jorgenson sponsored KLEMS project[27] is a strong step in the right direction to alleviate the paucity of international estimates of production structure parameters.

Thus, similar to many global CGE models, the ENVISAGE models uses an elaborate nested CES structure that aims to capture the different substitution and complementarity relations across the various inputs — both material goods and factors of production. The standard version has a non-energy bundle of goods combined with a value-added plus energy bundle to produce output. The former is further disaggregated assuming fixed coefficients. The value-added plus energy bundle is composed of capital and energy, on the one, and all of the other factors of production, on the other.[28] In its dynamic version, ENVISAGE has a vintage structure for capital that allows for different elasticities depending on the vintage. Typically energy will be less substitutable for capital in the short-term, i.e. with older vintages, but more substitutable in the longer term,

26 See Dixon *et al.* (1982, 2002), Dixon and Rimmer (Chapter 19 of this Handbook) and Jorgenson et al. (Chapter 17 of this Handbook). It should be noted as well that Dixon and Rimmer (2004) have replicated there Australia work for the US in the development of the USAGE model.

27 http://www.worldklems.net/.

28 The model allows for different ways of treating skilled labor. In some versions, skilled labor is treated as a near complement with capital. Alternatively, skilled and unskilled labor are treated as substitutes.

i.e. with newer vintages. The energy bundle is decomposed into various energy components – electricity, coal, gas, and so on. The ENVISAGE model allows for multiactivity and joint production. The former allows, for example, for multiple power technologies in the production of electricity (e.g. nuclear, hydro, coal, amongst others). A CES aggregator is used to aggregate the multiple activities into a single marketed commodity. Joint production allows, for example, the production of ethanol and distiller's dried grains with solubles (DDGS) in the biofuel production sector with DDGS used as feed in livestock production.

Income is essentially derived from returns to factors of production – labor, capital, land and natural resources. All income accrues to a single representative household. Government derives its income from various taxes – sales, excise, import duties, export, production, factors, direct. Investment revenues derive from three sources – household and government savings and net foreign savings.[29]

Household demand is implemented with a consistent demand system. The ENVISAGE model allows for four different specifications. The linear and extended linear expenditure systems (LES/ELES) have been used for many years.[30] They are easy to implement and require few inputs for calibration. However, they have poor Engel behavior as they converge relatively rapidly to a Cobb–Douglas utility function with unitary income elasticities without some mechanism that re-calibrates the parameters as incomes rise. This matters significantly in long-term dynamic scenarios particularly for commodities such as food where income elasticities have been shown empirically to trend down towards zero as incomes rise. The third system is the constant differences in elasticity (CDE) specification that is the default utility function in the standard GTAP model.[31] The CDE has more flexibility than the LES/ELES, but is also somewhat restrictive in a dynamic setting. The fourth system is known as An Implicitly Directly Additive Demand System (AIDADS) and was developed initially by Rimmer and Powell (1992a, 1992b). Yu *et al.*, 2002 used the AIDADS function to provide parameter estimates in the context of the GTAP dataset and global model. In many respects it is similar to the LES where consumption is divided into two parts – a so-called subsistence minimum (or floor expenditure) and a marginal budget expenditure from supernumerary income, defined as disposable income after subtracting floor expenditures. Unlike the LES, the AIDADS allows the marginal budget shares to change with income providing more plausible Engel behavior. However, calibration of the AIDADS system is inherently more complex than the aforementioned demand systems and is still the focus

29 The GTAP data does not distinguish between private and public savings. The latter are therefore initialized at zero in the base year, and the residual between investment expenditures and net foreign capital inflows is allocated to household savings.

30 The ELES extends the LES to integrate household savings in the top level utility function (see Lluch, 1973; Howe, 1975).

31 See Hertel (1997).

of considerable econometric work. The ENVISAGE model allows for a different classification of consumed and produced goods. A so-called "transition" matrix converts consumed goods into produced goods.[32] This allows for more plausible implementation of energy demand on the household side where energy can be linked to demand for transportation, cooking, heating and cooling, and so on. Data is the limiting factor at the moment as few national input/output tables include a transition matrix.

Government and investment expenditure functions are implemented using a CES functional form.

Domestic absorption at the commodity level is added up across all agents — production and all final demand — and allocated between demand for domestically produced goods and imports by region of origin using a two-nested CES structure as described in the global 1—2—3 model above.[33] Analogously, domestic production is allocated across all markets — domestic and export markets — using a two-nested CET structure. Equilibrium conditions determine the price of domestic goods and all bilateral trade prices.

Bilateral trade is associated with three different price wedges. The first introduces a wedge between the producer or farm-gate price and the border [or f.o.b. (free on board)] price. These export taxes/subsidies are often used to subsidize the export of food by high-income countries. The second wedge captures the cost of port-to-port transportation, or the difference between the f.o.b. and c.i.f. price. The third wedge incorporates import tariffs and measures the difference between the c.i.f. and (presales tax) end-user price. Note that the international transportation and trade margins are linked to demand for actual services — transportation, insurance, and so on. The demand for these services is allocated across the model's regions so as to minimize cost.[34]

ENVISAGE has five factors of production — unskilled and skilled labor, capital, land (usually only in agriculture), and natural resources that are sector-specific (forestry, fisheries, coal, crude oil, natural gas and other mining). In most versions of the model, unskilled and skilled labor are assumed to be perfectly mobile across sectors with an economy-wide wage rate clearing the labor market. Some versions of the model introduce labor market segmentation for unskilled workers using a Harris—Todaro framework that allows for rural to urban migration as a function of expected relative wages.[35] Aggregate (agricultural) land supply follows a logistic curve with an absolute maximum available supply that has been calibrated to FAO data. Land is allocated across sectors using a CET specification whereby land supply tends to go where returns are

32 This was also implemented in the GREEN model (see Burniaux *et al.*, 1992 and van der Mensbrugghe 1994).

33 The GTAP database allows the top nest of the Armington structure to be agent-specific, i.e. the allocation between domestic demand and aggregate imports. This is an optional component of the ENVISAGE model, but it significantly increases the dimensionality of the model.

34 Unlike the LINKAGE model, ENVISAGE does not allow for iceberg transportation costs that can capture improved logistics and similar efficiencies in the transportation of goods.

35 Harris and Todaro (1970).

highest. With a finite CET elasticity land is only partially mobile and sectoral land demand and supply are set equally to provide a sector-specific return to the land. Natural resources are supplied using an isoelastic supply function.[36] Sectoral supply and demand balance generate their equilibrium price.[37]

The capital market in the dynamic model factors in the vintage nature of capital. The model tracks only two vintages – installed (or *Old*) capital and *New* capital that is available at the beginning of each period. Each sector starts out at the beginning of the period with a depreciated stock of capital that it had at the end of the previous period. New capital is allocated across all sectors such that its rate of return is equalized across sectors. If a sector is in expansion, i.e. its derived demand for capital exceeds its installed capacity, it will demand new capital. Its installed capital then reaps the same return as the new capital. If a sector is in contraction – that may occur from policy changes for example – it will wish to release some of its installed capacity and does so with an upward sloping supply curve. The released capital is assumed to have the same return as new capital, the assumption being that the capital being released is a perfect or near substitute for new capital. The rate of return to the installed capacity in a contracting sector will be set by supply/demand equilibrium and will be lower than the economy-wide return to capital.

The standard scenario incorporates three closure rules. The first relates to government closure. Aggregate expenditures are assumed to be constant as a share of GDP. The government fiscal balance is exogenous (and assumed to converge towards zero within some time horizon). The household direct tax schedule adjusts to any shortfall or surplus on the government fiscal balance. In the single household model this is equivalent to a change in lump-sum taxes. With this closure rule changes in policies that affect government revenues (e.g. a reduction in import tariffs or implementation of a carbon tax) leads to a change in lump-sum taxation.

The second closure rule relates to savings investment balance. Household save a proportion of their total income. In dynamic scenarios, the average propensity to save is influenced by demographics – with higher savings associated with lower dependency ratios – and overall growth. Government savings, as mentioned above are exogenous. Foreign savings are likewise exogenous. Investment is savings driven, which means that it is mostly influenced by household saving behavior in nominal terms, although the price of investment goods will influence the overall volume of investment as well.

The third closure rule relates to external balance. The default closure has fixed foreign savings and thus fixed trade balances. The implication of this assumption is that *ex ante* changes to trade flows will affect the real exchange rate. For example, a reduction in

36 The GREEN model (Burniaux *et al*., 1992 and van der Mensbrugghe 1994) had resource depletion models for crude oil and natural gas and they have been developed for ENVISAGE but not yet implemented.

37 In the baseline scenario, supply shifters may be used to target trend paths for world prices (e.g. of crude oil and natural gas).

tariffs that would *ex ante* trigger a rise in import demand, will have to be accompanied by a rise in exports that would be generated by a real exchange rate depreciation.

14.3.5 Model dynamics

The ENVISAGE model is a recursive dynamic model with origins in simple neoclassical growth models, i.e. it relies on factor and productivity growth. Population and labor supply growth are exogenous and based on the UN regular release of their population projections. The population projections are used to calibrate the dependency ratios (youth and elderly). Labor growth is assumed to match growth of the working age population, i.e. those aged between 15 and 64. Capital accumulation in each period is simply the sum of the previous period's depreciated capital stock and the previous period's volume of investment. Supply of the other factors of production depend on their respective supply curves — albeit there are dynamic shifters on the supply of some of the natural resources in the baseline to target a given profile of world prices.

Productivity assumptions in the model are segmented by three broad sectors — agriculture, manufacturing and services. In agriculture, productivity growth is assumed to be fully exogenous and neutral across all inputs, i.e. a uniform expansion of the production possibilities frontier. In most of our past work we have made the default assumption that in the near-term agricultural productivity tracks the long-term average of around 2% *per annum*,[38] but declining over time. In a modeling comparison exercise coordinated by the OECD and in collaboration with International Food Policy Research Institute (IFPRI) and Agricultural Economics Research Institute LEI, we have currently aligned our assumption of agricultural productivity with IFPRI's that is based on country- and crop-specific crop modeling.[39] Further details are provided below. Productivity growth in manufacturing and services is labor-augmenting only (both unskilled and skilled). The two are linked with productivity in manufacturing assumed to be higher than in services. The default baseline scenario has a two percent wedge with services productivity calibrated to achieve a given growth path for *per capita* incomes.[40] A primary reason for this assumption — at least for emerging economies — is the ability to capture the so-called Samuelson—Balassa effect. The effect is driven by high-productivity growth in manufacturing that raises economy-wide wages. With slower productivity growth in services, the price of non-tradable goods and services tends to rise relative to tradable goods (i.e. manufacturing), or in other words a real exchange rate appreciation linked to high growth.

38 See, e.g. Martin and Mitra (1999).

39 See Rosegrant *et al*. (2008) for a description of IFPRI's IMPACT model, which is a global multimarket partial equilibrium model. See Nelson *et al*. (2010) — an IFPRI monograph that explores different agricultural scenarios through 2050 including climate change effects.

40 This is an area of increased focus and research that will eventually be linked to empirical work with the Harvard-based KLEMS project.

In addition to the productivity assumptions described above, dynamic scenarios also incorporate rising energy efficiency using the so-called autonomous energy efficiency improvement (AEEI) parameter that is set to increase by 1% *per annum* across all uses and fuels, and a 1% *per annum* decline in average international trade and transport margins.

14.3.6 Emissions and climate module

ENVISAGE incorporates emissions of the so-called Kyoto greenhouse gases – carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and the fluoridated gases (F-gases). All emissions are converted to carbon equivalent using the IPCC's global warming potential conversion factor. Most of the emissions are directly produced by the consumption of goods, e.g. through combustion. There are some emissions directly linked to factor use (e.g. methane emissions from livestock) and/or to total output (e.g. methane emissions from waste management facilities). The baseline assumes no controls on emissions, but does include trend declines in certain emission coefficients based on historical trends. The model allows for flexible carbon emission control regimes including carbon taxes, caps with and without trade, variable coalition sizes and domestic exemptions (e.g. of key sectors). ENVISAGE also includes carbon border tax adjustments that have entered the policy discussion as countries that have unilaterally implemented domestic carbon taxes aim to tax the embedded carbon in imports.[41]

Emissions are added to the atmosphere generating changes in concentration, radiative forcing and atmospheric temperature measured as the change in global mean temperature since 1900.

Temperature change feeds back to the economy through "damage" functions. These feedbacks include changes to agricultural productivity, water availability, on the job labor productivity, human health, sea-level rise, changes in tourism revenues and changes to energy demand. Despite the use of the term "damage" functions, the economic impacts in some sectors and countries can be positive at least in the near and medium term.

14.4 MACROECONOMICS OF THE BASELINE SCENARIO

14.4.1 Core dynamic drivers

Derived findings from a forward looking exercise (e.g. the price of food or carbon emissions) rely to a very large extent on the core drivers of economic growth. The two most basic drivers are simply population and the components of GDP growth – in the simplest neoclassical model, labor, capital and productivity. The underlying basis for these core drivers in a baseline are continuously undergoing evolution as new information becomes available and/or new methodologies or assumptions are implemented.

41 See Mattoo *et al.* (2009a, 2009b).

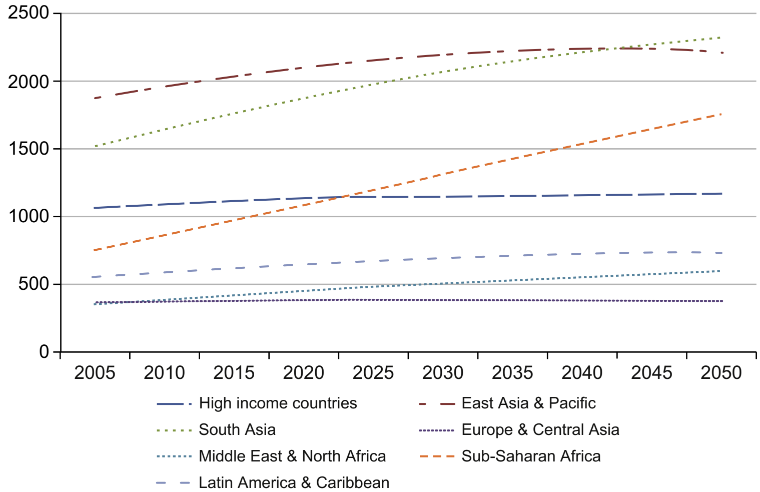

Figure 14.2 Population scenario, various regions through 2050 (million). *(Source: UN Population Division, 2008 Revision.)*

Most global forward looking scenarios take as their core drivers for population and labor growth the UN population forecast. The current population forecast used for ENVISAGE is based on the 2008 revision.[42] This would see a rise in total population from 6.5 billion in 2005 to 9.15 billion in 2050 — an increase of some 2.6 billion persons. Figure 14.2 summarizes the UN forecast for the seven major World Bank regions — high-income (HIC), East Asia and Pacific (EAP), South Asia (SAS), Europe and Central Asia (ECA), Middle East and North Africa (MNA), Sub-Saharan Africa (SSA) and Latin America and Caribbean (LAC).[43] Several key findings emerge from this population projection:

- Almost all of the growth occurs in developing regions with only around 100 million of the 2005/2050 increment of 2.6 billion occurring in high-income countries.
- South Asia and Sub-Saharan Africa — regions with the highest fertility rates — will account for two-thirds of the total population increase, respectively adding 800 and 990 million persons. In the case of Sub-Saharan Africa this translates into more than a doubling of its base year population. The Middle East and North Africa region will see a 70% increase in its population over this time period.
- The global growth rate declines rapidly over the next 40 years — from 1.2% *per annum* in 2010 to around 0.3% *per annum* in 2050.

42 The 2010 revision was released by the UN Population Division in May 2010. There are modest changes relative to the 2008 revision with global population in 2050 projected to be 9.31 billion versus 9.15 billion in the 2008 release — albeit more differences between the two revisions for specific countries and regions that to some extent cancel out at the global level.

43 The regional and sectoral aggregations of the global model used for the empirical findings of the rest of this chapter are presented in the Appendix.

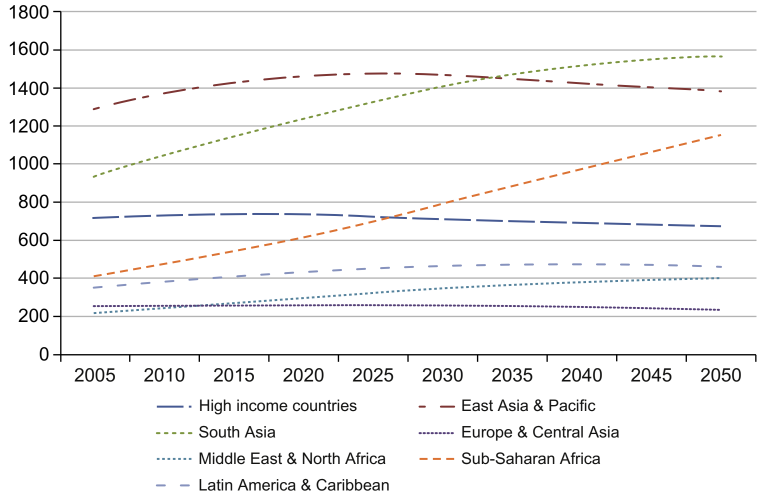

Figure 14.3 Working age population (15—64) through 2050 (million). *(Source: UN Population Division, 2008 Revision.)*

- Three regions will peak and decline — high income after 2045, East Asia and Pacific after 2040, and Europe and Central Asia after 2025. The growth in Latin America and Caribbean drops sharply and approaches 0 by 2050.
- The percentage of the world's population in high-income countries will drop from 16 to 13%.

The implication for food demand is that agricultural production needs to increase at least as rapidly as population growth to avoid major shortages (to the extent there are no changes in food consumption and waste patterns). Moreover, much of the population increment is in the poorer regions where income elasticities for food are likely to be higher than in the other regions. Similarly, the impact on emissions growth is bound to be high — linked to both population and income growth — perhaps to be partially offset by greater energy efficiency and a switch to cleaner energy technologies.

Labor force growth is by assumption equated to the growth of the working age population — those between the ages of 15 and 64.[44] With the UN's population forecast (Figure 14.3) we would witness a peak and decline in the labor force in high-income countries and Europe and Central Asia starting after 2015, in East Asia and Pacific after 2030 and Latin America and Caribbean after 2040. South Asia and Sub-Saharan Africa would see very rapid growth — in the case of the latter, a near-tripling of the working age

44 There are many reasons why this might be a simplistic assumption. In many developing regions one could foresee an increase in overall labor force participation rates particularly as more women enter the labor force. High-income countries may witness a rise in labor force participation rates as the sustainability of pension systems force a rise in retirement age and/or a decline in pension benefits.

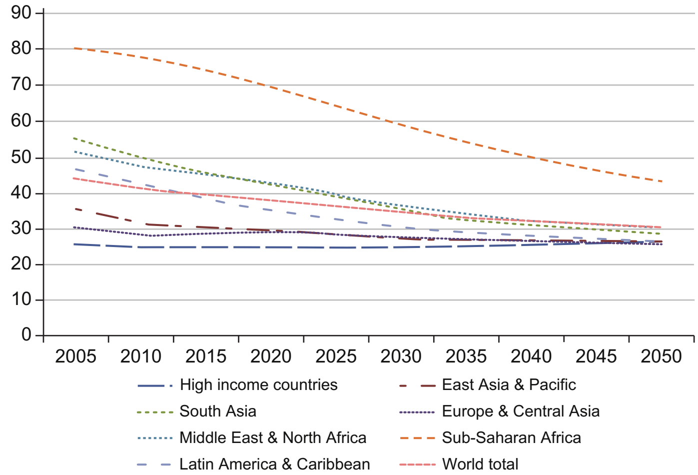

Figure 14.4 Youth dependency ratio: number of persons aged under-15 relative to 100 working age population. *(Source: UN Population Division, 2008 Revision.)*

population. For these latter two regions, growth of the working-age population potentially provides a basis for rapid income growth, but also requires complementary investments in education and infrastructure to maximize overall potential.

Although the aggregate labor force is assumed to be exogenous, there are other assumptions that may have an impact on overall economic growth and structural transformation. In the default baseline, the growth of skilled and unskilled labor is assumed uniform. With rising rates of education, it would be plausible to skew labor growth towards skilled labor. Second, the default baseline assumes that wages clear economy-wide, i.e. that there is perfect mobility of labor across all sectors. A variant from the baseline allows for labor market segmentation, where rural and urban labor markets clear separately and a rural to urban migration function is introduced along the specification of Harris and Todaro where migration is a function of relative expected wages.[45] The baseline assumes no changes in international migration (other than what is implicit in the UN population projection). Several studies have shown that a rise in South to North migration would lead to a rise in global economic output for the same reason that rural to urban migration can accelerate growth — workers and economies can benefit from movements from low productivity to high productivity employment.[46]

Capital accumulation in the model is driven by a number of key assumptions. The standard neoclassical growth dynamics has capital in any one period equal to the previous

45 Harris and Todaro (1970).
46 See World Bank (2006) and Walmsley and Winters (2003).

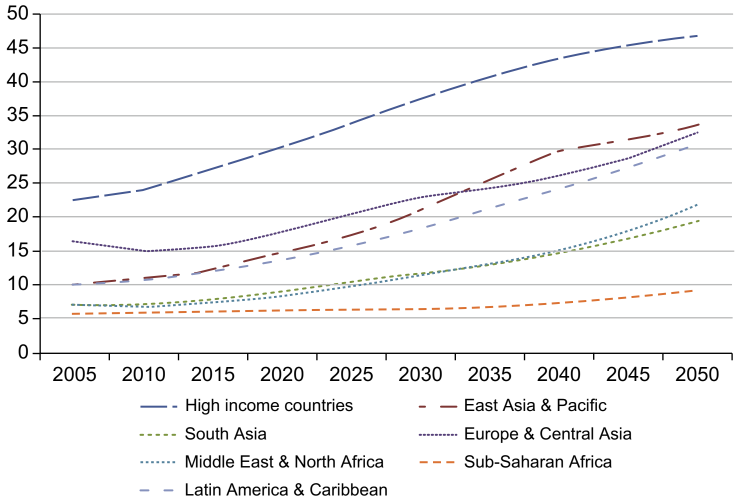

Figure 14.5 Elderly dependency ratio: number of persons aged over 65 relative to 100 working age population. *(Source: UN Population Division, 2008 Revision.)*

period's depreciated stock plus new investments. Thus, the rate of depreciation will be an important exogenous parameter. Investment in turn is savings driven. The national savings rate is a function of several variables — *per capita* growth, and the youth and elderly dependency ratios.[47] All of the regions are slated to see strong changes in these dependency ratios. Figure 14.4 shows the under-15 dependency ratio — defined here as the number of youths under the age of 15 per 100 in the working age population.[47] The global average is converging towards a level of 31 youths per 100 with a lower bound of around 26. All developing regions see a declining trend with a very sharp decline in Sub-Saharan Africa — from 80 per 100 to nearly a halving, leaving 43 per 100. This sharp decline is part of the so-called demographic transition where fewer resources need to be diverted to the raising of children and more can be saved and invested. While the youth dependency ratios decline and stabilize, old-age dependency (defined as number of persons 65 and over relative to 100 in the working age population) increases sharply in many regions (Figure 14.5). At the global level, the age-old dependency rate increases from 11 per 100 to 25 per 100 between 2005 and 2050. The proportion of the 65 and over population increases from 7 to 16% relative to the global population. The highest dependency ratio in 2050 would be among the high-income countries, averaging per 100, but the old-age dependency ratio rises rapidly for East Asia and Pacific (10 in 2005 to 33 in 2050), Europe and Central Asia (16 to 32) and Latin America and Caribbean (10 to 31) — so the phenomenon is not limited to the high-income countries. Beyond the

[47] See Loayza *et al.* (2000) and Masson *et al.* (1998) for saving function specification and parameterization.

impacts on savings and fiscal solvency, aging may also affect consumer demand, notably food demand, and perhaps a shift towards services — notably health-related — and away from consumer goods, durables and housing. These latter effects on demand are not currently captured in the ENVISAGE model.

While the national savings rate is influenced by the growth rate and demographic variables, net foreign capital inflows are exogenous. In the baseline, these decline linearly to zero by 2025. A variant of the model allows for partial inter-regional capital mobility that reacts to changes in relative profit rates across regions (similar to the GTAP model),[48] but a more consistent treatment of capital flows would require a model with foresight and consistent investor behavior (of which the G-Cubed model[49] is a leading example).

The assumptions regarding productivity were discussed above. In the standard baseline, labor productivity in the services sector is calibrated to a given scenario of *per capita* income growth. There are infinite ways to generate such a scenario and apart from the resulting implications for productivity, prices, structural transformation etc. and their plausibility that emerge from running the baseline, any given scenario is as good as the next. ENVISAGE's long-term baseline scenario is based on the combination of two methodologies. The first is used for the short- and medium-term. Over the historical period, GDP growth is lined up with observed growth, i.e. between 2004 and 2010. Typically, only GDP is lined up, although in principle other variables could also be targeted (to the extent that observed data leads to a consistent set of value flows, e.g. globally balanced trade and capital flows). The World Bank's medium-term forecast is used to guide GDP growth 2—3 years ahead. The second methodology assumes that eventually developing countries will catch-up to high-income countries (whose long-term *per capita* growth is assumed to be around 1.5% *per annum*). Countries catch-up at different speeds and there is some overall notion where countries might be in 2100 relative to the high-income countries. Figure 14.6 depicts the *per capita* growth assumptions for the seven broad regions. The growth patterns reflect in part the deep downturn in the late 2000s related to the financial crisis as well as the merging of the two different methodologies. What is perhaps most relevant for the focus on food and natural resources is the overall growth achieved over the 40- to 45-year period. On average, developing country growth over this period is 5.2% *per annum*. At constant prices, this implies that average incomes would rise from 5% of the high-income average to 11% at market exchange rates, or from 15 to 31% measured in 2004 prices and purchasing power parity exchange rates. In terms of overall economic size, developing countries' share of global output would rise from 21% in the 2005 base year to 42% in 2050 (at constant prices and market exchange rates) or jump to two-thirds evaluated in constant purchasing power parity prices. With Samuelson—Balassa-type effects,

48 See Hertel (1997).
49 See McKibbin and Wilcoxen (1995) and McKibbin and Wilcoxen, Chapter 3 of this Handbook.

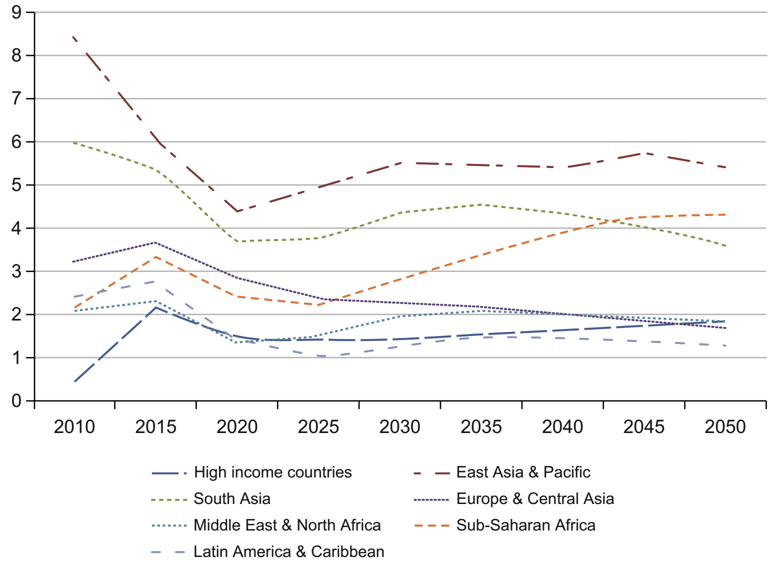

Figure 14.6 *Per capita* income growth rates (% *per annum*). (Source: *World Bank.)*

the nominal shares at market exchange rates would be higher as one would expect relative prices to rise in developing countries relative to high-income countries.[50]

14.5 AGRICULTURE TOWARDS 2050

14.5.1 Introduction

Since 1950 (and even earlier) agricultural prices have been on a long downward trend as agricultural productivity and to a lesser extent land expansion have been sufficient to produce abundant supplies for a commodity that in most cases has a very inelastic income demand. There have been three large spikes since 1950 — during the Korean War, a spike in the mid-1970s linked to the oil price rise and of course the more recent 2007/08 episode that eased somewhat with the financial crisis, but appears to be rebounding (see Figure 14.7).[51]

50 The standard baseline has limited Samuelson—Balassa effects. Using alternative specifications and parameter modifications it is possible to get much stronger effects and it is an area of active research. Some of the changes to model specification include specifying skilled-capital complementarity that tends to lead to a more significant rise in skilled wages. Another change has been to partially model land markets in the services sectors as it well known that urban land prices tend to rise rapidly with growth and lead to an overall increase in the price of non-tradables. In terms of parameter changes, they are of at least two varieties. One is to increase the Armington elasticities for manufactured goods. This tends to keep the price of manufactures in developing countries in line with world prices, thus attracting resources from other sectors in the economy. A second is to increase the labor productivity in manufacturing relative to services thereby keeping a lid on efficiency wages in manufacturing, but raising them (in relative terms) in services.

51 See van der Mensbrugghe *et al.* (2011) for a more in-depth exposition.

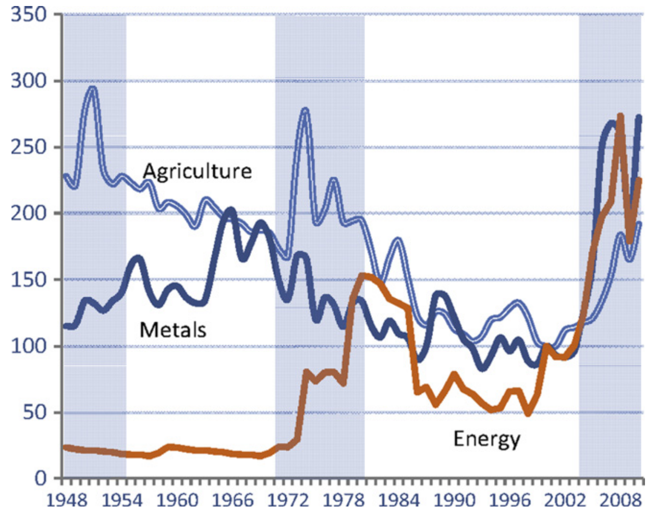

Figure 14.7 Unlike earlier booms, the current boom involved all commodity groups (deflated by manufacturing unit value, 2000 = 100). *(Source: World Bank.)*

Multiple structural factors have been cited for the recent spike that include:

- Rapidly rising incomes in large developing countries and a diet change towards higher-valued proteins such as meat and dairy.
- A slowing down of yield increases over recent years.
- Cost-push factors — notably higher energy and fertilizer prices.
- Rising demand for biofuels raising competition for land and other agricultural resources.
- Climate change induced weather variability such as the recent drought in Australia and Russia's 2010 heat wave.
- Policy responses to the spike such as export bans and consumer subsidies.
- An increase in speculative activity in commodity markets.
- Depreciation of the US dollar

All of the above likely have had some impact on the recent price rise — though the precise allocation of the cause of the price rise over these different factors is still widely debated as well as how many of them are long-term and likely to persist. There is little doubt that the inventory cycle has played a significant role and that none of these factors taken in isolation can explain the price rise (Figure 14.8).[52] Take for instance biofuels. Land diverted to the main biofuels cereal feedstocks (maize and oilseed) represented some 2% of global grain and oilseed area in 2008/2009[53] — a not insignificant amount, but hardly a sufficient shock to produce the observed sharp price increase in this period

52 See Wright (2011).
53 See van der Mensbrugghe *et al.* (2011).

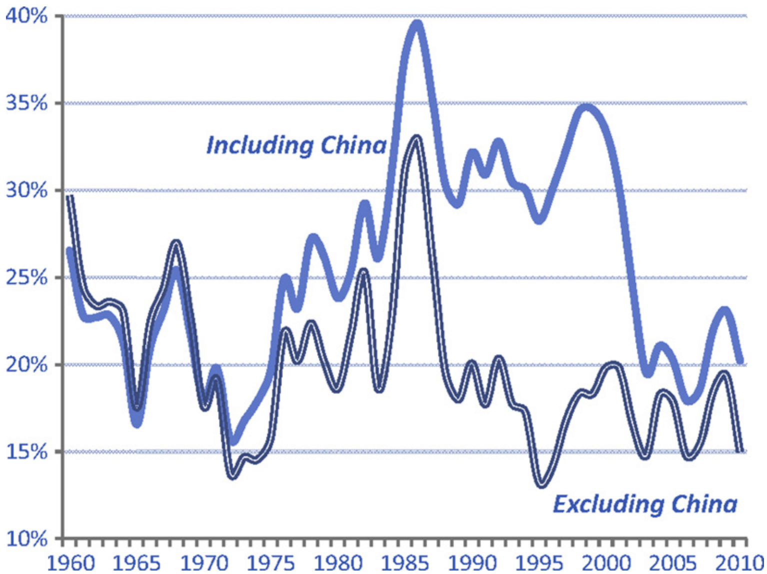

Figure 14.8 Global stock-to-use ratios declined to levels not seen since the mid-1970s (%). *(Source: World Bank calculation based on USDA data.)*

using a standard economic model with long-term supply elasticities. A model that captures short-term rigidities combined with an inventory cycle and policy reactions would be able to capture the rapid price increase, but this is more in the nature of a cyclical phenomenon than a long-term phenomenon. The aim of this section is to look at some of the factors listed above and to assess to the long-term changes to agricultural markets as measured by prices and trade. We will mostly focus on demand and productivity – though clearly climate change and biofuels potentially will have strong implications in the decades ahead.

14.5.2 Supply-side assumptions

ENVISAGE, unlike LINKAGE, has a single production structure for all sectors.[54] Land, capital and labor are all substitutable in a single nest. The implication for most developing countries is that agricultural production will become relatively more capital intensive as capital costs remain relatively close to their initial level but labor and land costs rise – the former due in part to higher labor productivity in manufacturing. Countries with greater availability of land will tend to see more modest increases in land prices and therefore relatively more land expansion.

54 The LINKAGE model segments sectors into three archetype production structures – crops, livestock and other. The objective of the crops production structure is to highlight the tension between intensification and extensification capturing the substitution of labor and chemicals versus capital and land. In livestock, the key substitution is between land and feed, i.e. between range-fed versus ranch-fed.

Table 14.1 Land supply potential, multiple of current agricultural land

	ENVISAGE	LEITAP
High-income countries	2.109	1.442
East Asia and Pacific	1.651	1.891
South Asia	1.117	1.060
Europe and Central Asia	1.896	2.800
Middle East and North Africa	1.079	1.020
Sub-Saharan Africa	5.624	1.893
Latin America and Caribbean	6.749	2.070
World total	2.288	1.594

Aggregate land supply is modeled using a logistic function whose asymptote in our default baseline is derived from the International Institute for Applied Systems Analysis (IIASA)/FAO's land database.[55] The FAO segments land into three: (i) Arable, currently exploited, (ii) "very suitable, suitable and moderately suitable" and (iii) "marginally suitable land." Potential land expansion is assumed to be the sum of the two latter categories. The expansion potential data is provided in Table 14.1 for the seven major regions. At the global level, the FAO data suggests that there is significant land expansion potential — over 100%. The greatest potential would be in Latin America and Caribbean with Sub-Saharan Africa not far behind. The least potential would be in the Middle East and North Africa region and South Asia both with less than 12% expansion possibility. The FAO data only refers to the suitability of the land for agricultural production, without taking into consideration the potential side-effects (e.g. carbon emissions from deforestation or land-use changes) or on the other potential uses for the land (e.g. an increase in land used for urbanization or infrastructure). The model also implicitly assumes that the idle potential has the same productivity as the land currently being exploited.

The LEI group, using its LEITAP model, has a different set of land potential values — also given in Table 14.1. Under LEITAP's assumptions, global land expansion would be limited to 60% of current arable land, half of the default ENVISAGE assumption with much lower potential in Sub-Saharan Africa and Latin America and the Caribbean, but somewhat higher in Europe and Central Asia. These differences in supply potential may not matter too much depending on supply elasticities and the shape of the supply curves, i.e. the actual increase in supply may be much lower than the potential in which case the asymptote is not immediately relevant.

By default countries in ENVISAGE are segmented into two — land abundant and land scarce. The initial land supply elasticity in the land abundant regions is 1, whereas in the land scarce region the supply elasticity is 0.25.

[55] Data and analysis available at http://www.iiasa.ac.at/Research/LUC/GAEZ/index.htm.

Table 14.2 Average productivity increase between 2005 and 2050 (% *per annum*)

	High-income	**East Asia and Pacific**	**South Asia**	**Europe and Central Asia**	**Middle-East and North Africa**	**Sub-Saharan Africa**	**Latin America and Caribbean**	**World average**
Rice	0.48	0.65	0.92	1.38	0.79	1.66	0.67	0.71
Wheat	1.21	0.67	1.15	1.56	1.57	2.08	1.29	1.27
Maize	0.91	1.07	1.66	1.73	1.39	1.65	1.13	1.22
Oil seeds	1.12	0.87	0.70	1.46	0.87	0.78	1.21	1.02
Sugar	0.69	0.88	0.83	1.14	1.02	0.91	1.17	0.88
Vegetables and fruits	0.95	0.87	1.61	0.98	1.67	1.36	0.95	1.08
Other crops	1.02	1.02	0.63	0.40	1.01	0.95	0.70	0.91
Cattle	0.64	1.26	1.66	0.92	1.50	1.18	1.20	0.97
Other livestock	0.62	0.84	0.79	0.58	0.98	0.79	0.81	0.74
Dairy cows	1.39	1.52	1.61	0.76	1.50	1.32	1.32	1.33
Agriculture	*0.91*	*0.85*	*1.10*	*1.01*	*1.40*	*1.24*	*1.02*	*0.99*

ENVISAGE assumes perfect land mobility across agricultural sectors, this is equivalent to assuming that the law-of-one price holds for land. The model has been tested with partial land mobility, the results of which are discussed below.

The current baseline has aligned the agricultural productivity assumptions to those of IFPRI's IMPACT model. The averages across crops, livestock and major regions is presented in Table 14.2. At the world level, the average over the next 40 years is around 1% *per annum*, about half the long run recent historical average (see Martin and Mitra, 1999). The highest assumed average across sectors is for wheat, maize and dairy cows, with lower levels for rice and other livestock. The regional variation is somewhat narrower with the highest productivity growth in the Middle East and North Africa followed by Sub-Saharan Africa. Note that these reflect averages relative to base year production shares.

14.5.3 Demand-side assumptions

There are two main sources for agriculture and food demand — intermediate use (e.g. seed, feed, food processing, etc.) and households. Intermediate demand elasticities are currently set to zero as a Leontief specification is assumed in production. The CDE demand system is the default assumption for household demand. It is less than ideal for the analysis of agriculture and food because income elasticities tend to remain constant over the income range. The AIDADS functional form in principle is better suited for plausible Engel curve behavior, but finding the right parameterization has proven elusive and is a field of active research. Another strategy is to glide the parameters of the CDE (or the oft-used LES functional form) to mimic the desired Engel behavior. It is a pragmatic strategy, but leads to more complicated welfare analysis as the parameters of the utility function change over time. Table 14.3 provides the base household income elasticities for all modeled commodities. The average food elasticity for high-income countries is just below 0.3, but is between 0.54 and 0.66 for developing countries — with somewhat higher elasticities for processed foods. These food demand elasticities may be high[56] — though they have been econometrically estimated (see Seale *et al.*, 2003). Table 14.3 also shows the budget shares that, befitting different income levels, vary significantly across regions. In particular, high-income countries have a services budget share of around 67%, consuming only 12% on food. The food shares range from a low of 17% in Latin America and Caribbean to nearly 40% in South Asia.

Income and population growth and the base year elasticities will drive a significant part of the growth in food demand in the decades ahead. For technical reasons, the intermediate demand for food in the services sector has been shifted to household demand — this is essentially food used in the hospitality sectors (restaurants, hotels, hospitals, and so on). The main reason for the database modification is that services are

56 See, e.g. van der Mensbrugghe *et al.* (2011).

Table 14.3 Base household income elasticities

	High-income	East Asia and Pacific	South Asia	Europe and Central Asia	Middle-East and North Africa	Sub-Saharan Africa	Latin America and Caribbean
Rice	0.16	0.29	0.44	0.41	0.42	0.51	0.40
Wheat	0.20	0.27	0.48	0.38	0.43	0.55	0.40
Other grains	0.22	0.31	0.50	0.41	0.43	0.46	0.39
Oil seeds	0.21	0.38	0.50	0.35	0.47	0.56	0.42
Vegetables and fruits	0.24	0.43	0.57	0.46	0.51	0.44	0.50
Sugar	0.32	0.65	0.74	0.64	0.70	0.73	0.66
Other crops	0.33	0.68	0.76	0.82	0.82	0.68	0.72
Cattle	0.34	0.61	0.81	0.67	0.74	0.79	0.66
Other livestock	0.26	0.53	0.75	0.64	0.69	0.75	0.65
Raw milk	0.30	0.74	0.63	0.67	0.77	0.84	0.72
Forestry	1.24	1.35	1.49	1.33	1.41	1.60	1.34
Other mining	1.25	1.40	1.48	1.40	1.38	1.67	1.33
Red meat	0.25	0.61	0.77	0.61	0.68	0.68	0.61
Other meat	0.30	0.55	0.76	0.62	0.53	0.70	0.63
Vegetable oils	0.21	0.29	0.50	0.40	0.47	0.52	0.41
Dairy products	0.31	0.60	0.82	0.67	0.71	0.76	0.68
Other food	0.29	0.62	0.83	0.68	0.77	0.78	0.66
Textile and clothing	0.89	0.90	0.88	0.90	0.86	0.86	0.87
Energy intensive manufacturing	1.21	1.30	1.47	1.29	1.36	1.42	1.27
Other manufacturing	1.18	1.25	1.43	1.26	1.28	1.33	1.25
Energy	1.14	1.17	1.21	1.14	1.14	1.19	1.14
Construction	1.14	1.18	1.22	1.19	1.20	1.22	1.17
Services	1.09	1.25	1.33	1.15	1.16	1.23	1.02
Memo item, budget shares							
Food	12.1	31.9	43.9	29.7	29.4	40.2	16.8
Manufacturing	21.0	26.2	21.5	31.2	29.9	22.5	29.0
Services	66.8	41.9	34.6	39.1	40.7	37.3	54.2

Source: Seale *et al*. (2003) and author's calculations.

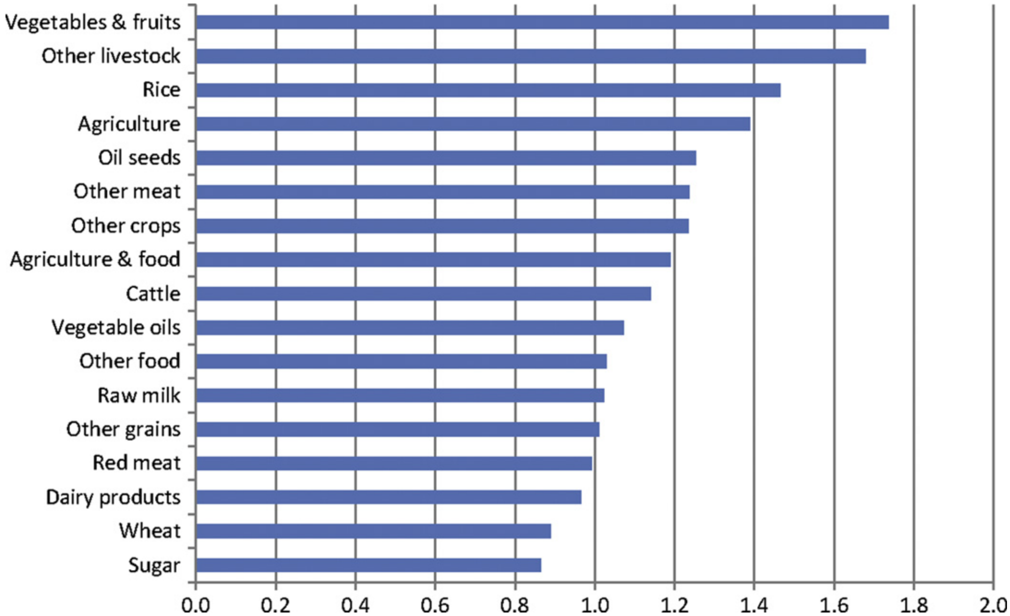

Figure 14.9 Average global producer price in 2050 (2004 = 1).

very income elastic and thus derived demand for food from the services sector would grow at an implausible rate. An alternative to changing the base data is to dynamically change the input-output coefficient of food demand in services.

14.5.4 Global implications

The baseline results suggest that with the above assumptions world agricultural prices would increase some 50% on average between 2005 and 2050, translating into a more modest 20% increase in the average food price (Figure 14.9).[57] The highest price increase would occur for vegetables and fruits and other livestock (poultry and pig meat), followed by rice, oil seeds, other meat (processed poultry and pig meat) and other crops. These results reflect a combination of differential regional growth rates, demand elasticities and productivity growth. One distinguishing feature of vegetables and fruits is that it is the only agricultural sector with a high share of direct consumption by households. This implies that, relative to other agricultural commodities, the "national" price elasticity will be higher as the elasticity of demand for intermediate goods is zero. Secondly, the price pass-through will be relatively high as the activities associated with the processing of foods is bypassed through direct consumption. On the other hand, the

57 The average world price is the production weighted producer price across all regions/countries in the model. Trade prices could deviate as in the Armington assumption — combined with different trade weights — could generate a somewhat different profile.

other livestock sector is assumed to have relatively low productivity growth compared with many other sectors and thus costs tend to rise abetted by relatively high income demand elasticities. Raw milk presents a somewhat contrasting picture as the derived demand through dairy products has a relatively high elasticity, but average productivity growth is some 0.6 percentage points higher in this sector than for other livestock. All in all, the picture presented suggests a structural break with the 50 years previous to the 2007/08 price spike that may be a precursor event for longer term sustained agricultural prices. Several factors may alter this conclusion. Climate change is likely to (and maybe already has had an) impact on agricultural productivity growth — perhaps quite differentially across regions. This would affect relative comparative advantage in agriculture, but in the medium term may not necessarily have an impact on average global prices. Greater penetration of biofuels may also take away resources from the production of food. A recent paper (Timilsina *et al.*, 2010) suggests that the current biofuels mandates (for 2020) are unlikely to have a dramatic impact on food prices in the long-run, but could increase overall agricultural land-use and potentially increase carbon release in the short-run. The role of agricultural productivity is also critical and more will be said below. Finally, given the demand elasticity assumptions, it is likely that demand is growing somewhat more rapidly than desired. It is also possible that food preferences may change as health, environmental and efficiency concerns lead to healthier diets for humans, better management of natural resources and less waste in the agro-food system.

There is a relatively large shift in comparative advantage over the next four decades in the baseline scenario. Productivity growth combined with land expansion provides agricultural surpluses for the high-income countries and Latin America and Caribbean, and even the Middle East and North Africa is able to generate an aggregate agricultural surplus on the back of its exports of fruits and vegetables (Figure 14.10). The other regions would be net agricultural importers in 2050 — particularly East Asia and Pacific, with Sub-Saharan Africa having a small overall deficit. For East Asia and Pacific, the

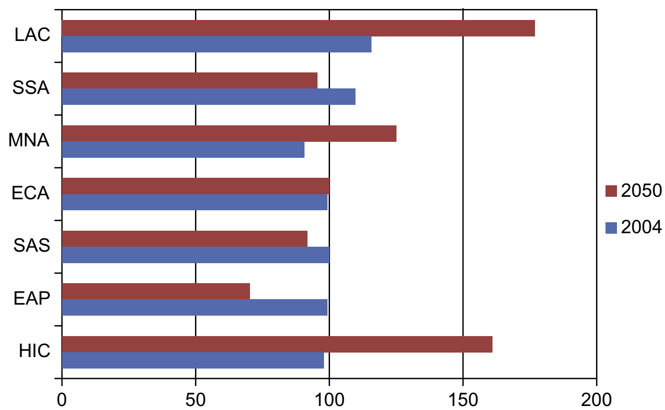

Figure 14.10 Ratio of agricultural production to consumption (%).

Table 14.4 Land supply and price growth from 2005 through 2050

	Land supply growth (% *per annum*)	**Land price growth (% *per annum*)**	**Implicit land supply elasticity**
World total	0.7	3.1	0.23
High-income countries	0.5	2.1	0.26
East Asia and Pacific	1.0	3.9	0.26
South Asia	0.2	4.0	0.06
Europe and Central Asia	0.6	1.5	0.44
Middle East and North Africa	0.2	4.1	0.04
Sub-Saharan Africa	2.0	1.7	1.19
Latin America and Caribbean	1.2	1.7	0.70

deficit translates into a net agricultural import bill of some 4% of 2050 GDP — and net agricultural exports of Latin America would also be some 4% of GDP.

There are more significant gaps between demand and production at the sectoral level, notably for cereals and oil seeds in the case of East Asia and Pacific. The baseline scenario suggests that countries may eventually intervene to prevent such a large reversal in food self-sufficiency — dealt with in more detail by Anderson *et al.* in Chapter 13 of this Handbook. Nonetheless, Japan, with the exception of rice, has allowed itself to become highly dependent on the imports of other grains and oil seeds.

The implications on aggregate land use suggest a fairly large expansion. While in the base year, expansion potential is some 2.3 times actual use, potential drops to 1.7 globally. This implies an average annual growth rate of land supply of 0.7% on a global basis with rapid expansion in Sub-Saharan Africa (2% *per annum*) and to a lesser extent in Latin America (1.2% *per annum*), Table 14.4. Under this scenario, East Asia and Pacific, Middle East and North Africa and South Asia would exploit all of their remaining arable land. Land prices would rise considerably as well. On a global basis the rise would be some 3.1% *per annum* and much higher in the land-scarce regions. The implied land supply elasticity is provided in the final column for information.

Agricultural growth in the baseline relies more on land expansion than in the past.[58] There are doubts about the extent to which certain regions can expand, in particular the availability of water, infrastructure and perhaps more fundamentally the quality of the soils. With climate change an emerging issue at the global level, there might also be pressure to limit land expansion, particularly if it involves deforestation and the associated emissions of currently sequestered carbon.

Is the baseline a dire scenario? For net food producers (and owners of land), the scenario is relatively positive with broadly rising food and land prices. For net consumers,

[58] For example the expansion over the 1985—2005 period has been estimated to have been 3% globally although with large regional differences (Foley *et al.*, 2011).

particularly poor urban dwellers, rising food prices potentially pose concerns, although the price of staples overall appears to be in check with the possible exception of rice. Higher food prices will be offset to some extent by high economic growth and rising wages. On the environmental side, there is cause for concern from the increase in land expansion. More investment in research and development, extension services and other policies that would enhance productivity (and therefore intensification), may reduce pressure on land and could also lead to lower agricultural prices.

14.5.5 Robustness of baseline

This section will describe the results of running sensitivity analysis on some of the key underlying assumptions — notably land supply and its allocation across agricultural activities and productivity. A first part of the robustness analysis compares the results of the standard baseline when using the specification and parameterization of the land markets with another model that has been done as part of a model comparison exercise. Subsequently, more extensive sensitivity analysis will shed additional light on the productivity versus land issue.

The LEITAP model is in many ways similar to ENVISAGE — a GTAP-based global CGE model.[59] LEITAP's land specification and parameterization is incorporated in ENVISAGE to test the robustness of ENVISAGE results. The robustness analysis features two changes in model specification — the aggregate land supply function and the allocation of land across agricultural activities — and three different parameterizations — initial land supply elasticity, maximum land availability and degree of land mobility.

The standard ENVISAGE land supply function is a logistic function, Equation (14.20), where S is land supply, P is the return to land, $\bar{S}$ is the maximum land potential, ε is the curvature parameter calibrated to an initial supply elasticity and β is the supply shifter, calibrated to base year data. LEITAP uses a hyperbola (Equation 14.20). The variables and parameters have the same description. Over a fairly broad range both functions overlap. The logistic function potentially has an inflection point, that appears to hold for ENVISAGE's Latin America results:

$$S = \frac{\bar{S}}{1 + \beta e^{-\varepsilon P}} \tag{14.19}$$

$$S = \bar{S} - \beta P^{-\varepsilon}. \tag{14.20}$$

The other specification change is that LEITAP by default assumes only partial mobility of land across activities — using a three-nested CET function. The top nest has a cereals and pasture bundle that competes for land with horticulture and other livestock.

[59] See van Meijl *et al.* (2006) and Eickhout *et al.* (2006).

Table 14.5 Aggregate land supply parameters for ENVISAGE and LEITAP

Region	Expansion potential		Initial supply elasticity	
	ENVISAGE	LEITAP	ENVISAGE	LEITAP
China	1.298	1.174	0.250	0.100
Japan	2.787	1.050	0.250	0.200
Rest of East Asia	2.328	3.537	1.000	2.213
Indonesia	2.001	2.321	1.000	0.200
India	1.145	1.050	0.250	2.317
Rest of South Asia	1.010	1.100	0.250	2.317
Canada	2.446	7.870	1.000	1.384
US	2.244	1.843	1.000	1.384
Mexico	1.921	1.634	0.250	1.384
Argentina	3.333	2.043	1.000	1.554
Brazil	8.657	3.045	1.000	2.000
Russia	2.383	4.461	1.000	0.902
Turkey	1.382	1.897	1.000	1.702
Rest of Europe and Central Asia	1.619	1.446	1.000	0.685
Sub-Saharan Africa	5.624	1.893	1.000	1.162
EU27 and EFTA	2.019	1.149	0.250	0.170
Middle East and North Africa	1.079	1.020	0.250	0.000
Australia and New Zealand	3.149	1.380	1.000	0.115
High-income Asia	1.532	1.155	0.250	0.180
Rest of Latin America and Caribbean	9.896	2.011	1.000	1.378
High-income countries	2.109	1.442	0.472	0.494
Developing countries	2.410	1.698	0.537	1.316
East Asia and Pacific	1.651	1.891	0.554	0.557
South Asia	1.117	1.060	0.250	2.317
Other developing Asia with rest of high-income Asia	1.644	1.942	0.503	1.508
Europe and Central Asia	1.896	2.800	1.000	0.968
Latin America and Caribbean	6.749	2.070	0.784	1.496
LAC less Brazil and Mexico	8.719	2.017	1.000	1.410
World total	2.288	1.594	0.511	0.982

The second nest has a cereals bundle that competes for land with pasture and sugar. And the bottom nest has cereals competing for land. The CET elasticities are relatively small with values of 0.4, 0.6 and 0.8, respectively, for the top, middle and bottom nests. The standard ENVISAGE model assumes perfect transformability; in other words, all land is suitable for all agricultural activities.

Four sensitivity runs focused on the aggregate land supply were implemented. The first involved a simple swapping of the supply function — the hyperbola for the logistic. The second took LEITAP's aggregate supply elasticity as a starting point. The two are compared in Table 14.5. There are large differences across the regions and at the world level, LEITAP's initial supply elasticity is around twice as high as ENVISAGE's.[60] The third simulation involves swapping the land asymptotes. Again there are significant differences across regions. ENVISAGE — based on the FAO estimates — has very high expansion potential in Latin America and Sub-Saharan Africa. LEITAP is more optimistic about Canada and Russia. At the global level ENVISAGE would allow for an expansion of nearly 130% of currently used arable land. LEITAP would only allow for up to a 60% expansion. The fourth and final simulation implemented LEITAP's three nested CET allocation structure in ENVISAGE — including the use of LEITAP's transformation elasticities.

The results are not reported here as they barely changed the overall picture — at least not in any significant way. Focusing first on global prices, the swapping of the aggregate supply function and associated parameters (elasticities and asymptote) had barely any impact on the change in world agricultural prices by 2050.[61] The percent difference in the world price ranges between 1 and 5% with a simple average of 2.2. A price impact of this magnitude is well within the range of noise. The fourth simulation, that focused on land mobility, produced somewhat more significant changes and most obviously on the cost of land across sectors since the uniform land price no longer holds. In terms of world prices, the cereal grains would tend to see a drop in the world price in 2050 (relative to the baseline value where land mobility is perfect). The basic mechanism at work here is that, with relatively high productivity in these sectors combined with friction in land allocation, there is an *ex ante* relative oversupply in these sectors that depresses their price. A higher transformation elasticity would enable land used in these sectors to go to sectors with higher relative returns. The differences are again not huge. Wheat shows the highest drop in 2050 (relative to the baseline) of around 10%, followed by oil seeds with a relative decline of 5%. The modest changes in world prices are also reflected in relatively modest changes in food self sufficiency, at least at the aggregate level. It would be possible to think that relative comparative advantage could change sharply with differences in elasticities and expansion capacity. However, despite the sometimes sizeable differences between LEITAP and ENVISAGE, in both sets of parameter estimates one can fairly clearly delineate the land-scarce and land-abundant countries that by and large are driving the results. The introduction of the land CET allocation mechanism leads to some relatively more important impacts at the sectoral level as land sluggishness ties down production more than in the case of perfect mobility. We see, for example, that East Asia and Pacific is somewhat less reliant on the import of cereals when land is only partially mobile.

We now turn to more systematic sensitivity analysis — particularly the role of productivity. In part this reflects concerns about land expansion — even if the agro-ecological estimates of land potential used by either the ENVISAGE or LEITAP are

[60] Note that the aggregate elasticities are weighted by the returns to land in each region. If there are significant land price differences across regions, the world aggregate may be a biased estimate of the weighted average. Alternatives would be to weight by the value of production, or else by acreage (though the latter is not currently part of the ENVISAGE database).

[61] Results available from the author.

correct. Environmental concerns linked to land-use driven greenhouse gas emissions, the loss of biodiversity and/or potential water scarcity concerns may lead to domestic and international pressures to limit land expansion. In some regions, the lack of adequate infrastructure could also limit expansion. Thus, the systematic sensitivity analysis focuses on agricultural productivity relative to the baseline land potential and levels of land expansion potential that converge towards zero.

A suite of sensitivity simulations were run that varied the exogenous yield assumption and the land expansion potential. The assumptions on exogenous yield growth varied from 70% above the baseline (i.e. an average of 1.7% *per annum* over the entire time horizon) 50%, and 25, 50 and 75% below the baseline. These correspond to the rows in Table 14.6 where the row labeled "100" refers to the baseline assumption, so the rows go from most optimistic to most pessimistic. On the land expansion, we have assumed that the FAO estimate of potential is the maximum, thus the model was only tested in one direction. We varied the potential in increments of 20% and included no expansion. These are the columns of Table 14.6.

The sensitivity analysis thus involved 36 separate runs of the model. The result of the third row and first column is the baseline change in average agricultural price — nearly 50% in 2050. What is obvious from looking at the results in Table 14.6 is that the price impacts are highly sensitive to the yield growth assumptions and nearly invariant to changes in the land expansion assumption. Yield growth makes a 2:1 difference at the extremes, land potential affects price by 10% at best.

The sensitivity results suggest that we would have to be nearly at the 2% *per annum* growth rate in agricultural productivity to achieve a stable price level as observed throughout most of the last century. However, this is a conditional result as none of the other parameters in the model have been modified from their baseline values — and some of them could be quite critical in determining overall agricultural prices, e.g. the degree of substitution between land and the other factors of production (capital and labor). Our baseline would suggest a more capital-intensive agriculture as its price tends to stay

Table 14.6 Impact on agricultural price in 2050 varying assumptions on land expansion potential and exogenous yield growth

	Reduction in land asymptote (%)					
Yield factor	**100**	**80**	**60**	**40**	**20**	**00**
170	1.07	1.07	1.08	1.10	1.12	1.15
150	1.17	1.18	1.19	1.20	1.23	1.26
100	1.48	1.49	1.51	1.53	1.56	1.61
075	1.67	1.68	1.70	1.73	1.77	1.83
050	1.88	1.90	1.93	1.96	2.00	2.08
025	2.14	2.16	2.19	2.23	2.28	2.36

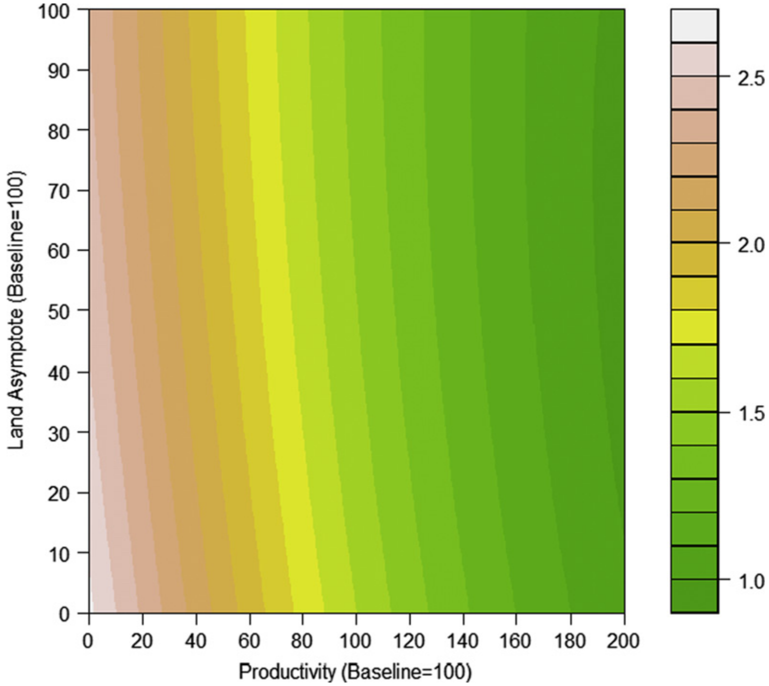

Figure 14.11 2050 price of agriculture (2004 = 1).

relatively stable compared to the prices of labor and land that rise. This is certainly consistent with history where most developed countries and many emerging countries have shed huge amounts of labor from the agricultural sector that have been absorbed into manufacturing and services.

Table 14.7 Price variability across crops

	Minimum	Baseline	Maximum
Agriculture	*107*	*148*	*236*
Crops	111	153	242
Wheat	85	123	205
Rice	116	154	233
Other grains	81	120	211
Oil seeds	114	160	260
Sugar	81	111	167
Vegetables and fruits	130	182	291
Other crops	111	145	223
Livestock	96	136	223
Cattle	78	112	193
Other livestock	127	171	262
Raw milk	60	96	184

Figure 14.11 provides the same information in graphic form. It shows the contours of the price level relative to the sensitivity analysis simulations.[62] The contours relative to the land assumptions are relatively flat, i.e. the prices stay within a relatively narrow range, but vary substantially more with respect to changes in productivity assumptions.

Table 14.7 provides more information as regards the price variability showing the minimum and maximum prices for the modeled agricultural sectors with respect to the sensitivity simulations. The range (compared to the baseline) varies more than the average price of agriculture where the range is − 28 to 60%. The widest range is for raw milk that is − 38 to 91%. For the majority of sectors the price rise remains above 0% even in the most optimistic scenario — the key exceptions being wheat, other grains (e.g. maize), cattle meat and milk.

In a somewhat different exercise, and pointing to the right direction in terms of where sensitivity analysis should be going — although it will be difficult with large-scale global CGE models, we develop a very small global model that aims to capture the essence of ENVISAGE as regards land, productivity and agricultural prices. It has only five equations. Equation (14.21) has land demand. L^{d}, coming from a CES production function where the other factors of production are collapsed into a single variable F. The substitution elasticity is given by σ, agricultural demand (equal to supply) is equal to X^{d} and we allow productivity increases, λ^{l}. The price of land is given by PL. Equation (14.22) represents the price of output, P as determined by the CES unit cost function. Agriculture demand, Equation (14.23) is a function of *per capita* income, Y, price and multiplied by population. Land supply, L^{s}, is an isoelastic function with supply elasticity ω, Equation (14.24). Finally, Equation (14.25) yields the equilibrium condition for the land market:[63]

$$L_t^{\mathrm{d}} = \alpha_t^{\mathrm{l}} \frac{X_t^{\mathrm{d}}}{\lambda_t^{\mathrm{l}}} \left(\frac{\lambda_t^{\mathrm{l}} P_t}{PL_t} \right)^{\sigma} \tag{14.21}$$

$$P_t = \left[\alpha_t^{\mathrm{l}} \left(\frac{PL_t}{\lambda_t^{\mathrm{l}}} \right)^{1-\sigma} + \alpha_t^{\mathrm{f}} \left(\frac{PF_t}{\lambda_t^{\mathrm{f}}} \right)^{1-\sigma} \right]^{1/(1-\sigma)} \tag{14.22}$$

$$X_t^{\mathrm{d}} = Pop_t \chi_t (Y_t)^{\eta} (P_t)^{-\varepsilon} \tag{14.23}$$

$$L_t^{\mathrm{s}} = \beta_t (PL_t)^{\omega} \tag{14.24}$$

$$L_t^{\mathrm{s}} = L_t^{\mathrm{d}}. \tag{14.25}$$

62 The surface was generated by linear estimation of the sensitivity runs using a quadratic specification.
63 The GAMS code is available from the author.

Table 14.8 Distributional assumptions of the unknown parameters and variables

		Minimum	Mode	Maximum	Mean
Land supply elasticity	ω	0.01	0.50	1.00	0.503
Income elasticity	η	0.01	0.20	0.40	0.203
Price elasticity	ε	0.01	0.20	0.40	0.203
Land factor substitution	σ	0.10	0.50	1.00	0.533
Land share	α^l	0.06	0.14	0.20	0.133
Land productivity growth	λ^l, λ^f	0.00	1.00	2.00	1.000
Growth in the price of other inputs	PF	0.00	2.00	3.00	1.667

The parameters have been calibrated more or less to those of the ENVISAGE model and this simple model is run with one time-step, between 2004 and 2050 where population and income *per capita* growth exogenous and determined as in the ENVISAGE baseline. The key parameters are land substitution in production (σ), income and price elasticities (η and ε), land supply elasticity ω and the share of land in the cost function α^l. The key future unknowns are the price of other inputs in production (PF) and the rate of growth of productivity (λ^l and λ^f). Each of these six unknowns have been assigned a triangular probability distribution function with a given range (minimum and maximum) and a mode. The defaults are provided in Table 14.8.

The land share range comes from the value share range in the GTAP dataset (albeit throwing out some outliers). The growth in productivity of other factors of production is assumed to be equal to land productivity growth, as it is in ENVISAGE. The range for the growth in the price of other inputs is wide. Wages rise quite sharply in a number of regions, but one would expect some substitution out of labor. Capital returns are relatively steady in many countries and with a slight downward trend in countries with very high savings. The prices of other inputs are relatively stable (relative to the model numéraire).

To test the sensitivity of the model, we make 10,000 random draws of the six "unknown" variables under the distributional assumptions of Table 14.8. The agricultural price goes up by around 36% on average over the 10,000 simulations – somewhat lower than that in ENVISAGE, but certainly the same order of magnitude. We then

Table 14.9 Elasticity of agricultural price with respect to key parameters under various assumptions for the mean substitution elasticity

		$\sigma = 0.53$	$\sigma = 0.38$	$\sigma = 0.20$
Land supply elasticity	ω	−0.017	−0.018	−0.019
Income elasticity	η	0.008	0.007	0.004
Price elasticity	ε	0.018	0.020	0.023
Land factor substitution	σ	−0.006	−0.006	−0.007
Land share	α^l	−0.035	−0.039	−0.043
Land productivity growth	λ^l, λ^f	−0.358	−0.362	−0.368
Growth in the price of other inputs	PF	0.923	0.915	0.906

regress the results of the 10,000 simulations to assess the importance of the key parameters on the price, i.e. we run the following regression:

$$\ln(P) = \alpha + a_1 \ln(\omega) + \alpha_2 \ln(\sigma) + \alpha_3 \ln(\eta) + \alpha_4 \ln(\varepsilon) + \alpha_5 \ln(\alpha_l) + \alpha_6(\lambda_l) + \alpha_7 \ln(PF). \tag{14.26}$$

The coefficients of the equation can be interpreted as the elasticity of the agricultural price with respect to the unknown parameters. Table 14.9 provides these elasticities for the six unknowns under three different assumptions regarding the distribution of the substitution elasticity. The substitution elasticity in ENVISAGE is 0.12 for installed capital and 1 for new capital, thus the average, depending on countries rate of investment, is between a low of 0.2 and a high of around 0.5 — more or less the range given in the final three columns of Table 14.9. The signs of the elasticities appear reasonable. A higher land supply elasticity reduces agricultural prices, higher income elasticities would raise them, and more factor substitution would tend to lower prices. The land-share parameter appears to be a puzzle, but presumably it is interacting with the price of other inputs that are rising more on average than the land price. Thus, raising its share would tend to lower the cost of production. Higher productivity has a depressing effects on output price and the output price is obviously linked to the price of other inputs and in fact the price pass-through is more or less in line with the cost share of other inputs.

The results produced in Table 14.9 suggest that the price of agriculture is least sensitive to the income elasticity and the substitution elasticity, and more sensitive to the price and land supply elasticity. The overall result is largely consistent with the results of the sensitivity analysis done with ENVISAGE, i.e. the price of agriculture is highly sensitive to assumptions on productivity. The simple model could be extended to be multiregional to test the sensitivity of regions/countries net trade as well.

This section has demonstrated the importance of agricultural productivity growth for assessing the price of agriculture and food in the long run. Where we have erred on the downside potential for food prices may be in the overall demand — although the small simulation exercise suggests this may not have a huge impact. There may be a large missing demand component if biofuel takes off, although without a more significant policy push in the form of further subsidies or an aggressive carbon tax, most analysts doubt that biofuel will garner a significant market share beyond the current mandates. Where there is potential upside risk on prices may be on the land expansion possibilities that is contested in terms of the physical potential (as seen in the differences between ENVISAGE and LEITAP), the economic potential and the potential negative externalities associated with expansion, but again the sensitivity analysis suggests that this may not have a huge impact on long-run agricultural prices. A more looming concern regards farmers' ability to cope with climate change, the subject of the next section.

14.6 CLIMATE CHANGE AND ITS IMPACTS

14.6.1 Introduction

The physics of global warming were posited at the end of the nineteenth century as expounded by Arrhenius (1896). Skeptics abounded during the first half of the twentieth century, but interest was renewed following the post-World War II acceleration in scientific discoveries and the beginning of the computer age.[64] Economists started thinking about climate change back in the 1970s led by the pioneering work of William Nordhaus who then developed the first version of his DICE model of climate change. The work intensified in the 1980s and early 1990s as global policy makers started taking a more active interest in the physics and economics of climate change. Global institutions were created, including the influential IPCC that is now working on its *Fifth Assessment Report* (AR5), and culminated in the signing of the so-called Kyoto Protocol in 1997 that was the first international treaty whose aim was to limit emissions of greenhouse gases.

Although work continued on the economics of climate change after the Kyoto Protocol signing, climate change took a back seat in the international policy arena for a number of years after the signing. The year 2007 regalvanized international attention on climate change with the publication of two major reports – the IPCC's AR4 and the *Stern Review* – combined with the screening of Al Gore's *An Inconvenient Truth*.[65] One of the key features of the IPCC's AR4 report was the much greater evidence of near-term negative impacts from climate change that in earlier reports were perceived more as a long-term threat. The *Stern Review* was also seen as a clarion call for quick action as the somewhat controversial estimate of the economic cost of climate change was dramatically higher than in most previous studies.

Despite the huge amount of research generated over the last few years, there remain very large gaps in our ability to understand the future of climate change and its potential economic impact. With a few notable exceptions, most of the economic studies have by and large focused on the economics of mitigation, i.e. policies that would limit the emissions of greenhouse gases. Most of the mitigation studies have focused on the necessary transformation in modern energy systems as many of the economic models of climate change have emerged from energy modeling groups – some of which had been set up in the 1970s to focus on the energy price spikes of the time and the changing configuration of energy supply and demand. Traditionally, the emphasis of mitigation studies has been on optimal policies to limit (largely energy-based) carbon emissions using some combination of carbon taxes, emission caps and carbon trading, the economic impacts of less than optimal policies, game theoretic considerations and the potential role of new technologies.

64 See Weart (2008) for more details.
65 See IPCC (2007) and Stern (2007).

Nordhaus' DICE model (and his RICE model offshoot)[66] provided true cost–benefit analysis in a perfect foresight world with climate-induced economic damages, and has proven to be an excellent tool to illustrate many of the key concepts of a truly complicated issue that integrates the physics of climate and the earth and oceans with economics and its dynamics. Hope's PAGE model — in many ways similar to DICE — was the backbone of much of the analytical work in the *Stern Review* and in addition had a strong focus on the uncertainties underlying our knowledge.[67] At the same time, many of these so-called integrated assessment models (IAMs) were highly aggregated both spatially and across economic dimensions. DICE itself is a single-region (i.e. global model) and single-sector model. Its RICE offshoot has some regional dimensionality as does PAGE, but neither has a sectoral focus. To date, there are very few detailed economic models similar in scope to ENVISAGE that have fully incorporated the climate change economic feedbacks, which we call damages, although for some periods and for some economic agents, climate change could also be beneficial.

This section introduces the climate change part of ENVISAGE and the interactions between climate change and the economy and *vice versa*. The focus is almost exclusively on the impact side as there is by now a very large literature on the economics of mitigation.

14.6.2 Climate change in ENVISAGE

ENVISAGE has been developed into an IAM with a fully closed loop between economics and climate change. Economic activity generates greenhouse gas emissions. ENVISAGE accounts for the so-called Kyoto gases that comprise of carbon (C or CO_2), methane (CH_4), nitrous oxide (N_2O) and the fluoridated gases (F-gases). Carbon is largely derived from the combustion of fossil fuels.[68] The other greenhouse gases are generated by a variety of different economic activities, e.g. methane is generated by rice cultivation, livestock production and waste management processes, nitrous oxides largely derive from agricultural practices and F-gases come from some industrial processes as well as leakage of chemicals from electronic equipment. Carbon emissions are fixed per unit of activity (e.g. combustion of fossil fuels). Exogenous abatement is assumed in some of the other gases so that they do not necessarily increase at the same rate as economic activity. On the other hand, there is some built-in autonomous energy efficiency in the baseline that leads to some carbon emission abatement relative to overall economic growth. What will also define the pattern of carbon emissions are relative energy prices and the availability of new technologies. A rise in the price of oil and natural gas relative to coal would lead to relatively more carbon intensive growth.

66 See Nordhaus (1977, 2008), Nordhaus and Boyer (2000) and Nordhaus (Chapter 16) of this Handbook.

67 See Hope (2006).

68 Currently ENVISAGE does not take into account carbon emissions from land use changes, notably from deforestation. These have been important in the last few decades with estimates of between 10 and 20% of total greenhouse gas emissions.

Table 14.10 Climate-induced economic impacts in ENVISAGE

Abbreviation	Description
agr	Agriculture with a quadratic feedback effect on agricultural productivity.
wat	Water stress as measured by the Palmer Draught Stress Index with a linear feedback on agricultural productivity.
sea	Sea-level rise that has a linear impact on capital and land supply.
onj	On the job productivity where heat related stress reduces labor productivity in certain activities.
hhe	Health impacts captured as an additional labor productivity effect.
end	Linear shift in energy demand related to more cooling demand and less heating demand in certain countries.
tou	Changes in tourism arrivals due to temperature change—captured as a change in international transfers.

Greenhouse gas emissions are added to the existing stock of atmospheric gases – that also interact with terrestrial and oceanic stocks – leading to changes in atmospheric concentration. Using a (very) reduced form set of equations, changes in atmospheric concentration convert into changes in radiative forcing that in turn drive changes in atmospheric temperature. In essence, the millions of relations in a global circulation model (GCM) that covers the globe at a highly spatially detailed level and on a time step that can be less than a day is reduced to a handful of equations that determine the change in global mean temperature.[69] The ENVISAGE model's climate module is largely based on that developed for the MERGE model.[70]

ENVISAGE closes the loop between the climate and the economy by converting the climate signal as summarized by the global mean temperature into an economic impact. The typical impact (or damage) function has the following generic form:

$$Dam_{c,agent,t} = H(\Delta T_t) = \alpha_{c,agent,t} \cdot \Delta T_t + \beta_{c,agent,t}(\Delta T_t)^2, \tag{14.27}$$

where *Dam* represents the climate impact in country (region or subregion) *c*, for an agent (or economic factor) *agent* in time period *t*. Typically the impact functions are assumed non-linear and for convenience quadratic.[71]

ENVISAGE incorporates seven different feedback mechanisms between climate and the economy (Table 14.10).[72] Parameterization of the damage functions, an area of very active research, being abetted by an increasing number of micro studies assessing recent

69 A recent study by van Vuuren *et al.* (2009) compared the aggregated IAMs with GCMs and concluded that the path for global mean temperature change generated by the IAMs is well within the range of potential paths produced by the GCMs.

70 See Manne *et al.* (1995).

71 Note that some models integrate the regional temperature change – although these could also be integrated into the damage coefficients directly if the global mean temperature change is easily mapped to regional temperature change.

72 See Roson and Sartori (2010).

and ongoing climate induced economic impacts. Much of the work has focused on agriculture that is believed to be one of the most vulnerable sectors and is also the sector that has a high concentration of the poor around the world. The results discussed below should be seen as still highly speculative and are bound to change as more and better information becomes available in the years to come.

14.6.3 Baseline emissions and climate

The Kaya identity is a succinct way to summarize emission growth:[73]

$$EMI_t = Pop_t \frac{Y_t}{Pop_t} \frac{E_t}{Y_t} \frac{EMI_t}{E_t} \Rightarrow emi_t = pop_t + \gamma_t + e_t + \phi_t. \qquad (14.28)$$

It decomposes emission growth into four factors — population (*Pop*), *per capita* income (*Y*/*Pop*), energy per unit of output (*E*/*Y*) and emissions per unit of energy (*EMI*/*E*). The lowercase version decomposes the percentage change in emissions, where *pop* is the percent increase in population, γ the percent increase in *per capita* income, *e* is the rate of energy efficiency improvement and ϕ measures the rate of decarbonization of the energy bundle. The first two factors were described above in Section 14.4. The third is composed of two elements in the ENVISAGE model — AEEI and endogenous changes in energy intensity that can be influenced by the price of energy relative to other factors. ENVISAGE has a vintage structure of capital and production where energy and installed capital are near complements, but new capital can substitute for energy. Energy prices tend to rise dynamically relative to capital, so there is limited installation of energy saving technology over time. The fourth factor, the carbon intensity of the energy system, will depend on the relative price of fuels and the availability of carbon-free technologies. In most countries there is a trend towards carbon intensification as the price of cleaner gas and somewhat cleaner oil rise leading towards more use of coal. There are clean electricity activities in ENVISAGE — hydro, nuclear and renewable energies. Hydro is limited by physical capacity constraints and there are no energy policies implemented in the baseline that influence the growth of nuclear and renewable relative to thermal power plants. Likewise, there is no implementation of new technologies in the transport sector.

At the global level, carbon emissions would rise from 7.3 gigatons of carbon (gtC) in 2004 to 18.6 gtC in 2050, Figure 14.12.[74] Carbon emissions are rising in all regions, but particularly in East Asia and Pacific that happens to have the highest assumed growth rate over the baseline period. The share in emissions from the

73 See Nakićenović (1997).

74 All greenhouse gas emissions are presented in terms of carbon equivalent. To convert from carbon (C) to carbon dioxide (CO_2), multiple volumes by $44/12 \approx 3.67$ (or 4 if rounding).

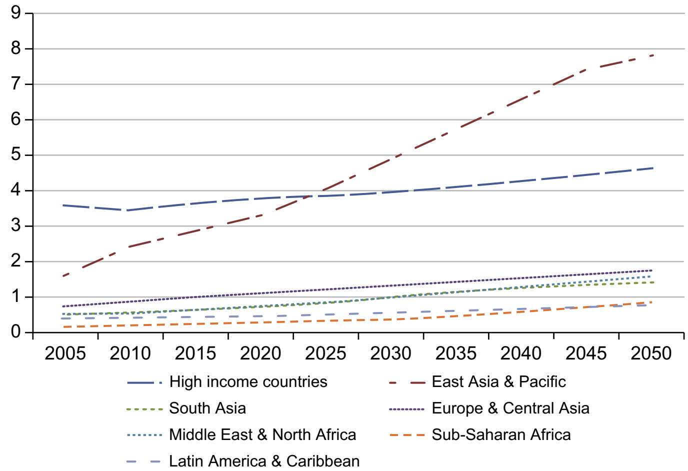

Figure 14.12 Carbon emissions in the baseline (gtC).

Table 14.11 Carbon emissions in the baseline

	Global share (%)		tC/$1000 per GDP		tC *per capita*	
	2004	**2050**	**2004**	**2050**	**2004**	**2050**
High-income countries	49.8	24.7	0.11	0.06	3.3	4.0
East Asia and Pacific	21.0	41.9	0.60	0.20	0.8	3.5
South Asia	4.8	7.5	0.42	0.15	0.2	0.6
Europe and Central Asia	9.9	9.3	0.63	0.49	1.9	4.6
Middle East and North Africa	7.1	8.3	0.46	0.33	1.5	2.6
Sub-Saharan Africa	2.0	4.3	0.28	0.15	0.2	0.5
Latin America and Caribbean	5.4	4.0	0.18	0.12	0.7	1.0
World total	100.0	100.0	0.17	0.13	1.1	2.0

high-income region declines from around 50% in the base year to around 25% by 2050, Table 14.11.

There is some evidence of relative decarbonization as the rate of growth of emissions is lower than the rate of economic growth. As shown in Table 14.11, the level of emissions per unit of output (measured as tons of carbon emissions per $1000 of GDP) is dropping in all regions. In the base year the average is around 0.17 tons of emitted carbon per $1000/GDP at the global level. It is important to note that this reflects GDP measured at market exchange rates. The implication of the base-year levels is that developing countries, with the exception of Latin America, are significantly more carbon intensive than high-income countries, although this conclusion would be moderated to some extent if economies are measured at purchasing power parity exchange rates. It is nonetheless true that high-income countries tend to be more energy efficient and as well tend to use less emitting fuels. The Latin American exception is in part due to the high share of hydroelectricity in many Latin American countries. The lesser carbon intensity in the high-income countries belies the fact that in *per capita* terms, high-income countries emit about three times the world average and well above all developing regions. There is clearly a measure of convergence over the next 40 years in a business-as-usual scenario, although still wide discrepancy across regions. These differences, combined with the relative responsibility of the existing stock of atmospheric carbon, are at the heart of the debate on distributing the burden of adaptation and mitigation. It is also worth noting that consideration should be made of the carbon intensity of imports since many manufactured goods are now produced in emerging countries but consumed in high-income countries.

The impact on the climate is depicted in Figure 14.13. Concentrations rise from around 380 parts per million (p.p.m.) in the base year to 546 p.p.m. in 2050 (carbon-only). Many scientists and policy makers are targeting a level not to surpass 550 p.p.m. for carbon equivalent total (Ceq), and many are even suggesting a lower limit of 450 p.p.m. Ceq. Thus the ENVISAGE baseline is set to go well above the higher threshold of 550 p.p.m. Ceq and is clearly on an upward path. Radiative forcing, that is replacing concentration as a policy target because it is more relevant to climate change, is set to go from 2.4 to 4.8 W/m^2. Policy targets are as low as a very ambitious 2.6 W/m^2 and as high as 4.5 W/m^2. Again, ENVISAGE's baseline, extended beyond 2050, is likely to be well above the less ambitious target. The change in temperature would rise to 2.2 °C by 2050, with significant built-in

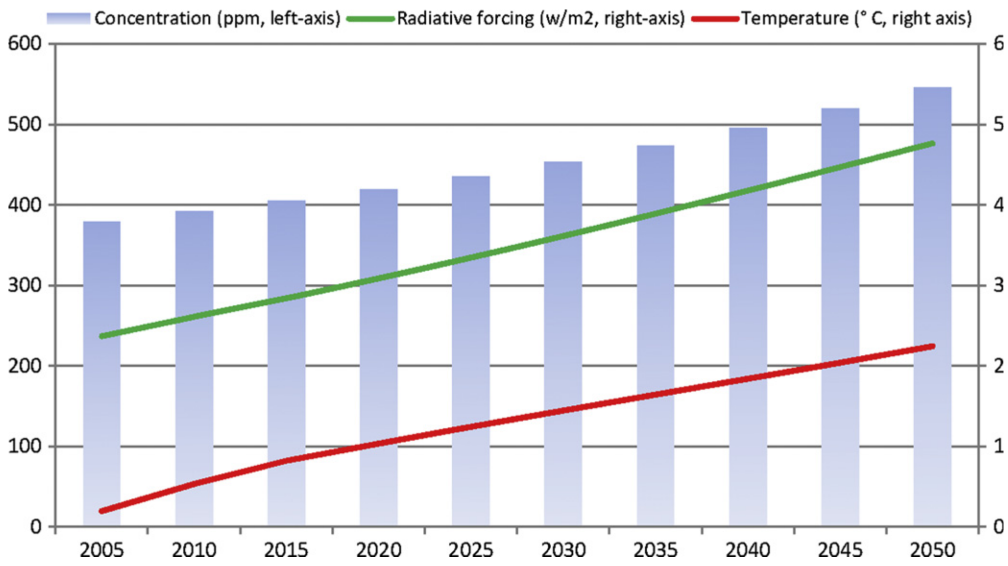

Figure 14.13 Climate implications of baseline emissions.

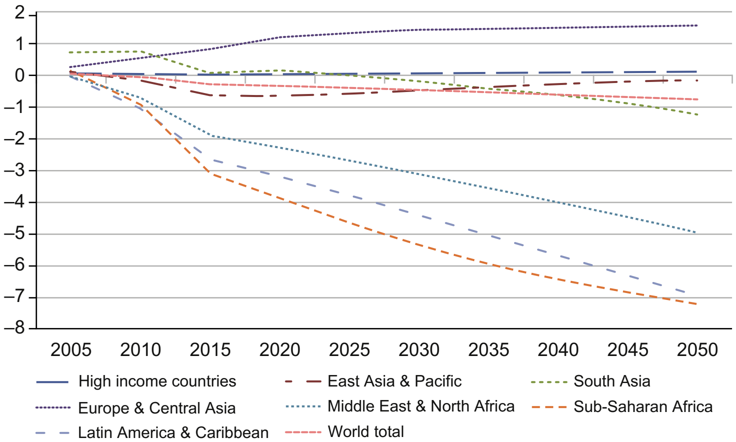

Figure 14.14 Climate induced deviation in GDP (% difference from baseline).

momentum given climate physics. The mean global temperature change in the AR4 scenarios for 2100 was 3.0 °C. The overall conclusion is that the baseline scenario could have serious consequences, and thus raises the stakes to act promptly to limit emissions and also to start ramping up on adaptations for the inevitable impacts.

14.6.4 Climate change and economic impacts

Combining the standard economic baseline with the climate module leads to an assessment of the climate-induced impacts on the standard no-impact baseline. For most regions and for the world average, climate change in aggregate will lead to lower overall economic growth by 2050. World GDP in 2050 would decline by 0.7%, Figure 14.14. The most negatively impacted region in percentage terms is Sub-Saharan Africa, followed closely by Latin America and Caribbean and Middle East and North Africa.[75] Europe and Central Asia, with the current parameterization would tend to see an improvement — at least within the time horizon of the current analysis.

Figure 14.15 attempts to unpack the impacts in order to see how the economies in the different regions react to the seven different impact channels. Focusing first at the global level (region labeled "wld"), the different impact channels tend to aggregate out — due both to different GDP weights as well as differences in sign. The largest negative impact in percentage terms arises from the labor productivity impact of higher temperature. Sea-level rise and tourism have impacts of almost the same order of magnitude.

75 The regional averages conceal much more significant variation across modeled regions. For example, both Indonesia and the rest of East Asia region would see significant losses — towards 10% of GDP in the case of the latter. These large losses are offset by a modest gain in China.

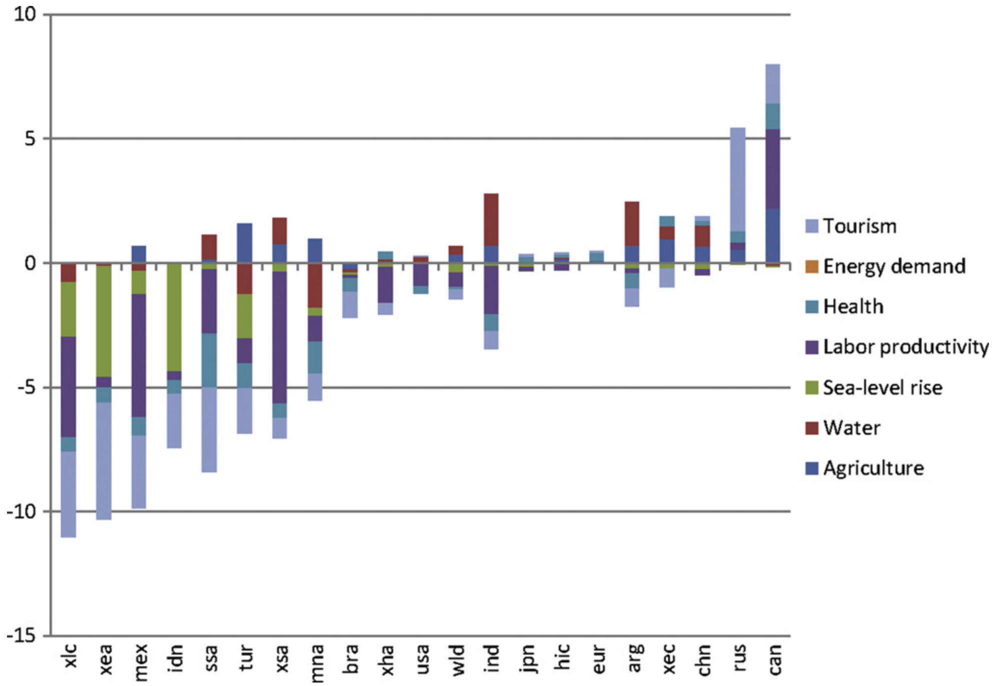

Figure 14.15 Climate change impact decomposed by effect in 2050 (% deviation from baseline). See Table A1 for region codes.

Perhaps somewhat more perplexing given the amount of attention paid to agriculture and water – these two channels would tend to have beneficial impacts at the global level – at least through 2050. The impact on agricultural productivity of climate change has been widely studied and debated and the results presented here likely reflect some of the large uncertainty in this area. Different methodologies tend to indicate very different impacts. Studies based on crop models have tended to be most pessimistic about rising temperatures and their impacts on productivity. They have been criticized in the past for not allowing enough adaptation and thus would tend to overstate the productivity losses. A different econometric approach, known as the Ricardian approach, has resulted in much lower impact on agricultural productivity – in part because it allows producers to adapt readily to different cropping patterns. Other issues arise that lead to a generally wide range of potential outcomes. For example, greenhouse experiments suggest that rising carbon concentrations could raise productivity as plants can more readily absorb carbon – a so-called carbon fertilization effect. It has been harder to verify this in field experiments. Newer crop models are increasing in sophistication and introducing other potential impacts of climate change on plant growth – notably pests and plant diseases – and are suggesting much higher negative impacts from these complementary effects. Water stress has even been more difficult to model. GCM scenarios tend to converge within a relatively narrow range on anticipated temperature change, but vary widely on water availability. All models show a more humid atmosphere as the temperature increases, but where and when rain falls is much more difficult to predict and evapo-transpiration is really the critical element for plant growth. Our measure of water stress uses a relatively crude index of droughts. However, for agriculture, timing of rain fall is critical. For example, a 2- to 3-week change in the timing of the monsoon can affect the whole growing season. To conclude, these results should be seen as highly speculative and are bound to change as new and more reliable information becomes available.

The overall impact on agricultural prices is beneficial, with prices dropping on average by around 8% as average agricultural productivity would rise in the climate impacted scenario. This has only modest impacts on food self-sufficiency with the exception of two regions. The Middle East and North Africa would see a relatively sharp increase in net imports and Latin America and Caribbean a drop in its exportable surplus.

For the most impacted regions — those at the left-side of Figure 14.15, the negative impacts are dominated by loss in tourism revenues and declines in labor productivity. The impact of sea-level rise is more based on geographic situation with relatively large impacts in Indonesia and rest of East Asia, and somewhat less in the rest of Latin America — that includes a significant region at risk in the Caribbean. Increasing water stress, on the other hand, is anticipated to impact Turkey, and the Middle East and North Africa.

For the two largest countries — China and India — the impacts are modestly positive in aggregate. Both would see some gains from less water stress and improvement in agricultural productivity. In the case of India this would be largely offset by heat- and health-related labor productivity impacts and loss in tourism arrivals. Russia would see a sizeable gain in tourism arrivals.

The high-income countries would tend to see a small gain. Gains in agriculture, lower water stress, health and tourism arrivals would be offset by small losses due to sea-level rise and negative impacts on labor productivity. The effects would tend to be small in most high-income regions with the exception of Canada.

14.7 CONCLUDING THOUGHTS

Sections 14.1—14.3 of this chapter are a broad introduction to global CGE modeling, particularly as reflected in the research work undertaken at the World Bank since the 1970s — with an emphasis on the traditional realm of global CGE modeling, notably international trade policies. Sections 14.4—14.6 reflect the most recent work undertaken at the World Bank using global CGE modeling where the focus has been much more on natural resources, the environment and commodities. This reflects to some extent the recent preoccupation of the international policy community — particularly in light of the large rise in commodity prices, which may have a more sustained basis than past commodity price boons in part as it relates to a changing global climate.

The results described herein suggest that the recent commodity price spike was the result of a perfect storm of negative shocks and that the global food system is poised to be able to feed the future world population with little stress as measured by sharply rising world prices. These results are predicated on continued improvements in agricultural productivity and with some expansion of cultivated land. The former could require renewed emphasis on publicly funded research and development that has been neglected in recent years and/or improvements to the profitability of private research — particularly in regions where agricultural productivity has been lagging. Land expansion is apparently feasible in some significant parts of the world, but a careful assessment of the environmental consequences is needed. Comparative advantage in food production could change dramatically in the future as regions below the agricultural production frontier improve yields and/or regions with significant land expansion potential cultivate more land. This has the potential to drive substantial changes in agricultural trade patterns. If traditional patterns hold, food-deficit countries may erect policies to limit trade dependence that may prove costly for their consumers and for the exporting producers.

Climate change is also likely to change the global food system. Here the future is much less clear. The current results suggest that globally climate change may improve food supply, at least in the medium term. This could be true on average, with higher mean temperatures in the upper latitudes extending growing seasons and offsetting the negative impacts in the lower latitudes. However, the story may not be in the averages, but in the extremes, in which case we may witness more volatility in supply and prices in the future than over the near past.

Despite the significant progress in global CGE modeling over the last four decades, there are still significant gaps. Data, although vastly improved through the efforts of the GTAP consortium, is still lacking both in terms of quality and completeness. To emulate the estimation and validation work of Dixon in Australia and Dixon and Jorgenson in the US at a more comprehensive level globally will require significantly more data collection. This process has started, but it still has a long way to go. In terms of more completeness, some gaps include domestic margins (that affects the price pass-through of basic prices to consumer prices), price/volume splits of the factors of production, price/volume splits in agricultural production and consumption, water as an input in agriculture and additional representative households to better assess distributional issues.

Parameterization of the global databases remains a huge challenge. The aforementioned country efforts to econometrically estimate parameters have been critical, but harder to emulate at the broader global level. The challenges multiply as more global CGE models become dynamic, requiring an understanding of how key parameters evolve with economic development. The long-standing Energy Modeling Forum exercises have been beneficial in elucidating model result differences — particularly those focused on the energy sectors and/or carbon mitigation policies. A similar exercise is currently underway for agricultural models. Model comparison is not a substitute for estimation and validation, but it can highlight critical parameters and set priorities for the econometricians.

A critical challenge for agricultural economic modelers is to convert the results of the bio-physical models of climate and crops into economic shocks — on yields, land and water resources and eventually on extreme events. The results presented in this chapter should be considered as highly speculative as we improve the linkages across the different types of models and better understand some of the key drivers of change.

Despite the many caveats whenever producing results with CGE models, they are an indispensable tool to analyze and understand the economic consequences of changes to economic policies — such as trade or carbon pricing — or to changes in the external environment such as climate change. The up- and down-stream linkages as picked up in the input-output matrix or between factor payments and demand, or the international linkages as transmitted through trade, migration or capital flows can only be captured consistently in the global CGE framework that has become the work horse of global economic policy analysis.

APPENDIX

The empirical findings of Sections 14.4—14.6 are based on an aggregation of the GTAP database, release 7.1. The aggregations listed in Tables A1 and A2 refer to the GTAP level of aggregation. For countries, GTAP (release 7.1) groups the more than 200 countries and territories into 112 countries/regions. The various industry classifications used by different statistical agencies are mapped to 57 sectors and goods.[76]

The regional mapping provided in Table A1 has two levels. For the purposes of the model simulations, the 112 countries/regions of GTAP have been aggregated into 20 countries/regions. Many of the results are presented at a higher level of aggregation that correspond (roughly) to the World Bank's seven regions — High-Income, East Asia and Pacific, South Asia, Europe and Central Asia, Middle East and North Africa, Sub-Saharan Africa, and Latin America and Caribbean.[77] For the modeled composite regions, e.g. rest of High-income Asia (XHA), Table A1 also shows the GTAP countries/regions included in the composite region (including the GTAP three-letter country/region code).

Table A2 shows the classification of goods and services used for the model results presented in this chapter. The 57 GTAP sectors have been aggregated into 28 sectors with a focus on agriculture, food and energy.

[76] Further information on the GTAP regional and industrial concordances can be found at www.gtap.org.

[77] Note that the World Bank classifications change annually as countries graduate to the World Bank's high-income classification.

Table A1 Regional concordance

High-income (HIC)	(1) Australia and New Zealand (ANZ) [Australia (aus), New Zealand (nzl)]
	(2) Japan (JPN)
	(3) Rest of high-income Asia (XHA) [Hong Kong (hkg), Korea (kor), Taiwan (twn)]
	(4) Canada (CAN)
	(5) US (USA)
	(6) EU27 and EFTA (EUR) [Austria (aut), Belgium (bel), Cyprus (cyp), Czech Republic (cze), Denmark (dnk), Estonia (est), Finland (fin), France (fra), Germany (deu), Greece (grc), Hungary (hun), Ireland (irl), Italy (ita), Latvia (lva), Lithuania (ltu), Luxembourg (lux), Malta (mlt), Netherlands (nld), Poland (pol), Portugal (prt), Slovakia (svk), Slovenia (svn), Spain (esp), Sweden (swe), United Kingdom (gbr), Switzerland (che), Norway (nor), Rest of EFTA (xef), Bulgaria (bgr), Romania (rou)]
East Asia and Pacific (EAP)	(7) China (CHN)
	(8) Indonesia (IDN)
	(9) Rest of East Asia (XEA) [Rest of Oceania (xoc), Rest of East Asia (xea), Cambodia (khm), Laos (lao), Malaysia (mys), Philippines (phl), Singapore (sgp), Thailand (tha), Viet Nam (vnm), Rest of Southeast Asia (xse)]
South Asia (SAS)	(10) India (IND)
	(11) Rest of South Asia (XSA) [Bangladesh (bgd), Pakistan (pak), Sri Lanka (lka), Rest of South Asia (xsa)]
Europe and Central Asia (ECA)	(12) Russia (RUS)
	(13) Turkey (TUR)
	(14) Rest of Europe and Central Asia (XEC) [Albania (alb), Belarus (blr), Croatia (hrv), Ukraine (ukr), Rest of Eastern Europe (xee), Rest of Europe (xer), Kazakhstan (kaz), Kyrgystan (kgz), Rest of Former Soviet Union (xsu), Armenia (arm), Azerbaijan (aze), Georgia (geo)]
Middle East and North Africa (MNA)	(15) Middle East and North Africa (MNA) [Iran (irn), Rest of Western Asia (xws), Egypt (egy), Morocco (mar), Tunisia (tun), Rest of North Africa (xnf)]
Sub-Saharan Africa (SSA)	(16) Sub-Saharan Africa (SSA) [Nigeria (nga), Senegal (sen), Rest of Western Africa (xwf), Central Africa (xcf), South-Central Africa (xac), Ethiopia (eth), Madagascar (mdg), Malawi (mwi), Mauritius (mus), Mozambique (moz), Tanzania (tza), Uganda (uga), Zambia (zmb), Zimbabwe (zwe), Rest of Eastern Africa (xec), Botswana (bwa), South Africa (zaf), Rest of South African Customs Union (xsc)]
Latin America and Caribbean (LAC)	(17) Argentina (ARG)
	(18) Brazil (BRA)
	(19) Mexico (MEX)
	(20) Rest of Latin America and Caribbean (XLC) [Rest of North America (xna), Bolivia (bol), Chile (chl), Colombia (col), Ecuador (ecu), Paraguay (pry), Peru (per), Uruguay (ury), Venezuela (ven), Rest of South America (xsm), Costa Rica (cri), Guatemala (gtm), Nicaragua (nic), Panama (pan), Rest of Central America (xca), Caribbean (xcb)]

Table A2 Sectoral concordance

Agriculture	(1) Rice (RIC) [Paddy rice (pdr), Processed rice (pcr)]
	(2) Wheat (WHT)
	(3) Other grains (GRO)
	(4) Vegetables and fruits (V_F)
	(5) Oil seeds (OSD)
	(6) Sugar (SUG) [Sugar cane and sugar beet (c_b), Refined sugar (sgr)]
	(7) Other crops (OCR) [Plant-based fibers (pfb), Crops, n.e.s. (ocr)]
	(8) Cattle (CTL) [Bovine cattle, sheep and goats, horses (ctl), Wool, silk-worm cocoons (wol)]
	(9) Other livestock (OAP)
	(10) Raw milk (RMK)
	(11) Forestry (FRS)
Mining and manufacturing	(12) Coal (COA)
	(13) Crude oil (OIL)
	(14) Natural gas (GAS)
	(15) Other mining (OMN)
	(16) Red meat (CMT)
	(17) Other meat (OMT)
	(18) Vegetable oils (VOL)
	(19) Dairy products (MIL)
	(20) Other food (OFD) [Fishing (fsh), Food products n.e.s. (ofd), Beverages and tobacco products (b_t)]
	(21) Textile wearing apparel and leather goods (TWP) [Textiles (tex), Wearing apparel (wap), Leather products (lea)]
	(22) Energy-intensive manufacturing (KE5) [Paper products, publishing (ppp), Chemical, rubber, plastic products (crp), Mineral products n.e.s. (nmm), Ferrous metals (i_s), Metals n.e.s. (nfm)]
	(23) Refined oil products (P_C)
	(24) Other manufacturing (XMN) [Wood products (lum), Metal products (fmp), Motor vehicles and parts (mvh), Transport equipment n.e.s. (otn), Electronic equipment (ele), Machinery and equipment n.e.s. (ome), Manufactures n.e.s.]
Utilities, construction and services	(25) Electricity (ELY)
	(26) Gas distribution (GDT)
	(27) Construction (CNS)
	(28) Services (SRV) [Water (wtr), Trade (trd), Transport n.e.s. (otp), Sea transport (wtp), Air transport (atp), Communication (cmn), Financial services n.e.s. (ofi), Insurance (isr), Business services n.e.s. (obs), Recreation and other services (ros), Public administration and defence, education, health services (osg), Dwellings (dwe)]

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