The Impact of Environmental and Climate Constraints on Global Food Supply*

by

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Abstract

The goal of this Chapter is to study the complex interaction between agriculture, economic growth and the environment, given future uncertainties. We combine economic concepts and biophysical constraints in one consistent modeling framework to be able to quantify and analyze the long-term socio-economic and environmental consequences of different scenarios. Here, we present the innovative methodology of coupling an economic and a biophysical model to combine state of the art knowledge from economic and biophysical sources. First, a comprehensive representation of the agricultural and land markets is required in the economic model. Therefore we included a land demand structure to reflect the degree of substitutability of types of land-use types and we included a land supply curve to include the process of land conversion and land abandonment. Secondly, the adapted economic model (LEITAP) is linked to the biophysical-based integrated assessment model IMAGE allowing to feed back spatially and temporarily varying land productivity to the economic framework. Thirdly, the land supply curves in the economic model are parameterized by using the heterogeneous information of land productivity from IMAGE. This link between an economic and biophysical model benefits from the strengths of both models. The economic model captures features of the global food market, including relations between world regions, whereas the bio-physical model adds geographical explicit information on crop growth within each world region. An illustrative baseline analyses shows the environmental consequences of the default baseline and a sensitivity analyses is performed with regard to the land supply curve. Results indicate that economic and environmental consequences are very dependent on whether a country is land scarce or land abundant. The introduction of an endogenous land supply curve has therefore important implications for analyses of the impact of climate, agricultural and trade policy reforms as it changes the impacts for the different countries.

Table of Contents

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B. Eickhout, H. van Meijl, A. Tabeau and E. Stehfest

1. Introduction

Food supply and food distribution have, for many decades, been among the most important issues playing a role in the global political arena. At the first World Food Summit in 1974, political leaders from around the world set a goal to eradicate hunger in the world within 10 years. Obviously, this ambitious goal was not met, leading to new goals at the second World Food Summit in 1996. The world leaders committed themselves to reduce by half the number of chronically undernourished by the year 2015. This target has been endorsed at many other meetings since then and is now known as one of the eight Millennium Development Goals (MDGs) of the United Nations (United Nations, 2001). The MDGs commit the international community to adopt an extended view on development and recognize the importance of creating a global partnership to achieve sustainable economic growth.

The term 'sustainable economic growth' embraces the marriage of economy and ecology introduced by Brundtland (1987) in 'Our Common Future'. This report emphasizes the importance of development for poor countries in the world as a prerequisite for peace, security and protection of the environment. However, over the years many studies paid attention to overcome poverty worldwide, ignoring the environmental side of development. This lack has been highlighted by the Millennium Ecosystem Assessment (MA, 2005), in which it is concluded environmental goods and services are essential for

human development. One of the greatest future challenges that are identified in the Millennium Ecosystem Assessment is the potential consequences of climate change (IPCC, 2007). Although climate change is related most directly to energy, agriculture also plays an important role. Some even claim the livestock sector is a larger contributor to climate change than the transport sector (FAO, 2006a).

Agriculture is not only a contributor to climate change; it can also play a role in mitigating climate change. A large number of climate scenario studies have been published over the last 15 years to identify mitigation strategies for achieving different stabilization levels of CO_2. Most of these studies have concentrated on reducing the energy-related CO_2 emissions only, leaving aside abatement options in the land-use system (Morita and Robinson, 2001). This lack of attention to land-use mitigation potentials in the scientific literature has been partly compensated by new publications on land-use mitigation potentials the last few years, with the Energy Modeling Forum (EMF-21) as main contributor (Rose et al., 2007). Most of the existing models with a detailed land scheme are based on biophysical relations only and address land-use change by looking at environmental consequences of different long-term baseline scenarios with exogenous driving forces of population, economic growth and agricultural food supply (Strengers et al., 2004; Rounsevell et al., 2006). Progressively over the years, the socio-economic disciplines have seriously contributed to a refined effort of implementing land use modeling within socio-economic models. Over the years land has been implemented in both Partial Equilibrium (PE) and General Computable Equilibrium (GCE) models. Nevertheless, most of these current economic models do not consider the land mobility

and availability, nor the heterogeneity of land within the region. And more important, environmental constraints on land productivity are seldom taken into account.

The key challenge is therefore to construct a modeling framework that combines the advantages of the global CGE approach, taking into consideration the impact of non-agricultural sectors on agriculture and a full treatment of factor markets with the specific features of mobility and availability of land. Moreover, such a modeling framework needs to take into account marginal lands and changes in productivity due to changes in land use and climate change. The *goal of this study* is to deal with the complex interaction between agriculture, economic growth and the environment, given future uncertainties. We combine uncertainties in one consistent modeling framework, and quantify and analyze the long-term socio-economic and environmental consequences of different scenarios. In the end, depletion of environmental resources could potentially hamper human development. And studies should consider these effects as well.

To assess economic consequences and land-use changes, a modeling framework capable of capturing both economic and environmental consequences is needed. The Integrated Model to Assess the Global Environment (IMAGE; Alcamo et al., 1998; IMAGE Team, 2001; MNP, 2006) is one of the most frequently used global land models, to simulate land use emissions (Strengers et al., 2004), environmental impacts (GEO3, 2002; Eickhout et al., 2006; Eickhout et al., 2007) and impacts on ecosystems (Leemans and Eickhout, 2004; Bakkenes et al., 2006; MA, 2005). However, the IMAGE model is less suitable for economic analyses, given the scarce elaboration of the agricultural economy

model (Strengers, 2001). Therefore, the IMAGE model needed to be expanded with an agricultural economy model capable of implementing different agricultural policies. The adjusted version of the Global Trade Analysis Project (GTAP; Hertel, 1997; LEITAP; Van Meijl et al., 2006) model offers a viable framework taking into consideration the impact of non-agricultural sectors on agriculture and a full treatment of factor markets with special features concerning land modeling. Hence, the combination of IMAGE and LEITAP offers a modeling framework that can achieve an analysis that takes into account both economic and environmental circumstances determining the future food market.

First, we describe shortly the expanded version of GTAP (LEITAP) that is linked to the IMAGE model (Section 2). Next, the IMAGE model is introduced in Section 3 and the link of LEITAP and IMAGE through land-supply curves is elaborated upon in Section 4. In Section 5, we show the results of an illustrative baseline analysis in which we show the environmental consequences of a default baseline. In Section 6, we show the importance of using a land supply curve and we conclude with a Discussion in Section 7.

2. The Extended GTAP Model LEITAP

The standard GTAP model is characterized by an input-output structure, based on regional and national input-output tables. It explicitly links industries in a value added chain from primary goods, over continuously higher stages of intermediate processing, to the final assembling of goods and services for consumption (Hertel, 1997).

To better represent some key characteristics of agricultural and land markets the standard GTAP model is extended. Particularly the functioning of the land and agricultural markets are crucial. Therefore we included a new demand structure to reflect that the degree of substitutability of types of land differs between land types (Huang, et al. 2004). Furthermore, we included a land supply curve to include the process of land conversion and land abandonment (Van Meijl et al. 2006). In comparison to Van Meijl et al. (2006) we improved the empirical implementation of the land supply curve. Furthermore, agricultural labor and capital markets are segmented from the non-agricultural factor markets (Hertel and Keeney, 2003). Some key features of the Common Agricultural Policy are introduced, such as the introduction of endogenous agricultural quota as a complementarity problem (Van Meijl and Van Tongeren, 2002). The regional breakdown of LEITAP as currently applied is given in Appendix A. The commodities that are simulated are given in Appendix B.

An extended land allocation tree

The standard version of GTAP represents land allocation in a CET structure (Figure 1) assuming that the various types of land use are imperfectly substitutable, but with equal substitutability among all land use types. For our purposes, the land use allocation structure is extended by taking into account that the degree of substitutability differs between types of land (Huang et al., 2004) using the more detailed OECD's Policy Evaluation Model (PEM) structure (OECD, 2003) (Figure 1). It distinguishes different types of land in a nested 3-level CET structure. The model covers several types of land

use with different suitability levels for various crops (i.e. cereal grains, oilseeds, sugar cane/sugar beet and other agricultural uses).
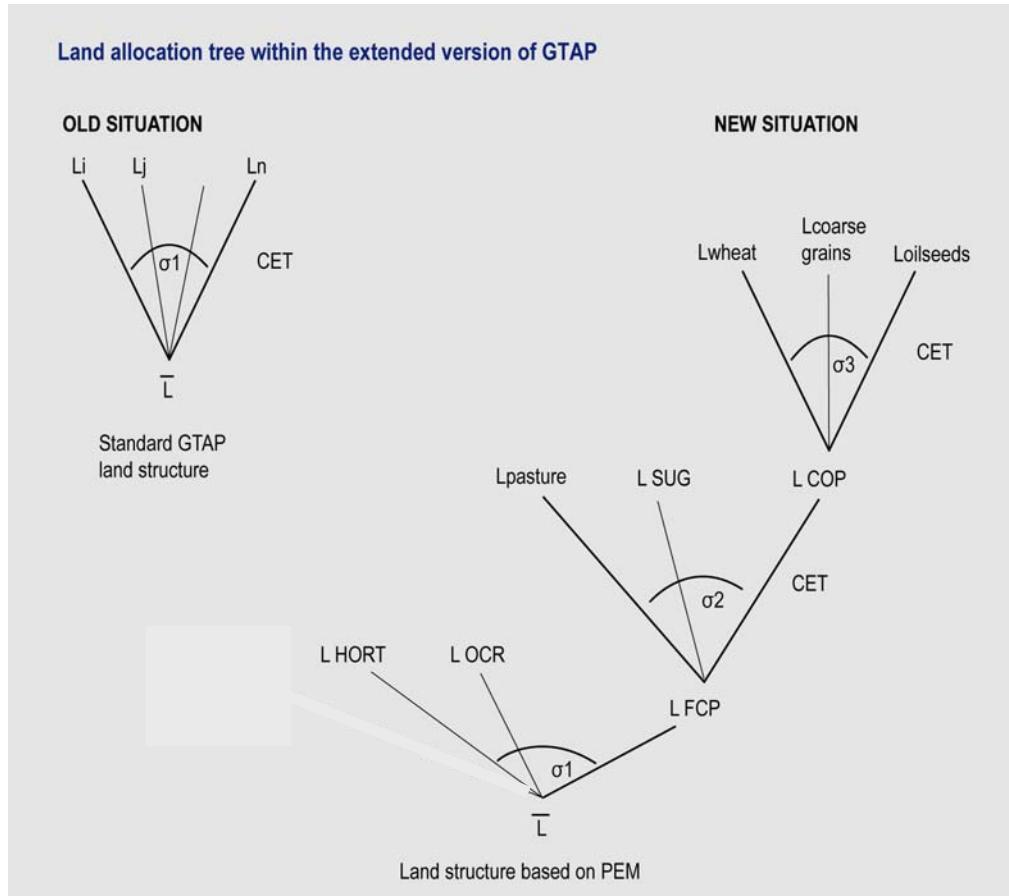
Figure 1. Land allocation tree within the extended version of GTAP. Following the PEM approach (OECD, 2003), there is nested substitutability between land for horticulture (LHORT), other crops (LOCR) and field crops and pasture (LFCP), between land for pasture (Lpasture), sugar crops (LSUG) and cereal, oilseed and protein crops (LCOP), and between land for wheat (Lwheat), coarse grains (Lcorse grains) and oilseeds (Loilseed).

The lower nest assumes a constant elasticity of transformation between 'vegetables, fruit and nuts' (HORT), 'other crops' (e.g. rice, plant-based fibers; OCR) and the group of

'Field Crops and Pastures' (FCP). The transformation is governed by the elasticity of transformation σ1. The FCP-group is itself a CET aggregate of Cattle and Raw Milk (both Pasture), 'Sugarcane and Beet' (SUG), and the group of 'Cereal, Oilseed and Protein crops' (COP). Here, the elasticity of transformation is σ2. Finally, the transformation of land within the upper nest, the COP-group, is modeled with an elasticity σ3. In this way the degree of substitutability of types of land can be varied between the nests. Agronomic features are captured to some extent. In general it is assumed that σ3> σ2 >σ1, which implies that it is easier to change the allocation of land within the COP group, while it is more difficult to move land out of COP production into, say, vegetables. The values of the elasticities are taken from PEM (OECD, 2003).

Land supply curve

Moreover, in this extended version of the GTAP model the total agricultural land supply is modeled using a land supply curve which specifies the relation between land supply and the rental rate (Van Meijl et al., 2006). Through this land supply curve an increase in demand for agricultural purposes will lead to a modest increase in rental rates and land conversion to agricultural land when enough land is available, whereas if almost all agricultural land is in use increases in demand will lead to increases in rental rates. The land supply curve and its empirical implementation are presented in section 4.

Factor market segmentation

Wage differentials between agriculture and non-agriculture can be sustained in many countries (especially in developing countries) through limited off-farm labor migration

(De Janvry et al., 1991). Returns to assets invested in agriculture also tend to diverge from returns of investment in other activities.

To capture these stylized facts, we incorporate segmented factor markets for labor and capital by specifying a CET structure that transforms agricultural labor (and capital) into non-agricultural labor (and capital) (Hertel and Keeney, 2003). This specification has the advantage that it can be calibrated to available estimates of agricultural labor supply response. In order to have separate market clearing conditions for agriculture and non-agriculture, we need to segment these factor markets with a finite elasticity of transformation. We also have separate market prices for each of these sets of endowments. The economy-wide endowment of labor (and capital) remains fixed, so that any increase in supply of labor (capital) to manufacturing labor (capital) has to be withdrawn from agriculture, and the economy-wide resources constraint remains satisfied. The elasticities of transformation were calibrated to fit estimates of the elasticity of labor supply from OECD (2003).

Feed conversion in livestock

The intensification of livestock production systems also influences the composition of the animal feed required by livestock production systems. In general, intensification is accompanied by decreasing dependence on open range feeding and increasing use of concentrate feeds, mainly feed grains, to supplement other fodder. At the same time, improved and balanced feeding practices and improved breeds in ruminant systems enable more of the feed to go to meat and milk production rather than to maintenance of

11

the animals. IMAGE simulates the production of livestock products, the animal stocks, productivity per animal, feed conversion and the use of different feedstuffs (crops, residues and fodder crops, animal products, grass and scavenging).

In the LEITAP model, future shifts in feed composition are taken from the IMAGE implementation of the FAO projection until 2030 (Bruinsma, 2003) as described in Bouwman et al. (2005). Consequently, these future shifts in feed composition are not responsive to relative prices of feed and grazing land.

3. The IMAGE Model

The Integrated Model to Assess the Global Environment (IMAGE), initially developed to assess the impact of anthropocentric climate change (Rotmans et al., 1990), is a dynamic integrated assessment framework to model global change. Later it was extended to include a more comprehensive coverage of global change issues in an environmental perspective (IMAGE team, 2001). The current main objectives of IMAGE are to contribute to scientific understanding and support decision-making by quantifying the relative importance of major processes and interactions in the society-biosphere-climate system (MNP, 2006).

IMAGE provides dynamic and long-term perspective modeling on the systemic consequences of global change up to 2100. The model was set up to give insight into causes and consequences of global change up to 2100 as a quantitative basis for

analyzing the relative effectiveness of various policy options for addressing global change. Demographic and economic projections are used as an input in three parts of the IMAGE model.

- The IMage Energy Regional Model (TIMER), which calculates regional energy consumption, energy efficiency improvements, fuel substitution, supply and trade of fossil fuels and renewable energy technologies. On the basis of energy use and industrial production, TIMER computes emissions of greenhouse gases (GHG), ozone precursors and acidifying compounds (Van Vuuren et al., 2007). These emissions are simulated for 24 regions (Figure 2; Greenland and Antarctica are not simulated).

- The Terrestrial Environment System (TES), which computes land-use changes on the basis of regional consumption, production and trading of food, animal feed, fodder, grass and timber, with consideration of local climatic and terrain properties. The agricultural production comes from LEITAP which has been run on the basis of the same demographic and economic projections. TES computes emissions from land-use changes, natural ecosystems and agricultural production systems, and the exchange of CO_2 between terrestrial ecosystems and the atmosphere.

- The Atmospheric Ocean System (AOS) calculates changes in atmospheric composition using the emissions and other factors in the TIMER and TES, and by taking oceanic CO_2 uptake and atmospheric chemistry into consideration. Subsequently, AOS computes changes in climatic properties by resolving the

changes in radiative forcing caused by greenhouse gases, aerosols and oceanic

heat transport (Eickhout et al., 2004).
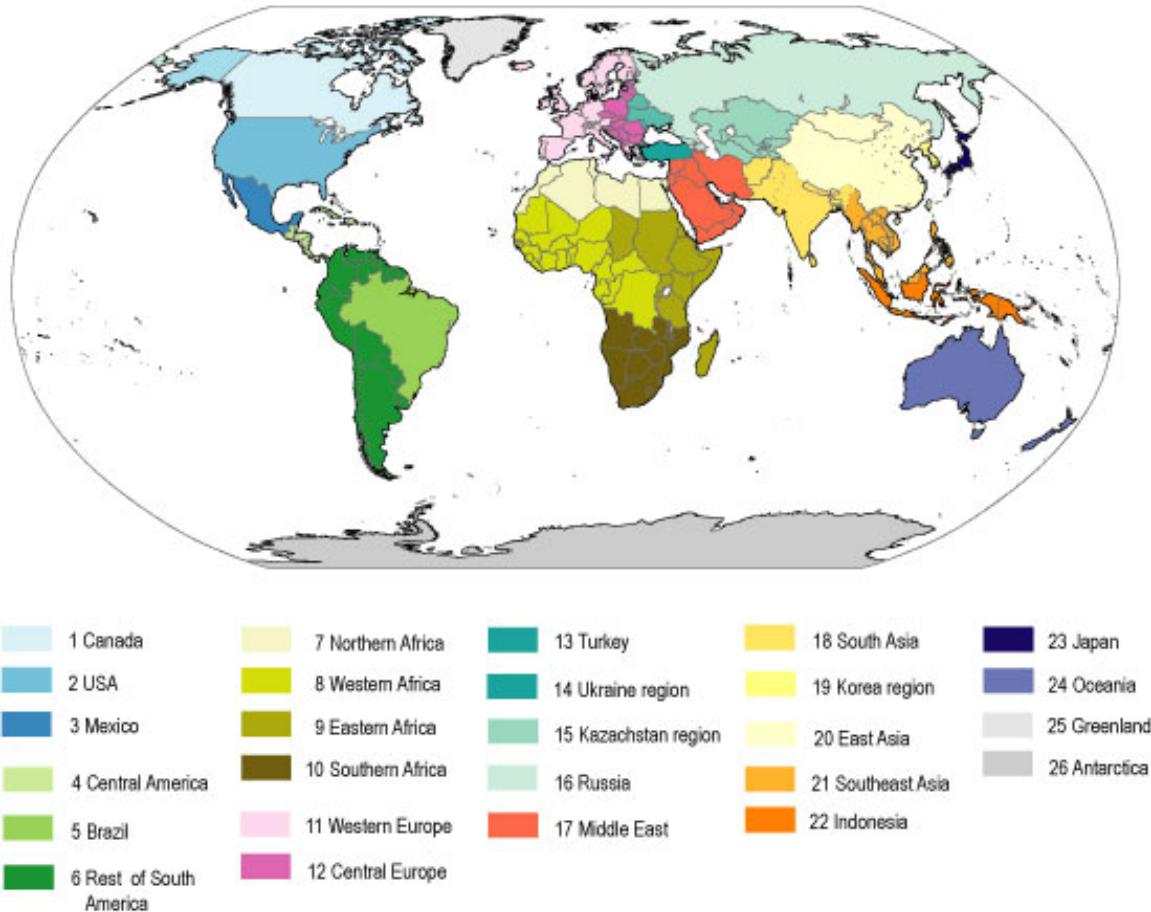
Figure 2. Regional breakdown of the IMAGE model in 24 regions. The overlap with the LEITAP regions is given in Appendix A.

In this study we focus our analysis on the output of the terrestrial models (the Terrestrial

Vegetation Model and the Land Cover Model) of the IMAGE framework which are

coupled to the LEITAP model. The Terrestrial Vegetation Model (TVM) simulates the

potential distribution of natural vegetation and crops on the basis of climate conditions

and soil characteristics on a spatial resolution of 0.5 degree latitude by 0.5 degree

longitude. It also estimates potential crop productivity, which is used by Land Cover

Model (LCM), to determine the allocation of the cropland to different crops. First, TVM calculates 'constraint-free rain fed crop yields' accounting for local climate and light attenuation by the canopy of the crop considered (FAO, 1981). The climate-related crop yields are adjusted for grid-specific conditions by a soil factor with values ranging from 0.1 to 1.0. This soil factor takes into account three soil quality indicators: (1) nutrient retention and availability; (2) level of salinity, alkalinity and toxicity; and, (3) rooting conditions for plants. The adjustment factor is calibrated using historical productivity figures and also includes the fertilization effect of changes in the atmospheric concentration of CO_2. The resulting crop productivity, called 'reduced potential productivity of crops', is used in the land cover model. The objective of the Land Cover Model is to simulate global land use and land cover changes by reconciling the land use demand with the land potential. The basic idea of the LCM is to allocate land cover on a grid within each world region until the total demands for this region are satisfied. The results depend on changes in the demand for food and feed as computed by LEITAP. The allocation of land use types is done at grid cell level on the basis of specific land allocation rules like crop productivity, distance to existing agricultural land, distance to water bodies and a random factor (Alcamo et al., 1998). In Figure 3, a detailed scheme of the land-use model of IMAGE is given.
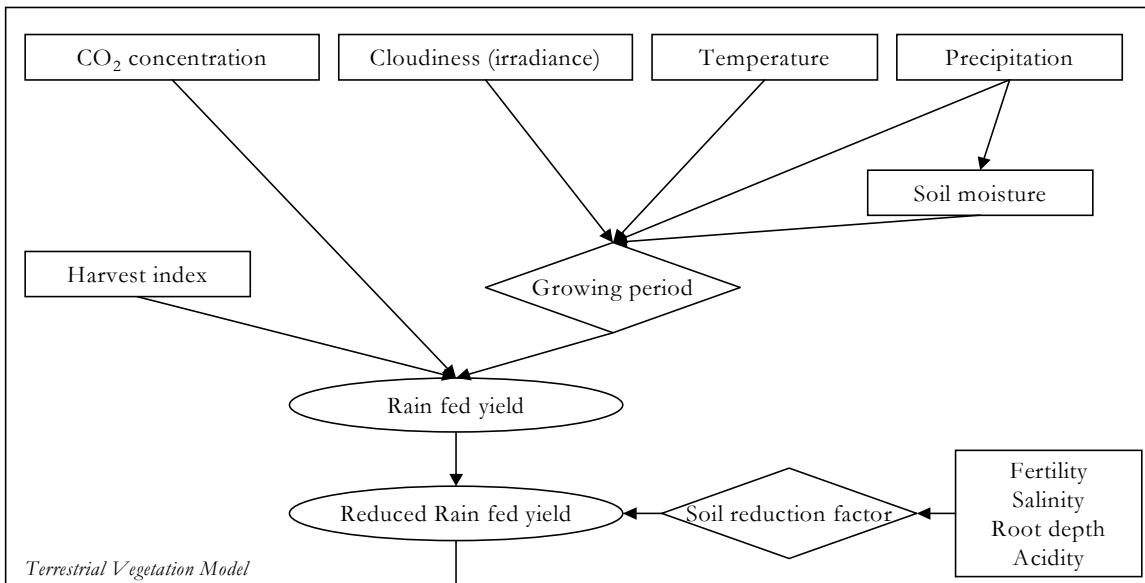
Figure 3. Schematic representation of the IMAGE crop model (based on Leemans and Van den Born, 1994; taken from Hoogwijk et al., 2005).

In the IMAGE model climate change is simulated endogenously: changes in the energy system and land-use changes lead to greenhouse gas emissions that are linked to a carbon cycle model (Leemans et al., 2002) and an atmospheric chemistry model (Eickhout et al., 2004). These two models simulate atmospheric concentrations of the most important greenhouse gases, leading to climate change through their radiative forcings (Eickhout et al., 2004). Climate change is also affecting the food production in the future. Although the extent of climate change is highly uncertain, it is obvious this environmental feedback needs to be included in analyses focusing on future food production. Rosenzweig et al. (1995), Parry et al. (2001) and Fischer et al. (2002) indicated that increasing adverse global impacts because of climate change will be encountered with temperature increases above 3 to 4°C compared to pre-industrial levels. On the other hand, CO_2 fertilization effect may increase food productivity (see also IPCC, 2007). By using information from

the IMAGE model in LEITAP, these heterogenic environmental circumstances can be included in economic analyses.

4. Coupling IMAGE and LEITAP

The combination of IMAGE and LEITAP encompasses two parts: the implementation of a land supply curve on the basis of IMAGE data in the base year and the exchange of information of IMAGE and LEITAP during a simulation period.

Implementation of land supply curves in LEITAP

From an economic point of view, the agricultural land supply is a function of the price of land as expressed by land rent. These land supply curves serve to translate the biophysical information on land productivity (based on soil and climatic conditions as described above) to land rent. Van Meijl et al. (2006) implemented these supply curves in a general equilibrium framework and they calibrated the curves using FAO land use projections and IMAGE results (see, also Tabeau et al., 2006).
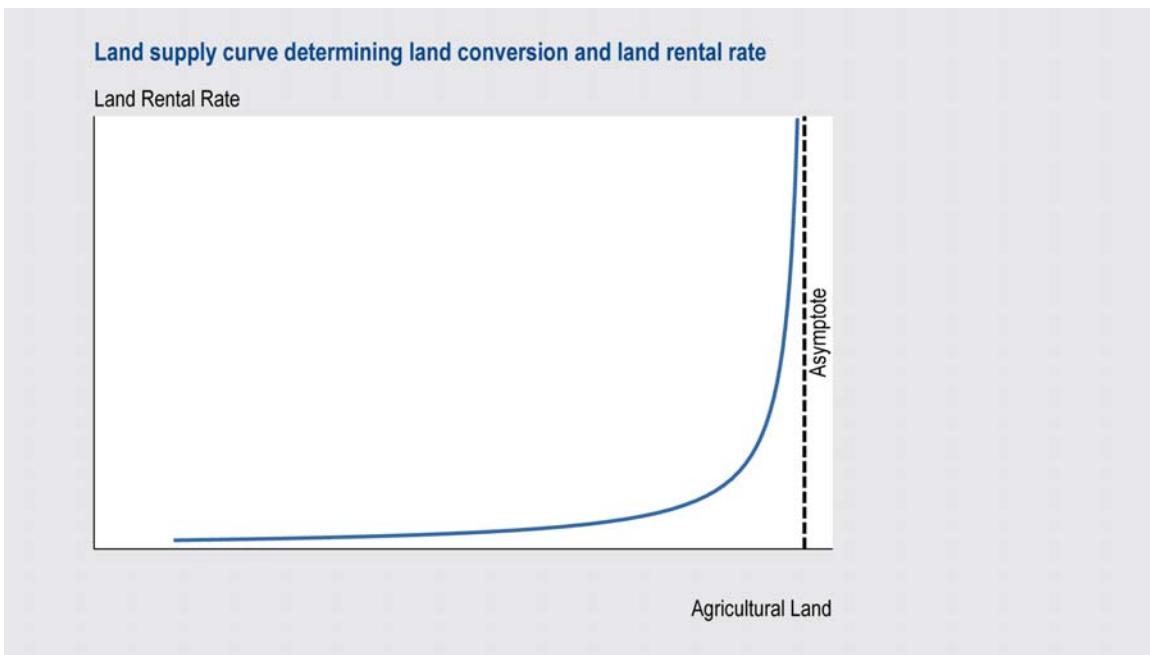
Figure 4. Land supply curve determining land conversion and land rental rate.

The supply of agricultural land depends on its biophysical availability (potential area of suitable land), institutional factors (agricultural and urban policy, policy towards nature) and land price. The assumption that the most productive land is taken into production first leads to the shape of the agricultural land supply curve presented in Figure 4. If the gap between agricultural land potentially available and land actually used in the agricultural sector is large, any increase in demand for agricultural land will lead to a modest increase in land price, and will be accompanied by land conversion to agricultural use. Such a situation occurs in the flat part of the land supply curve (Figure 4). In contrast, when the agricultural land that is in use is close to the potential area, an increase in demand for agricultural land will lead to an increasing land price (land becomes scarce). Here, land conversion is difficult to achieve, and therefore the elasticity of land supply with respect

to land price is also low. Points situated on the steep part of the land supply curve in Figure 4 describe this situation.

The land supply curve drawn on Figure 1 can, in general, be described using the following rational function:

$$L = a - b/[c_o + r^p + \Sigma_{i=1,...,n} \, c_i \, r^{p+i}] \tag{1}$$

where *L* is the amount of land on the land supply curve, *r* is the land rental rate, *a* (>0) is the asymptote determining the maximum potentially available agricultural land and b, c_o, c_i and p are positive parameters determining the shape of the curve.

The estimation of such a function is not a simple task. It requires long time series of data concerning land use and land rental rate development, which are not available for the majority of countries. The required data are only available in the case of the 15 "old" EU member states. However, these data only describe the land use development of a small part of the land supply function. Therefore, by using this information to parameterize the function incorrect results could be introduced.

Therefore, for all regions a simplified version of Equation (1) is used:

$$L = a - b/r^p \tag{2}$$

This function is easy to calibrate to the benchmark data, as long as the asymptote *a* and the price elasticity are known. The price elasticity is given by the equation:

$$\varepsilon = p \, b/(a \, r^p - b) \tag{3}$$

If the asymptote (*a*), price elasticity (*ε*) and a land price (*r*) and the corresponding land supply (*L*) are known, the parameters *b* and *p* can be determined by solving a system of

equations (2)-(3). Function (2) was parameterized by Cixous (2006) for the 15 "old" EU member states.

Information to determine asymptote a is taken from IMAGE data. It is determined by the total available land excluding non-productive land (mainly ice and desert in regions like Canada and Middle East), urban areas and protected reserves to take into account nature conservation. The asymptote is determined for each of the 26 world regions that are used within LEITAP (see Appendix A). Information for the current land price (r) and land supply (L), i.e. the current position on the curve, are taken from GTAP-6 and FAO data (FAO, 2006a) respectively.

The price elasticity of the land supply (ε) is only available in literature for the 15 "old" EU member states (Cixous, 2006). We used these elasticities to calibrate the land supply curve for the regions EU14 and the Netherlands (Appendix A). For the other regions, data from the IMAGE model are used to get to an approximation of Equation 1. Therefore, IMAGE data are used to determine the price elasticity. The most important assumption is that the marginal land price is inverse proportional to the marginal yield.

In IMAGE, the productivity for seven food crops is calculated for each 0.5 by 0.5 degree grid cell with the crop growth model of IMAGE (Leemans and Van den Born, 1994). For LEITAP this information is aggregated to an estimate of the overall productivity for each grid cell. This overall crop productivity is expressed on a relative scale between 0 and 1 on the basis of the potential crop productivity. Land productivity curves are obtained by

ordering all grid cells in each of the world regions (except for EU14 and the Netherlands) from high to low productivity, and summing the total area (Figure 5).
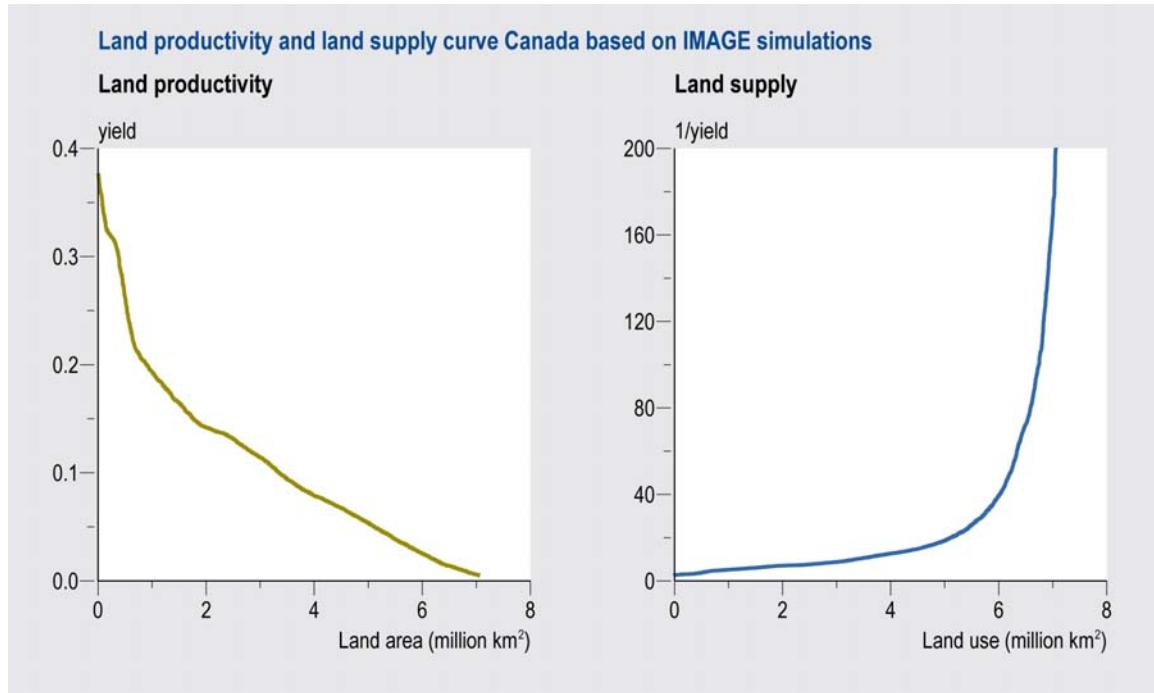
Figure 5. Land productivity and land supply curve for Canada on the basis of IMAGE simulations.

The inverse of the land productivity curve determines the curve of the land supply of the non-EU15 regions (see Appendix A). By using these data from this empirical land supply curves[1], the parameters of Equation (1) are determined. The estimation procedure leads (after leaving out non-significant and negative parameters) again to Equation (2) plus a constant c_o. The selected estimation results of the land supply curve are presented in Appendix C. In general, the fitting of the estimated land supply curve to the data is very good; the R^2 exceeds 0.90, often being close to 1. However, since "last" observations

[1] For estimation procedure, we translate the inverse of yields to the land rental rates using the region specific proportionality coefficients. They are calculate from comparison of benchmark yields and land prices. The land price is calculated as land value in GTAP divided by land supply.

used to estimate the land supply curve are often irregular, the curve often does not fit the data very well at the end of the sample. Here the inverse of yield is not a good proxy of the real land rental rate since land is very scarce in those cases. The curve often does not fit the data very well at the beginning of the sample either: if an oversupply of land occurs, the inverse of yield is not a good proxy of the real land rental rate. The estimated parameters are significant.

The comparison between actual land use and total available area (according to IMAGE) shows agricultural land is scarce in North Africa, EU, Rest of Western Europe, Former Soviet Union, Middle Ease, Oceania and Japan. According to these results, all these regions are currently placed on the steep part of their land supply curve and the associated land supply elasticities in respect of the real land rental rate are lower than 1 for these regions.
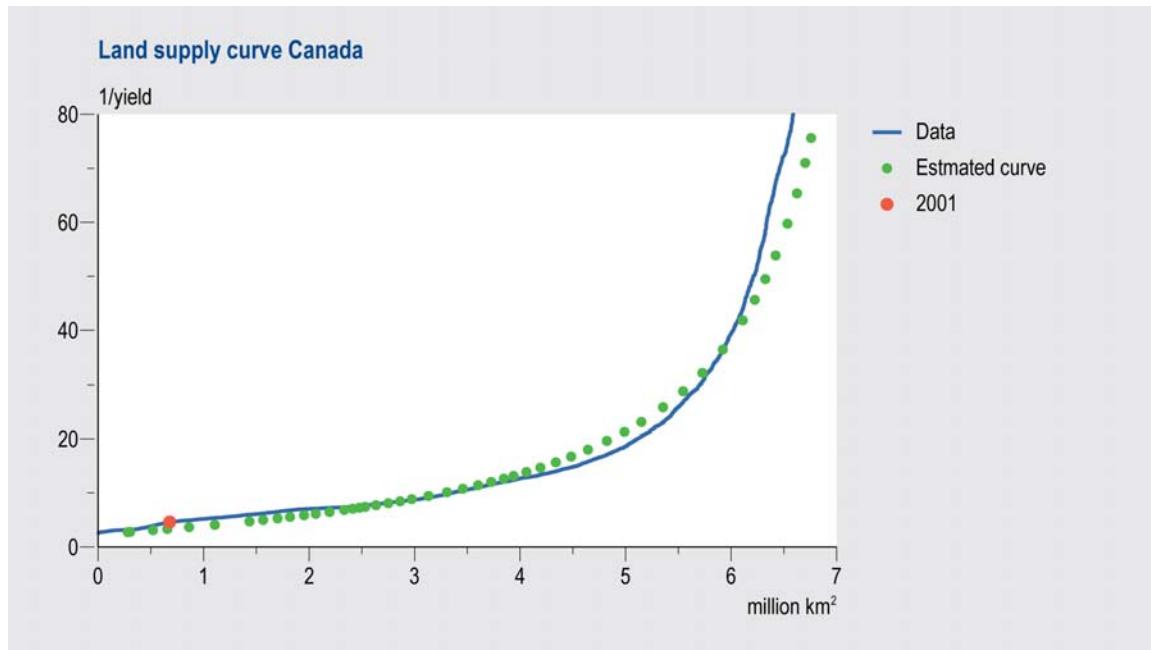
Figure 6. Land supply curve for Canada.

The current position of region on the estimated land supply functions differs for different

regions. For instance, the current position of Canada on their land supply curve indicates

that the agricultural land in Canada can still be expanded without a high increase in the

real land rental rate (Figure 6). The opposite situation is observed for China. Small

expansion in the agricultural land in China will lead to a high increase in the real land

rental rate, therefore stimulating intensification processes in the agricultural practices

(Figure 7).
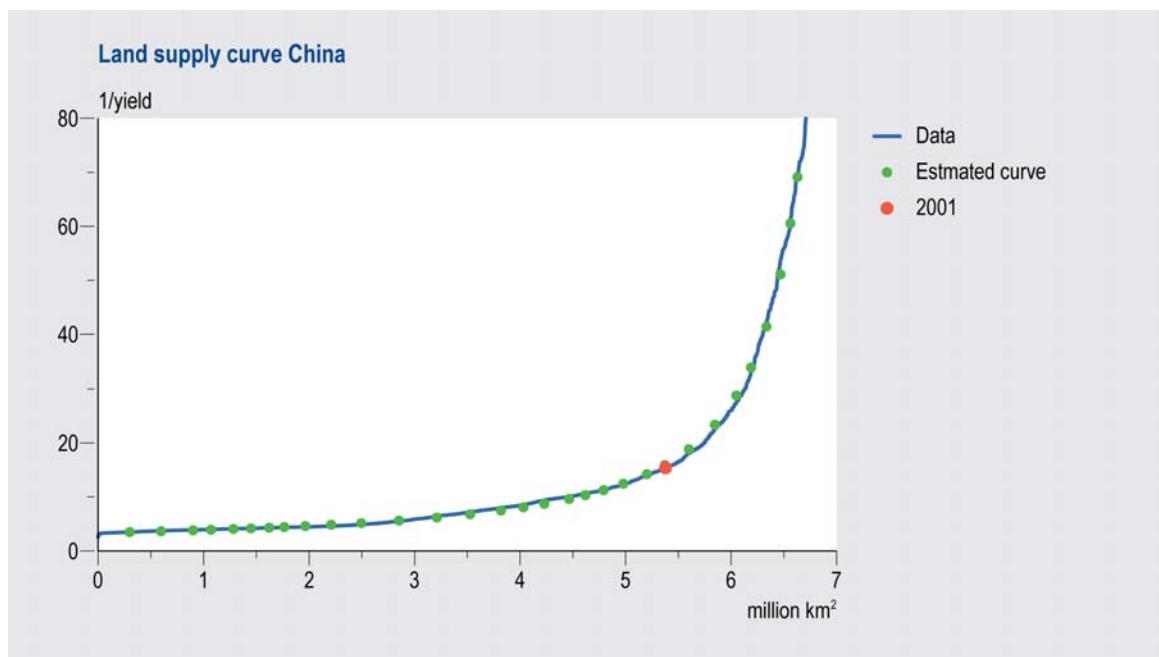
Figure 7. Land supply curve for China.

Iterating LEITAP and IMAGE

Figure 8 shows the methodology of iterating LEITAP with IMAGE. Yields in LEITAP

depend on an exogenous part (the trend component) and an endogenous part with relative

factor prices (the management component). The production structure used in LEITAP

implies that substitution is possible among the different production factors. If land prices rise, the producer will substitute land for other production factors such as capital and as a consequence land productivity (yields) will increase.

The exogenous trend of the yield in LEITAP and IMAGE is taken from Bruinsma (2003) where macro-economic prospects are combined with local expert knowledge to produce best-guesses of the technological change for each country for the coming 30 years. The FAO data were therefore used as exogenous input for a first model run with the LEITAP model.

Methodology of model interaction (iteration) between GTAP and IMAGE
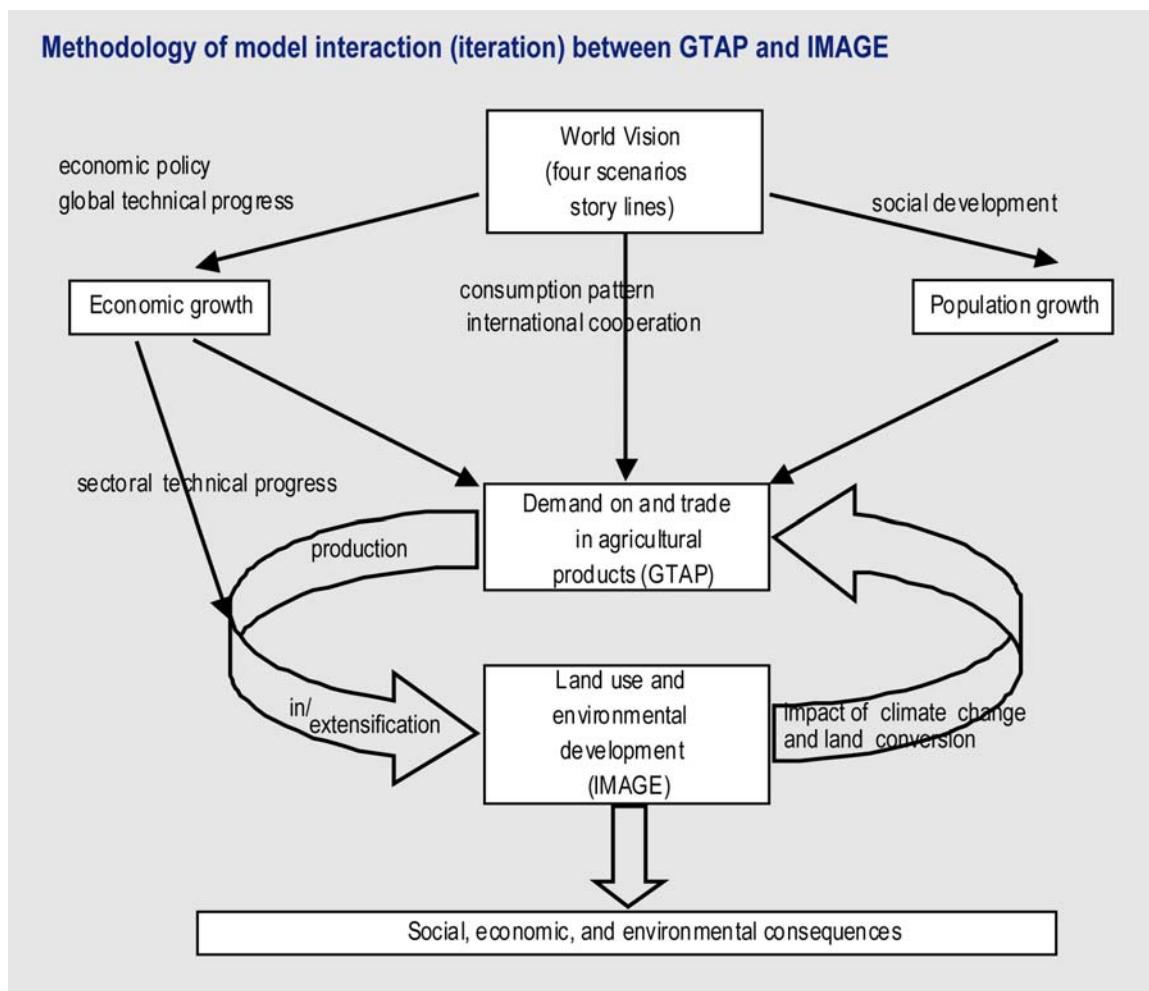
Figure 8. Scheme showing the methodology of model interaction (iteration) between LEITAP and IMAGE.

The output of LEITAP used for the iteration with IMAGE comprises sectoral production growth rates and the endogenous determined intensification or extensification (additional to the exogenous trend). For crops, the endogenous LEITAP values are added to the management factor within IMAGE. For pigs and poultry, the additional intensification is added to the animal productivity of these commodities. For dairy and non-dairy cattle and sheep and goats the additional value is added to the grazing intensity.

Subsequently, the IMAGE model calculates the yields, the demand for land and the environmental consequences on crop productivity. IMAGE simulates global land-use and land-cover changes by reconciling the land-use demand with the land potential. This procedure yields the area of agricultural land needed within each world region and the corresponding changes in yields related to the extent and productivity of the land and climate change. These additional changes in crop productivity are returned to LEITAP (Figure 8). A general feature is that yields decline if significant land expansions occur, as the productivity of land last taken into production is by definition lower than that of the existing agricultural area. When the agricultural land area is close to the potential area, even marginal land may be taken into production. In the short term, these factors are more important than the effects of climate change.

The iteration between LEITAP and IMAGE is ended when arable land use projections in both models are similar. This iteration is only performed for crops. Since LEITAP bases its calculations on land supply curves from IMAGE, the amount of iteration needed is limited. Convergence of the crop areas is not guaranteed, but several scenario studies showed that after three rounds of iteration, most of the crop areas in IMAGE and LEITAP are similar. After the iteration a consistent set of modeling results is obtained from LEITAP and IMAGE, allowing analyses on agricultural consumption, production and trade (from LEITAP) and land-use change, greenhouse gas emissions and climate change (from IMAGE).

5. **Application of the LEITAP-IMAGE Framework**

A baseline scenario (OECD, 2007) is developed on the basis of projections of land productivity from FAO (Bruinsma, 2003) and energy development from IEA (IEA, 2004). The scenario includes autonomous developments in demography, economics and technology, and current policies agreed upon in national and international treaties. The scenario assumes moderate population growth and economic development. The global population growth is from 6.1 billion in the year 2000 to 9 billion in 2050, but with a gradually declining growth rate. Over the same period, the global average annual income increases from US$ 5300 to US$ 16000 per capita. The combined effect of population and economic growth represents more than a fourfold increase in global GDP in the next half century. In the baseline, energy supply continues to rely on fossil resources (coal, oil and gas) leading to continued increase of emissions of greenhouse gases from

combustion. Together with emissions from land use and other sources, this leads to a rise in global temperature of 1.8°C over pre-industrial levels in 2050, which is faster than the observed increase in the last 130 years. After implementation of the Kyoto Protocol for 2008-2012, no further climate mitigation measures are included in the baseline scenario.

Production increases in all world clusters, but more strongly in the non-OECD clusters (Figure 9) due to higher population growth and a stronger effect of income on consumption in these low income clusters which currently face undernourishment. Traditional large food producers in the OECD maintain a strong position in the baseline scenario, where no significant changes to prevailing trade regimes and agricultural support policies are assumed (only approved policy changes are implemented, such as 2003 EU CAP reform). Nonetheless, trade in food crops expands, also between non-OECD clusters
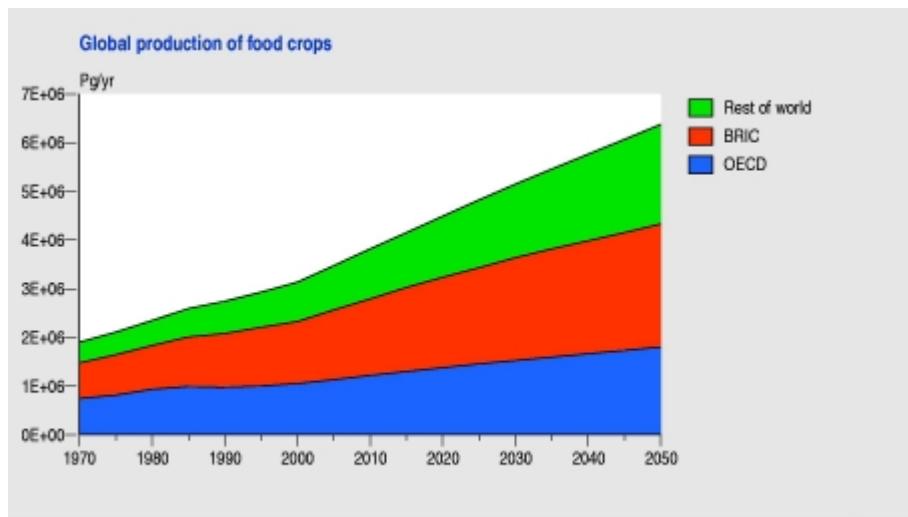
Figure 9. Total crop production in the baseline scenario until 2050 for OECD countries (Canada, US, EU, Oceania, Korea and Japan), BRIC countries (Brazil, Russia, India and China) and the rest of the world.

In line with growing overall consumption and the shift towards more animal products in the diet with rising income, total animal production increases. Production of pork and poultry grows rapidly, while beef, milk and other dairy products lag behind due to relatively high production cost, dietary preferences and less opportunities for high intensity production systems. In total the output doubles in 2050 (compared to 2000; Figure 10). A second important trend is the observed shift towards more intensive production like mixed and landless systems. In these more intensive systems, the share of grass and other fodder in the animal diets decrease, as they rely more on feed derived from food crops (Bouwman et al., 2005). The change in volume and the larger share of food crops associated with intensification imply that the amount of food crops, e.g. oil seeds meals and coarse grains, used as animal feed increases substantially.
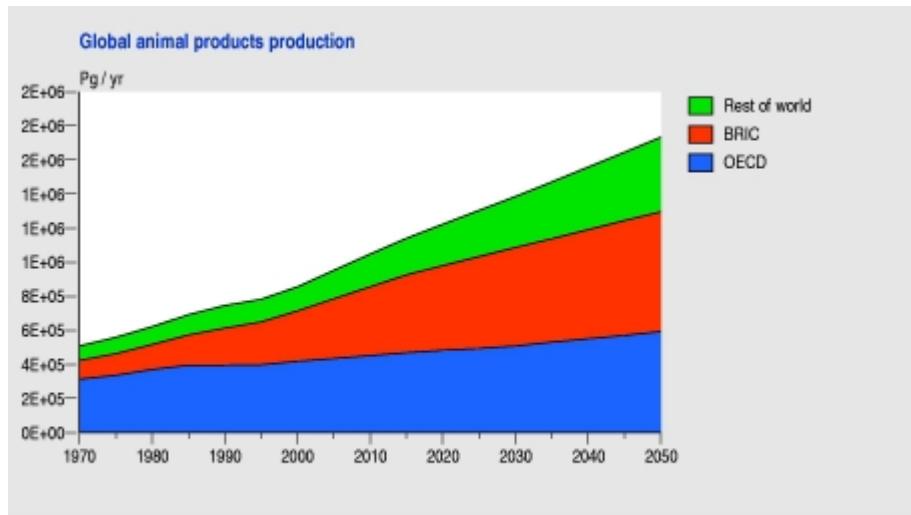

Figure 10. Total animal production in the baseline scenario until 2050 for OECD countries (Canada, US, EU, Oceania, Korea and Japan), BRIC countries (Brazil, Russia, India and China) and the rest of the world.

The large increase in per capita income in China and India, given a low initial income level, stimulates demand for meat in these countries. In China this trend is already very prominent in recent years and the share of China in world meat imports increased from 5% to 15% (FAO, 2006b). The biggest net-exporters of meat are USA, Indonesia and Brazil, while Oceania is the leading net-exporter of mainly sheep meat, but also beef, veal and goat meat. OECD countries lead the world dairy exports with a market share of about 80%.

Total agricultural land, comprising all food, fodder and grazing land, is gradually increasing from 2000 to 2050. More people and a growing per capita income, which increases the caloric intake and induces a shift to a larger share of animal products (meat and dairy products) in the diet, will tend to drive the demand for agricultural land up. The lower overall efficiency of animal production chains compared to other food, and the large (extensive) grassland areas both tend to increase agricultural land demands further. This is partly compensated, however, by two factors:

- First, productivity in agriculture is projected to increase, so that higher yields per hectare offset half of the growth in demand. In many areas of the world the actual productivity is currently still far below what the potential output, determined by climate and soil characteristics, could be. In particular in less developed clusters this so-called yield-gap is decreasing and hence output per hectare increases. The yield increases are taken initially from FAO (Bruinsma, 2003), but adjusted in the iteration between LEITTAP and IMAGE (Figure 8).

- Furthermore, the demand for animal products - typically requiring much more land per kg product - is increasingly produced in more intensive modes in mixed and landless systems at the expense of extensive grazing on vast land lots. In intensive systems, animals eat various products as compound feed including food crops (Bouwman et al., 2005). Hence the global grassland & fodder area grows much slower less than the production of meat and dairy products (Figure 11).

As the net result of these underlying developments, global agricultural area shows a moderate increase of 13% between 2000 and 2030 while agricultural outputs grow much faster. Food crop area expands to various degrees in almost all clusters, in absolute terms the most in South Asia (India) and Africa. Almost all of the expansion of (Extensive) grassland and fodder production areas occur in Africa (see Figure 11). These results follow the land supply curves closely: Latin America and Africa are still on the flat part of the land supply curve (like Canada in Figure 6), and therefore, land expansion is relatively cheap and no switch to agricultural intensification is made. This behavior is also seen in North America.
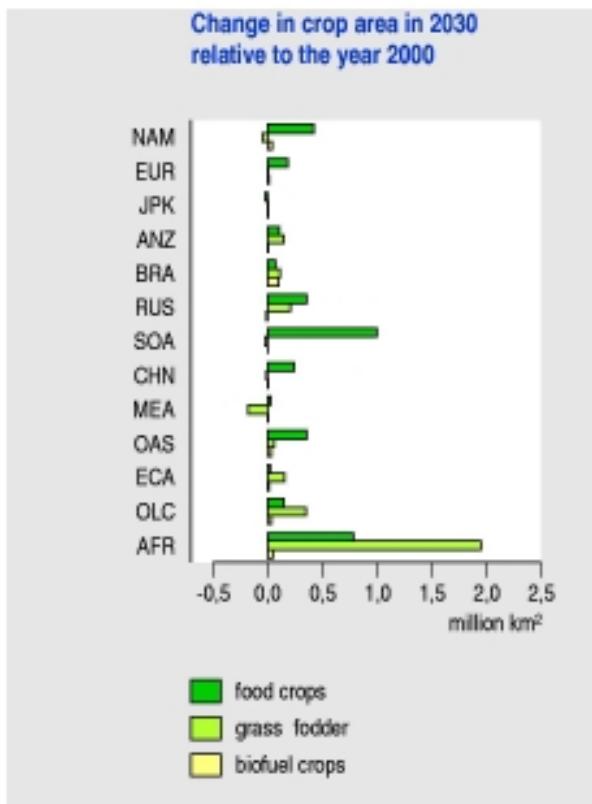
Figure 11. Change in arable land area and pastureland in the baseline scenario between 2000 and 2030 for different regions. [2]

South Asia (India) also shows an increase of arable land, but here, negative feedbacks from climate are playing an important role. Climate change is an aggregate effect of land-use emissions and energy related emissions. As far as land-use is concerned, other greenhouse gases than carbon dioxide play the bigger role. Besides animal husbandry, methane emissions are associated with paddy rice production and to a lesser extent with emissions from manure. Other land-use processes are of minor concern. The trend in land-use related CO_2 emissions is upwards, due to land clearing for agriculture, only

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[2] NAM = Northern America (Canada, USA and Mexico), EUR = EU 27 + Former Yugoslavia, JPK = Japan and Koreas, ANZ = Australia and New Zealand, BRA = Brazil, RUS = Russia, SOA = South Asia, mainly India, CHN = China, MEA = Middle East, OAS = Other Asia, ECA = Former USSR excl. Russia, OLC = Other Latin America and AFR = Africa.

partly compensated for by enhanced uptake as a result of rising atmospheric CO_2 concentration (CO_2 fertilization). The irregular profile over time reflects changing historical deforestation rates, which are not easily tracked by the model dynamics (the model chooses locations of land expansion on the basis of productivities).

Contrary to energy and industry sources, non-OECD groups are and remain dominant in land-use related emissions (Figure 12). Together with emissions from energy and industry, as simulated by the energy model of IMAGE (TIMER; Van Vuuren et al., 2007), total greenhouse gas emissions rise from 11.2 GtC-equivalent to almost 20 GtC-eq in 2050. Land-use changes make up roughly one fifth of the global total in 2050.
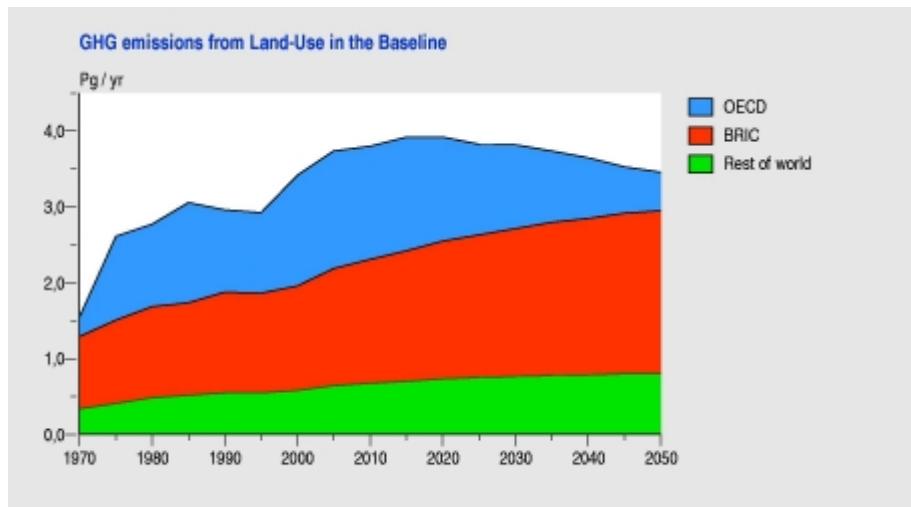
Figure 12. Greenhouse gas emissions from land-use change for the three aggregated regions (see Figure 9w).

The resulting temperature increase and changes in precipitation patterns (Figure 13) will have an impact on crop yield. However, these impacts are different per region: in higher latitudes the length of the growing season is increasing, leading to higher yields (Figure

14). Combined, with higher CO_2 levels and therefore faster plant growth (CO_2 fertilization), the impact of climate change at higher latitudes is positive in the first decades. Only at higher temperature increases (more than 2°C) the impact of climate change on the agricultural sector becomes negative (IPCC, 2007).
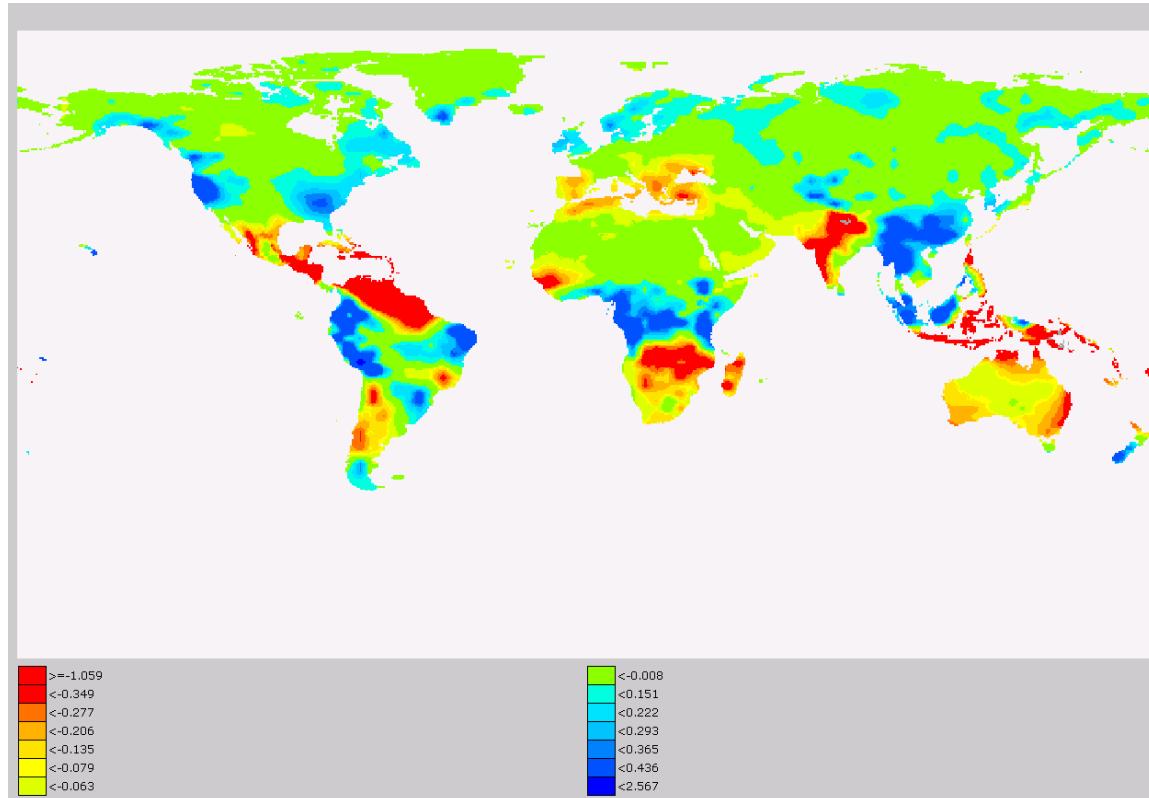
Figure 13. Absolute change in mean annual precipitation between 1990 and 2050 (in mm per day).

However, the climate impact is less positive in regions where more droughts are to be expected (Figure 13). In those regions, negative yield impacts are to be expected, already on the short term. South Asia is one of those regions, where the yield impact is expected to be negative. In Figure 14, the yield impacts of climate change are depicted in the different regions, confirming the negative impact of climate change for South Asia. This

IMAGE result, iterated with LEITAP, decreases the average yield in LEITAP. Within

LEITAP this decrease in yield leads to an increase in investments, a small increase in

prices (decreasing consumption) and a small increase in land use.
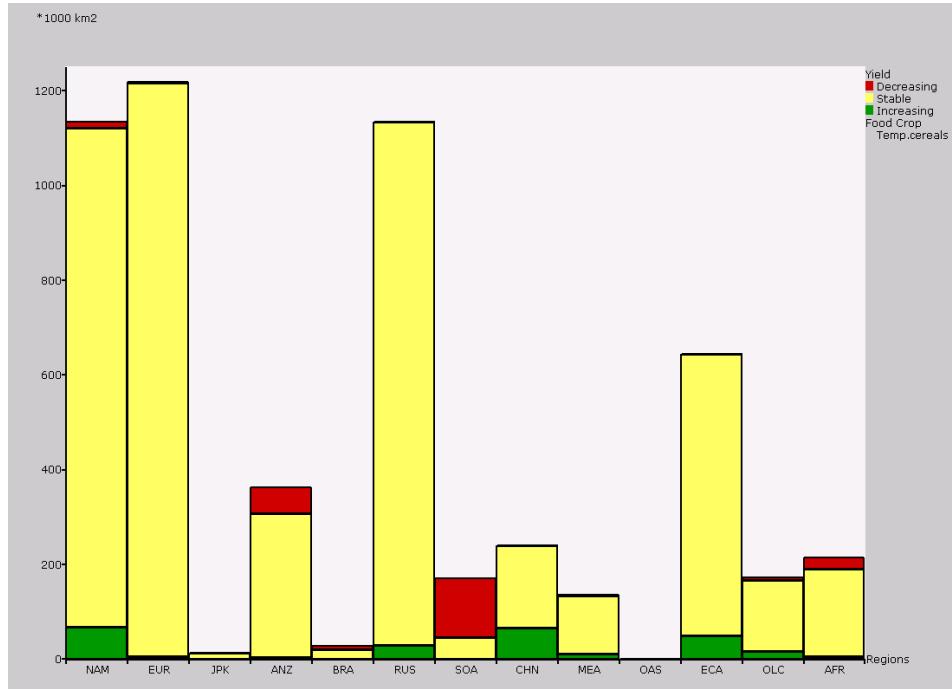
Figure 14. Area with decreasing (red), stable (yellow) and increasing (green) crop yield of wheat in 2050 relative to 1990. Area refers to the entire potentially available crop area.

6. Sensitivity to Land Supply Curves

In the projection described above, we used the LEITAP model with land supply curves

based on IMAGE data as described in Section 4. Inclusion of the land supply curve in the

model affects the overall production level of the agricultural sector as well as its regional

distribution compared with the model without the land supply curve. Here, we analyze to

what extent the inclusion of such a land supply curve influences the results of a baseline as described above.

Figure 15 shows the change in land use, production and intensity in two different model runs with and without an endogenous land supply curve for selected regions. Globally, the overall agricultural production increase is smaller in the model version without land supply curves than in a run including the land supply curve as described in Section 4. Moreover, the degree of intensification is higher in the model version without land supply curves. Introducing a land supply curve causes a higher production level and a lower level of intensification (Figure 15). Endogenous land use (model version with land supply curve) implies lower pressure on land prices and a decrease of the world price of agricultural products.

There are regional differences in the agricultural production and land use intensity development in different regions in a case of endogenous (with land supply curves) and exogenous agricultural land supply (no land supply curves) given a growing demand for agricultural products due to economic and population growth. In the case of endogenous land (with supply curves), agricultural production is especially higher and land use intensity is lower in those regions where land is abundant or unconstrained, such as Brazil and Canada (Figure 6). An increase in demand leads to a relatively large increase in land area and a smaller increase in land price compared to a case without land supply curves (exogenous land supply). The lower increase in land price leads to lower prices for agricultural products and therefore to an additional increase in demand (expansion

effect). The increased demand leads to an increase in production. The lower land price relative to the price of other production factors in the endogenous land scenario implies that producers substitute less land for other production factors (e.g. capital). This means that the intensification is less in the endogenous land scenario (Figure 15).
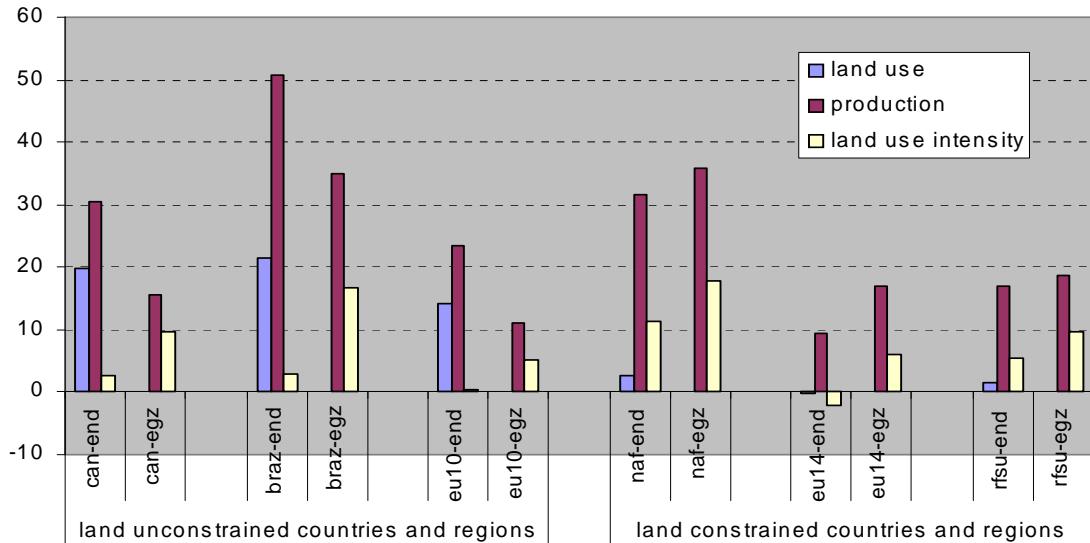
Figure 15. Agricultural land, production and land intensity development (% changes) in different regions production when the agricultural land is endogenous ("end"; a land supply curve is used) and "exogenous ("egz"; land supply is fixed per region).

However, in land-scarce or land-constrained countries, such as the EU15, the possibilities to increase agricultural land are less and therefore the relative decrease in land prices is lower than for land abundant countries. Therefore, prices of agricultural products from land scarce countries increase relatively compared with the prices of agricultural products from land abundant countries, which leads to a loss in market share in the domestic and world markets (substitution effect). The expansion effect is positive for all countries. The

substitution effect is positive for land abundant and negative for land scarce countries.

Endogenous land leads therefore always to an increase in production for land abundant

countries and it varies for land scarce countries. For countries on the steep part of the land

supply curve (Figure 7), with high income levels (lower prices do not lead to a high

increase in domestic food demand) and open markets (large exports or imports) the

substitution effect will be higher than the expansion effect and production is expected to

decrease. Figure 15 demonstrates this is the case for North Africa (NAF) and the EU15

countries ("old" member states of EU). For these land scarce countries the agricultural

production and land use intensity might be lower when the agricultural land is

endogenous due to deteriorating competitiveness (Figure 15).

The land supply curve parameters were estimated using biophysical data generated by the

IMAGE model. Such data as well as the resulting curve are surrounded with uncertainty.

Here, we further analyze the robustness of the simulation results with regard to the

parameters of the land supply curve. We assume that the asymptote (Figure 4) of the land

supply curve is estimated with an error of $\pm$ 2.5%. We run the simulation experiments

with the asymptote 2.5% lower and 2.5% higher than estimated and check the simulation

results concerning land supply and the real land rental rate.[3]

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[3] Before running the simulation experiments, we have to restore the initial benchmark
equilibrium situation on the land market when the asymptote "a" is changed. We have
assumed that real land rental rate is the same as the initial real land rental rate in the
model with estimated asymptote and we adjust the parameter "b" of the land supply
function to achieve the equilibrium situation for the new asymptote. This leads to steeper
land supply function when the asymptote is reduced and to flatter land supply function
when the assumptive increases.

Table 1 shows the impact of shifting the land asymptote on land use and the rental rate for three countries that have a different position on the land supply curve. Canada (Can) is a land abundant country (less than 20% of all available land is used; Figure 6), land is relatively scarce in North Africa (NAf) and the Rest of the Former Soviet Union (rFSU). North Africa and Rest of the Former Soviet Union use a similar percentage of agricultural land in total available area (97.1% and 95.2% respectively). However, the land supply curve is much steeper for North Africa than for Rest of the Former Soviet Union.

A decrease in total available land of -2.5% leads to an increase in land rental rate and a decrease in land use in all three cases. In the land abundant country Canada the shift in asymptote hardly affects land use and the related land price as there still is land available (Table 1). In contrary, for the land scarce country (NAf), a decrease of the asymptote by 2.5% leads to a decrease in agricultural area by 2.2% and an increase in land price by 33%. For Rest of the Former Soviet Union these percentages are more moderate and equal to 0.7% and 12%, respectively. This moderate response can probably be explained by the shape of the curve, which is less steep than the curve of North Africa.

Table 1. Simulation results with the shifted asymptote of the land supply curve: percentage change of the land supply and the real land rental rate compared with the results obtained for estimated land supply curve.

	Can-2,5	Can+2,5	rFSU-2,5	rFSU+2,5	NAf-2,5	NAf+2,5
Land use	-0.05	0.04	-0.71	0.63	-2.20	2.00
Land rental rate	0.17	-0.16	12.10	-10.20	33.75	-27.20

This analysis shows the importance of assumptions on the land supply curve, especially in regions where the remaining availability of land is scarce and the further increase of agricultural land is on the steep part of the land supply curve. Therefore, more sources to determine the shape of the land supply curve should be considered to determine the robust outcome of our introduced modeling approach.

7. Discussion

This chapter has presented a coupling of an economic and a biophysical model, with the aim to be able to quantify and analyze the long-term socio-economic and environmental consequences of different scenarios. The methodology is innovative as it combines state of the art knowledge from economic and biophysical sources. First, the treatment of agriculture and land use is improved in the economic model. For example, information from the OECD Policy Evaluation Model (PEM) was incorporated to improve the agricultural production structure. The new land allocation method that was introduced takes into account the variation of substitutability between different types of land use. The introduction of a land supply curve gives a better representation of the conversion of idle land to productive land or the other way while given consideration to the level of intensification. Secondly, the adapted economic model is linked to the biophysical-based integrated assessment model IMAGE allowing feedbacks of heterogeneous information of land productivity to the economic framework.

In the link of an economic with a biophysical model we profited from the strengths of both models. The economic model captures features of the global food market, including relations *between* world regions, whereas the bio-physical model adds geographical explicit information on crop growth *within* each world region. The simulation experiments in Section 6 shows that the shape of the land supply curve and the current position of the region on its land supply curve has very important impact on simulation results. If land supply curves are introduced and the world economy is expanding, agricultural prices decrease and agricultural production and trade increase more than in the case of an exogenously determined agricultural land. Moreover, the implications for counties where the land is scarce and land is abundant may be the opposite. There are two main effects; firstly, the introduction of endogenous land supply leads to an increase in agricultural demand due to lower land and agricultural product prices. This might be called the positive expansion effect. Secondly, there is a substitution effect that is positive for land abundant countries and negative for land scarce countries as the land and agricultural product prices decease relatively faster for land abundant than for land scarce countries. Therefore, endogenous land leads in land abundant countries to an expansion of agricultural production whereas this might be the opposite for land scarce countries if the substitution effect dominates the expansion effect. This implies in land abundant countries that the increase in the rental rate for land is less than with a fixed land supply. This gives these countries a comparative advantage, which leads to more exports and less imports. The reverse is true for countries where the land is scarce. The introduction of an endogenous land supply curve has therefore important implications for analyses of the

impact of agricultural and trade policy reforms as it changes the impacts for the different countries.

In our current approach we defined the shape of the land supply curve by using yields of the IMAGE model. For this, a crucial assumption is that the inverse of the yield is determining the land rental rate. This assumption is well in line with Ricardo's Principles of Political Economy and Taxation (Ricardo, 1817), where Ricardo stated that there will be no rent on land if land is fertile and abundantly available (just like the use of air and water is without any charge as long as they are inexhaustible and at every man's disposal). However, land does not have the same properties, it is not unlimited in availability and certainly not uniform of quantity, and therefore, more rent will be paid for the use of it (Ricardo, 1817). This logic lies behind the assumption of our land supply curve that is the inverse of the marginal yield of land within a region, being an approximation of the quality of land. However, in that sense our approximation of the land supply curve is very important in determining the outcome of our models. In Section 6, we showed our assumptions are of most importance in regions where land is scarce and especially, in regions where land is scarce and the land supply curve shows a steep increase towards its asymptote (North Africa). For these regions, more approximations of the land supply curve would help in determining the robustness of our results

Nevertheless, the methodology introduced in this Chapter shows the importance of including environmental consequences in trade policy analyses. Where poverty alleviation may come in reach because of certain policy measures, other policy targets on

climate and biodiversity may become impossible to meet due to the same measures. We strongly argue to use modeling frameworks that can assess both sides of the story. Not only both stories need to be told to policy makers, also the environmental feedback may hamper the economic prospects that are shown by economic models alone.

Here, we have not quantified the environmental costs in LEITAP yet. Therefore, our modeling framework is only used to show the economic consequences on one side and the environmental consequences on the other side. Through the iteration of LEITAP and IMAGE and the use of land supply curves in LEITAP, we feel a necessary improvement to LEITAP in including environmental circumstances has been made, but we have not assessed the possibilities to invest in environmental services in the LEITAP model. This is the next crucial step in linking an economic tool with a bio-physical tool.

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Appendix A. Regional breakdown of LEITAP and IMAGE

LEITAP regions	IMAGE regions	Original GTAP regions
Canada	Canada	Canada.
USA	USA	United States.
Mexico	Mexico	Mexico.
Rest of Central America	Central America	Rest of North America; Central America; Rest of FTAA; Rest of the Caribbean.
Brazil	Brazil	Brazil.
Rest of South America	Rest of South America	Colombia; Peru; Venezuela; Rest of Andean Pact; Argentina; Chile; Uruguay; Rest of South America.
North Africa	Northern Africa	Morocco; Tunisia; Rest of North Africa.
Central Africa	Eastern Africa	Rest of SADC; Madagascar; Uganda; Rest of Sub-Saharan Africa.
	Western Africa	
South Africa	Southern Africa	Botswana; South Africa; Rest of South African CU; Malawi; Mozambique; Tanzania; Zambia; Zimbabwe.
Netherlands	Western Europe	Netherlands.
EU14		Austria; Belgium; Denmark; Finland; France; Germany; United Kingdom; Greece; Ireland; Italy; Luxembourg; Portugal; Spain; Sweden.
Rest of Western Europe		Switzerland; Rest of EFTA.
EU10	Central Europe	Cyprus; Czech Republic; Hungary; Malta; Poland; Slovakia; Slovenia; Estonia; Latvia; Lithuania.
Bulgaria, Romania		Bulgaria; Romania.
Rest of Europe		Rest of Europe; Albania; Croatia.
Turkey	Turkey	Turkey.
Rest of Former Soviet Union	Ukraine region	Rest of Former Soviet Union.
	Kazakhstan region	
Russian Federation	Russia	Russian Federation.
Middle East	Middle East	Rest of Middle East.
South Asia	South Asia	Bangladesh; India; Sri Lanka; Rest of South Asia.
Korea	Korea region (incl. Democratic Republic of Korea)	Republic of Korea
China	East Asia (incl. Mongolia)	China; Hong Kong; Taiwan.
South-East Asia	Southeast Asia	Rest of East Asia; Malaysia; Philippines; Singapore; Thailand; Vietnam; Rest of Southeast Asia.
Indonesia	Indonesia	Indonesia.
Japan	Japan	Japan.
Oceania	Oceania	Australia; New Zealand; Rest of Oceania.

Appendix B. Sector disaggregation in LEITAP

Sectors in LEITAP	Original GTAP sectors
Rice	Paddy rice; Processed rice.
Wheat	Wheat.
Cereal grains nec	Cereal grains nec.
Oil seeds	Oil seeds.
Sugar cane and beet, sugar	Sugar cane, sugar beet.
Vegetables, fruit, nuts	Vegetables, fruit, nuts.
Other crops	Plant-based fibers; Crops nec.
Cattle,sheep,goats,horses	Cattle,sheep,goats,horses.
Animal products nec	Animal products nec.
Raw milk	Raw milk.
Wool, sil-worn cocoons	Wool, silk-worm cocoons.
Meat:cattle,sheep,goats,horse	Meat: cattle,sheep,goats,horse.
Meat products nes	Meat products nec.
Dairy products	Dairy products.
Sugar	Sugar.
Rest of agro	Fishing; Vegetable oils and fats; Food products nec; Beverages and tobacco products.
Industry	Forestry; Coal; Oil; Gas; Minerals nec; Textiles; Wearing apparel; Leather products; Wood products; Paper products, publishing; Petroleum, coal products; Chemical,rubber,plastic prods; Mineral products nec; Ferrous metals; Metals nec; Metal products; Motor vehicles and parts; Transport equipment nec; Electronic equipment; Machinery and equipment nec; Manufactures nec.
Services	Electricity; Gas manufacture, distribution; Water; Construction; Trade; Transport nec; Sea transport; Air transport; Communication; Financial services nec; Insurance; Business services nec; Recreation and other services; PubAdmin/Defence/Health/Educat; Dwellings.

Appendix C. Estimation results of the land supply curve

	Agricultural land used[*] (%)	Price elasticity	Land rental rate in GTAP[**] (1000$/ha)	R^2
Canada	8.8	3.06	5.24	0.97
USA	50.7	0.71	10.20	0.91
Mexico	65.1	0.76	7.97	0.97
Rest of Central America	52.0	3.80	11.97	0.99
Brazil	32.6	3.95	1.27	0.99
Rest of South America	50.0	1.64	3.37	0.99
North Africa	100.0	0.00	3.81	0.98
Central Africa	49.5	0.62	0.57	0.99
South Africa	66.9	0.43	0.42	0.91
Netherlands	88.1	0.08	52.59	N.A.[***]
EU14	90.3	0.15	23.52	N.A.[***]
Rest of Western Europe	63.5	1.17	43.91	0.87
EU10	78.9	0.15	12.45	0.99
Bulgaria, Romania	95.2	0.15	15.14	0.99
Rest of Europe	75.1	1.76	8.73	0.98
Turkey	50.3	1.70	4.25	0.99
Rest of Former Soviet Union	92.5	0.02	1.87	0.99
Russian Federation	14.0	1.87	1.67	0.99
Middle East	100.0	0.00	2.44	0.93
South Asia	60.1	0.85	22.05	0.98
Korea	78.9	2.29	424.84	0.98
China	92.2	0.05	7.33	0.99
South-East Asia	27.7	6.46	20.54	0.99
Indonesia	24.6	5.97	18.19	0.99
Japan	78.9	2.29	156.97	0.95
Oceania	89.8	0.11	0.75	0.93

[*] Percentage of agricultural land use is calculated as a ratio of current agricultural land supply (use) to potentially available agricultural land (the land supply curve asymptote).
[**] Equal to land value in GTAP divided by land supply.
[***] Land supply curve for EU14 and The Netherlands was calibrated using Cixous, (2006) results. Because of biodiversity policies, agricultural land is scarce in the EU. This is situation is not depictured by biophysical data. Therefore, other data are used to estimate the land supply curve for the Netherlands and the EU14.