# Climate change and land-based activities: a review of economic models

Working Paper No. 34

CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS)

Gaspard Dumollard, Petr Havlík, Mario Herrero

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# Abstract

The dual relationship existing between land-based activities and climate change has long been established. Land-based activities are responsible for about 30% (IPCC) of global GHG emissions and are at the same time particularly impacted by climate change as they are strongly dependent on weather patterns. Although physical and technical considerations may help to investigate these two kinds of issues, economic considerations are crucial to understand how agricultural producers react to climate change and to climate policies. Quantitative economic models are appropriate tools to examine these interactions and to understand how they influence human activities and ecosystems. However, there are many different economic models with different characteristics regarding the way economies are modelled, the way climate change is considered in the models and the way GHG emissions are accounted for. All these specificities determine the type of uses that each model can be employed for. This paper describes the different characteristics and uses of 13economic models that are currently used to investigate issues concerning land-based activities and climate change.

### Keywords

Climate Change; Economic Modelling; Land-Based Activities; Land Use Change

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# Acronyms

| | |
|---|---|
| AIM | Asia-Pacific Integrated Model |
| CIM-EARTH | Community Integrated Model of Economic and Resource Trajectories for Humankind |
| ENVISAGE | ENVironmental Impact and Sustainability Applied General Equilibrium model |
| EPPA | Emissions Prediction and Policy Analysis model |
| FARM | Future Agricultural Resources Model |
| GCAM | Global Change Assessment Model |
| GLOBIOM | GLObal BIOsphere Management Model |
| GTAP | Global Trade Analysis Project |
| GTEM | Global Trade and Environment Model |
| IMAGE | Integrated Model to Assess the Global Environment |
| IMPACT | International Model for Policy Analysis of Agricultural Commodities and Trade |
| MAgPIE | Model of Agricultural Production and its Impact on the Environment) |
| MIRAGE | Modeling International Relationships in Applied General Equilibrium |

# Introduction

The work carried out under the aegis of the Intergovernmental Panel on Climate Change (IPCC) and gathered in the $4^{th}$ Assessment Report (IPCC 2007) has shown the growing evidence that climate is changing because of human activities. The projections presented in the 4th Assessment Report (IPCC, 2007) show a global warming between +1.1°C and +6.4°C (with important spatial variability) depending on socio-economic assumptions and prediction uncertainty. The same work has predicted changes in rainfall patterns and a rise in sea level as well. All these changes will have important consequences on ecosystems and indirectly on human activities relying on natural processes, like agriculture.

In this context, land-related activities (agriculture, forestry) and in particular the land use changes they trigger are one of the major contributors to greenhouse gases (GHG) emissions and to climate change.  The technical summary of the contribution of Working Group III to the 4th Assessment Report states that in 2004, agriculture represented 13.5% of global GHG emissions and forestry (mainly through deforestation) 17.4% of emissions. Agricultural emissions represented 47% of global Methane (CH4) emissions that are mainly due to ruminants' enteric fermentation and anaerobic degradation of crop residues in paddy fields; and 58% of global Nitrous Oxide (N2O) emissions mainly due to the production and the use of nitrogenous fertilisers for crop production.

Apart from GHG emissions and climate change predictions, many studies have focused on the impacts of climate change on human activities. It is projected that the sectors relying on natural processes will be particularly impacted, as it is the case for agriculture and forestry for example. Although direct impacts will probably be concentrated on a few sectors, the whole economy could be affected indirectly. In particular, climate change impacts could compromise food security in already fragile countries with serious socio-economic and political consequences.

In order to mitigate climate change and subsequent impacts, policies are being planned or already implemented at different levels of governance (international, national, local). On the international level for example, the United Nations Framework Convention on Climate Change (UNFCCC) is an international treaty that has been implemented to support climate policies (both mitigation and adaptation policies) on a multilateral basis.

The design and implementation of such climate policies require important expertise in physical and climate sciences on the one hand, but also in economic sciences on the other hand. Climate policies are supposed to alter the behaviour of economic agents (i.e. consumers, producers) so that they include climate considerations into their decision making. In order to understand the quantitative relations that exist between economic activities, climate change and climate policies, quantitative economic models constitute a well-suited framework for their analysis (ref). These models aim at representing the behaviour of economic agents and the processes of production and consumption, and have two main roles:

- The projection of the impacts of climate change and of mitigation policies on the economy. Climate change and climate policies are exogenously input in economic models in order to assess their effects.

- The quantification of GHG emissions: in this case, GHG emission baselines are an output of economic models. Indeed, the quantity of anthropogenic greenhouse gases that is emitted depends on the extent and on the nature of economic activities, which are determined by models.

Many agricultural economic models are currently used to carry out climate-related studies and each model presents its own specificities. These specificities influence simulation results and make each model more or less suited for carrying out specific types of analyses. As a result, the choice of a given economic model is the first important step of every modelling process. This article provides a comparative review of 13 economic models that are widely used to assess the link between economic activities, especially land-based activities and climate change. These models are presented in Table 1, along with the main institutions involved in their development. For each of them, a key reference is provided. The purpose of this review is to present the different economic modelling mechanisms on which the models are based as well as the methods used to couple economic, crop and climate modelling and to relate these characteristics with the use of the different models.

The first part aims to present the different methods used to model economic characteristics whereas the second part focuses on the link between the economic side of the models and climate change considerations, that is to say how GHG emissions are accounted for and how climate change impacts are input into the models. Finally, the third section aims at analysing the different research issues that are dealt with by the different models. Appendix 1 provides more detailed descriptions of the models covered in this review.

## Table 1: A list of the models considered in this study and key references

| Models | Main institutions involved | Key reference |
|---|---|---|
| Computable General Equilibrium models | | |
| AIM (Asia-Pacific Integrated Model) | NIES (National Institute for Environmental Studies), Japan | "Integrated Assessment Model of Climate Change: The AIM Approach", Matsuoka et al. (2001);"Long-Term GHG Emission Scenarios for Asia-Pacific and the World, Technological Forecasting and Social Change", Jiang et al. (2000) |
| CIM-EARTH (Community Integrated Model of Economic and Resource Trajectories for Humankind) | University of Chicago jointly with the Argonne National Laboratory | "CIM-EARTH: Framework and Case Study", Elliott et al. (2010C); "CIM-EARTH: Community Integrated Model of Economic and Resource Trajectories for Humankind, Version 0.1", Elliott et al. (2010A) |
| ENVISAGE (ENVironmental Impact and Sustainability Applied General Equilibrium model) | World Bank and FAO (Food and Agriculture Organization) | "The Environmental Impact and Sustainability Applied General Equilibrium (ENVISAGE) Model", van der Mensbrugghe (2008) |
| EPPA (Emissions Prediction and Policy Analysis model) | MIT (Massachusetts Institute of Technology) | "The MIT Emissions Prediction and Policy Analysis (EPPA) Model: Version 4", Paltsev et al. (2005) |
| FARM (Future Agricultural Resources Model) | USDA (United States Department of Agriculture) | "World Agriculture and Climate Change: Economic Adaptations", Darwin et al. (1995); "FARM: A Global Framework for Integrated Land Use/Cover Modeling", Darwin et al. (1998);"The land-use effects of a forest carbon policy in the US", Wong and Alavalapati (2003) |
| GTAP (Global Trade Analysis Project) | Purdue University | "Structure of GTAP", Hertel and Tsigas (2000, updated in 2010, draft version); "The opportunity cost of land use and the global potential for greenhouse gas mitigation in agriculture and forestry", Golub et al. (2009) |
| GTEM (Global Trade and Environment Model) | ABARES (Australian Bureau of Agricultural and Resource Economics and Sciences) | "The Global Trade and Environment Model: A Projection of Non-Steady State Data Using Intertemporal GTEM", Pant et al. (2002) |
| IMAGE (Integrated Model to Assess the Global Environment) including the LEITAP model | PBL (Netherlands Environmental Assessment Agency) | IMAGE is described in detail on the website of the PBL: http://themasites.pbl.nl/tridion/en/themasites/image/ |
| MIRAGE (Modeling International Relationships in Applied General | IFPRI (International Food Policy Research Institute) and CEPII (Centre d'Etudes Prospectives et | The MIRAGE model is documented in a wiki : http://www.mirage-model.eu/miragewiki/index.php/Main_Page |

| | | |
|---|---|---|
| Equilibrium) | d'Informations Internationales) | "Modeling the global trade and environmental impacts of biofuel policies", Bouët et al. (2010) |
| Partial Equilibrium models | | |
| GCAM (Global Change Assessment Model) including the AgLU model (Agriculture and Land Use model) | University of Maryland, US Department of Energy, Pacific Northwest National Laboratory | GCAM is documented in a wiki: http://wiki.umd.edu/gcam/index.php?title=Main_Page<br>More details can be found in the following papers: "GCAM 3.0 Agriculture and Land Use: Technical Description of Modeling Approach", Wise and Calvin (2011);"GCAM 3.0 Agriculture and Land Use: Data Sources and Methods", Kyle et al. (2011) |
| GLOBIOM (GLObal BIOsphere Management Model) | IIASA (International Institute for Applied Systems Analysis) | "Global Land-Use Implications of First and Second Generation Biofuel Targets", Havlík et al. (2010) |
| IMPACT (International Model for Policy Analysis of Agricultural Commodities and Trade) | IFPRI (International Food Policy Research Institute) | "International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT): Model Description", Rosegrant et al. (2012) |
| MAgPIE (Model of Agricultural Production and its Impact on the Environment) | PIK (Potsdam Institute for Climate Impact Research) | "Global Food Demand, Productivity Growth, and the Scarcity of Land and Water Resources: a Spatially Explicit Mathematical Programming Approach", Lotze-Campen et al. (2008) |

# Modelling land-based activities: a land-use perspective

The models reviewed in this paper can be subdivided along two main “dimensions”: i) the type of representation of the economy: some models represent all sectors, while others deal only with land-based activities, and ii) the type of mathematical formulation used for the implementation of the models: some models are indeed based on the resolution of an equation system and others are based on an “optimization program”.

## Representation of the economy: CGE vs. PE models

Considering the first dimension, the models from our sample can be divided into two groups, Computable General Equilibrium (CGE) models on the one hand, which give an exhaustive representation of the economy and Partial Equilibrium (PE) models on the other hand, which describe a specific segment of the economy (i.e. only one or a few sectors). CIM-EARTH, ENVISAGE, EPPA, FARM, GTAP, GTEM and MIRAGE are CGE models. AIM and IMAGE are modelling frameworks encompassing a CGE model. For IMAGE, the CGE is called LEITAP and is an extended version of GTAP. GLOBIOM, IMPACT and MAgPIE are PE models. GCAM is a modelling framework encompassing two PE models, one for the energy sector and the other one, the Agriculture and Land Use model (AgLU), for land-based activities.

### Market equilibrium models and mathematical formulation

Both these two types of models are market models; this means that each type of goods is exchanged between the different economic agents (producers and economic agents) on a specific market, which mechanisms lead to the equality between supply and demand. This situation is called market equilibrium. The basic mechanisms of market models are strongly inspired by the neoclassical theory, in particular the producer and consumer choice theories, as well as the general equilibrium theory (cf. Kenneth and Debreu, 1954). Neoclassical theories are based on many theoretical assumptions among which the most important one is probably the hypothesis of rationality of economic agents (cf. Arrow, 1987). This hypothesis states that producers aim at maximizing their profit and consumers aim at maximizing their utility (the utility of a consumer is a quantification of the satisfaction resulting from his consumption). However, the present section is not aimed to describe in detail theoretical aspects of economic modelling (readers could refer to general microeconomics books[1] for this purpose) but rather to present in a concrete way the main characteristics of CGE and PE models.

There are two main different ways to model market mechanisms, from a mathematical specification perspective, both ways are represented in the set of models analysed in this review:

[1] For example, “Microeconomic theory”, Mas-Colell et al. (1995).

- Square systems of equations: in such systems, there are as many variables as equations, which results in a unique solution for the system. The “solution” of an equation system is a vector of values for the different variables that verifies the equations when input into the system. The way equation models are formulated varies across model types (CGE vs. PE) and model refinements. However, every model contains at least supply and demand equations that give the quantities of goods produced and demanded in function of some variables and parameters[2] as well as market equations (cf. the next section about CGE for further details). Market equilibrium is enabled by the adjustment of variables. All CGE models are based on this kind of representation and the IMPACT model, which is a PE model is also based on an equation system.
- Optimization approach: in this type of models, the simulation process is based on the maximization or the minimization of an objective variable subject to various constraints. These constraints include inter alia food balance and land supply (in)equations. The solution for this system consists in the set of variables (e.g. prices, land allocation) that optimizes the objective function while respecting the constraint equations and inequations. GLOBIOM, MAgPIE and AgLU follow an optimization approach.

This “mathematical” dichotomy between models is certainly as relevant as the dichotomy between CGE and PE models, which almost match in the context of this review, with the exception of IMPACT. For a simple and clear example of typology of agricultural economics models, please refer to Minot (2009). However for the sake of clarity, the next two sections present the main characteristics of CGE and PE models.

### Computable General Equilibrium models

Computable General Equilibrium (CGE) models make the synthesis between the general equilibrium theory and empirical economic observations. The general equilibrium theory describes the theoretical equilibrium state of an economy resulting from the theoretical (neoclassical) behaviour of economic agents. CGE models aim indeed to represent the different agents of an economy that are producers, consumers (and governments) and the different flows (goods transaction, factor remuneration[3]…) occurring between these agents. CGE models aim at modelling the economy as a whole, including the identity existing between factor remuneration resulting from production activities and the aggregated income used for consumption (and investment). In order to enable this macroeconomic “closure”, the whole economy must be modelled, that is to say all sectors (though in a more or less disaggregated way). This is why these models are called “general” equilibrium models.

Another notable characteristic of CGEs is that all flows are (normally) expressed in monetary terms. This enables the aggregation of flows that could not be carried out on the basis of physical values (different sectors producing different types of goods can then be aggregated, for example). This is important in climate change studies as carbon emissions accounting should be bound to physical driving variables (cf. section about emission accounting).

[2] Variables are endogenous to the equation system whereas parameters are exogenous values.

[3] i.e. wages and capital gains

*The system of equations in CGE models*

CGE models, as explained above, are square systems of equations. More precisely, equations are defined for each good (i.e. each sector) and each region of the model and include the main types of equations:

- Supply equations: give supply (in monetary terms) as function of output and input prices (inter alia).
- Demand equations (for final consumption goods): determine the final demand (in monetary terms) as function of prices and income.
- Production factors and intermediate inputs demand and supply equations: also as function of prices.
- Market equations: supply and demand are set equal on every market (i.e. final goods, intermediate inputs, factors), considering international trade.
- Macroeconomic closure equations: consumer income comes from the remuneration of production factors (wages, dividends).

Supply and demand equations are obtained through the resolution (prior to the implementation of the model) of profit and utility optimization programs (respectively for consumers and producers) according to the neoclassical theory.

*Profit maximization and production function in CGE models*

The determination of supply in CGE models is based on a profit maximization program (cf. Lofgren et al. 2002). For each region defined in the model, a set of representative firms is defined to represent the whole economy. There is one firm for each sector (i.e. each commodity produced) and these firms aim at maximizing their profits subject to a production function constraint. For a given firm, this production technology defines the potential level of production which is possible to reach when using a given combination of production factors and intermediate inputs[4] (Appendix 2 presents the production function used in the MIRAGE model as an example). In the case of agriculture, production factors consist mainly of cropland, capital goods (machinery, farm buildings…), labour and the intermediate inputs consisting mainly of fertilisers, pesticides and seeds (plus animal feed for the livestock sector).

The profit maximization program consists of determining the optimal output and input levels (that are both endogenous[5] in CGEs) for each sector so that profit is maximized. Supply equations are derived from this maximization program and give the volume of supply, in

[4] Production factors, also called primary factors of production, consist of "stocks" of resources such as capital, labor or land that enable production of a given good. An intermediate input is a good that is used as an input in the production of other goods, intermediate inputs either become part of the final product, or are simply used to enable the process.

[5] An endogenous variable has its value determined by the model itself when it is run; as opposed to exogenous variables whose values are determined outside of the model.

monetary terms, as a function of output and input prices and as a function of some parameters (notably price elasticities[6]).

*CGE models and climate studies*

CGE models are able to take into account economy-wide effects of climate change and climate policy (cf. Laborde Debucquet, 2011), that is to say not only effects on the primarily affected sectors (i.e. land-based activities) but also on the rest of the economy through indirect income and price effects. Indeed, negative impacts on the agricultural sector can affect the aggregated income (i.e. the GDP) and then affect the overall consumption and all the sectors. Although this phenomenon is probably of a limited extent in developed countries for which the share of agriculture in the GDP is low, it can be significant in some developing countries. However, the agricultural economics models addressed in this review are probably not the best ones to perform GDP projections; they rather provide sensitivity analyses on GDP that enable to compare different scenarios with each other rather than providing absolute projections.

In a similar way, impacts on agriculture can affect other sectors through inputs and factors prices. Indeed, inputs and factors are distributed across all sectors through markets (input goods can also be sold as final consumption goods but factor markets are specific), variations in the demand from the agricultural sector affect factors and inputs prices for all sectors.

CGEs have been widely used during the last decades to carry out policy analyses, in particular trade policy and food policy analyses. More recently, CGE models have been used to work on climate-related issues. Further details about standard CGE characteristics can be found in Lofgren et al. (2002).

## Partial equilibrium models

On the contrary of CGE models, partial equilibrium (PE) models represent (endogenously) only a part of the economy – i.e. only one or a few economic sectors, in the present case land-based activities (i.e. cropping activities, livestock, and forestry). As a consequence, there is no endogenous link between factors payments (wages and dividends) and the aggregated income as there are no factor markets. Moreover, there are no endogenous feedback effects from changes in the land-based sectors on the other sectors. As a result, PE models are not able to carry out economy-wide analyses. Aside from these similarities, the PE models considered in this review do not constitute a homogenous set of models and differ quite extensively in terms of implementation.

*IMPACT, an equation model*

IMPACT model is an equation model, similar to CGEs. But, in contrast to CGEs, supply, demand and market clearance equations are only defined for a few final goods, namely crops and animal products. There are neither factor markets nor intermediate input markets (with the exception of the share of crop products that is used to feed animals). Thus, factor and

[6] Price elasticities are empirical parameters that describe how supply is reacting to changes in prices.

input prices are exogenous in IMPACT. The second important difference from CGE is that variables in IMPACT are expressed in quantities, not in monetary values. This actually simplifies the way agricultural yields input into the model (cf. section about the intensive margin)

More concretely, in IMPACT, there are two types of supply equations – giving harvested areas[7] and crop yields. These equations are written for each region and for each crop or animal product(cf. Rosegrant et al. 2011):

- Equations for harvested areas:

$$Area_{tni} = \alpha_{tni} * (Output\ prices_{tni})^{\varepsilon_{iin}} * \prod_{j\neq i}\left(Output\ prices_{tnj}\right)^{\varepsilon_{ijn}} * (1 + gA_{tni}) - \Delta AC_{tni}(WAT_{tni})$$

- Equations for crop yields:

$$Yield_{tni} = \beta_{tni} * (Output\ prices_{tni})^{\gamma_{iin}} * \prod_{k}(Input\ prices_{tnk})^{\gamma_{ikn}} * (1 + gCY_{tni}) - \Delta YC_{tni}(WAT_{tni})$$

(t=time step, n=region, k=production factors or inputs and i and j=crop indices. α and β are parameters to be calibrated, ε and γ price elasticities.)

As far as it is concerned, the demand depends on output prices and on the aggregated income, which is exogenous in PE models.

*The optimization approach*

The other three PE models presented in this paper, namely AgLU (in GCAM), GLOBIOM and MAgPIE are based on an optimization approach. Implementation of such models requires the definition of an objective function, which defines the variable to maximize or minimize in function of some other variables of the models.

In all these models, the objective variable is expressed in monetary terms as are all terms in the objective function, this is necessary to allow for aggregation. Other non-economic costs, for example environmental damages, can be accounted for in the objective function at the condition of being expressed in monetary terms as well. The objective functions are not same in all models. Indeed, in GLOBIOM, global welfare[8] is maximized (cf. Havlík et al. 2010), in MAgPIE the global cost function (including mainly but not only production costs) is minimized (cf. Lotze-Campen et al. 2008) and in AgLU the profit of the producers is maximized (cf. GCAM wiki). However, in AgLU the profit resulting from the cultivation of one given crop in one given region is not defined by a unique value but instead by a probabilistic distribution of profit (cf. Wise and Calvin, 2011). This has an impact on land-use change modelling (cf. section about constraints to land-use change).

7 Harvested areas account for multiple harvesting, which means for example that plots of land that are harvested two times in a year are accounted for twice.

8 The global welfare is the sum of the producers' and consumers' surpluses. The producers' surplus corresponds to the profit they make. The consumers' surplus corresponds to the difference between their willingness to pay for buying goods and the amount they actually pay for getting them.

Apart from the objective function, optimization models are based on a series of constraints that endogenous variables must respect. These constraints can be expressed either in the form of equations or more commonly in the form of inequations. The inequations are not necessarily binding (i.e. the left-hand term can differ from the right-hand term, as long as the inequation is respected). As a consequence, there can theoretically be as many inequations as wanted by the modeller, the supernumerary information (non-binding inequations) do not influence the model resolution. However, the introduction of mutually exclusive constraints (e.g. two inequations that are impossible to respect simultaneously) will lead to infeasibility problems. Another characteristic and advantage of the optimization approach is that constraints (in)equations can be expressed in non-monetary units, which eases considerably the handling of physical quantities such as yields or land acreages (cf. section about land-use representation).

In these models, the objective function and the constraints are formulated as linear combinations of variables; this approach is sometimes referred to as linear programming. The basics of linear programming applied to sectorial modelling are well described in McCarl and Spreen (1980).

There are various types of constraints that can be found in the three PE models described in this review but common constraints include (cf. Havlik et al. 2010 for GLOBIOM and Lotze-Campen et al. 2008 for MAgPIE):

- Food supply constraints: which ensure that food production is sufficient to achieve minimum nutrition thresholds (in calories per capita).
- Wood and bioenergy constraints: which ensure that demand for wood and bioenergy can be satisfied.
- Resource constraints: limits the acreage of land available for agricultural production and the volume of water available for irrigation. Some inequations can also constrain land conversion from one use to another (cf. section about constraints to land-use change).

The mechanism of optimization for all three models is mostly based on land-use allocation between the different land-based activities (i.e. crops, pasture, forestry), that is to say, the most important endogenous lever to vary the objective variable are land use variables. The spatially disaggregated representation of land allocation featured in GLOBIOM and MAgPIE enables a higher relevancy of this mechanism. (cf. sections about simulation processes and about land-use representation).

Despite all their differences, there is a theoretical correspondence between equation models and optimization models as under certain conditions market equilibrium conditions are supposed to lead to maximization of global welfare. This equivalence is described in McCarl and Spreen (1980).

After this description of the basic mechanisms driving models' resolution, the next section describes the different steps occurring during simulation processes in more detail.

## Simulation processes and input scenarios

Simulation processes are not the same in all models; however they all follow the same general scheme. Indeed, all simulations start with a calibration step, which is followed by one resolution step in the case of static simulations or several successive resolution steps in the case of dynamic simulations.

### Calibration as a preliminary step

The calibration step consists of replacing endogenous variables with empirical values in the equations for a given reference year and to determine free parameters so that equations are verified. This allows reaching the so-called reference equilibrium state. The formerly free parameters are then fixed when simulations are run. Note that some parameters are not calibrated but are instead replaced by empirical values found in the literature; this is the case for most price elasticities, for example.

Although the principle of calibration is universal, it is not carried out in the same way in all the models. In CGEs, the calibration step is based on empirical data taken from Social Accounting Matrices (SAM, cf. Lofgren et al., 2002). A SAM contains the different economic flows (final and intermediate consumption of a given commodity, factor payments…) occurring between the different agents of an economy (consumers, producers, administrations) in monetary terms for a given country and a given year. All CGE models mentioned in this review (and certainly most of the existing CGE models) are based on the GTAP database[9] that includes SAM for 129 regions (countries or groups of countries) in its 8th version (2012). The use of monetary values enables to aggregate flows for given "broad" sectors (e.g. agriculture) whereas information in physical terms would have to be disaggregated for each variant of goods existing (e.g. crop 1, crop 2…) and for each sector, which would require vast amounts of information and would make the treatment of this information by a model on the economy-wide level very difficult. However, CGE models can be augmented to keep track of certain physical quantities (cf. section about direct emissions accounting).

In contrast, the calibration in PE models is based on physical quantities. In particular, agricultural partial models are based on production data (yields, areas, productions). FAOSTAT[10] data are used in all the four partial models to help with calibration. FAOSTAT presents exhaustive time series for production data, though only at country level. Although this is sufficient for IMPACT, the three other models are defined at a lower spatial scale and so should be the data used for calibration. AgLU is based on regions resulting from the crossing of a small number of geopolitical regions with agro-climatic regions (AEZ, cf. section about land-use representation). Production data for these regions are obtained from FAOSTAT data adjusted thanks to some (complementary) GTAP data. GLOBIOM and MAgPIE are defined on a highly disaggregated spatial level; therefore they require disaggregated data for the calibration. There is no complete database that gives observed data (like FAOSTAT) on such a low spatial scale. However, some statistical downscaling methods enable to disaggregate data. For example, the SPAM database[11], used in GLOBIOM,

[9] GTAP project website: https://www.gtap.agecon.purdue.edu/

[10] http://faostat3.fao.org/home/index.html

[11] http://mapspam.info/about/

estimates crop distribution and yields on the basis of a cross-entropy[12] method. Yields can also be determined thanks to crop models (cf. section about the intensive margin); this is the case in GLOBIOM and MAgPIE.

### Static vs. dynamic simulations

After the calibration step is completed, simulations can be carried out. There are two types of simulations that are carried out in the reviewed models: static simulations and recursive-dynamic simulations.

Static simulations consist of applying a “shock” to the reference year equilibrium, that is to say to input a shift in some parameters (for example, a change in agricultural productivity due to climate change), and to subsequently calculate a new equilibrium state given the new values of these parameters. By comparing final and reference equilibrium states, it is possible to draw conclusions about the effects of the shock on the economy. This is a comparative static analysis. GTAP is the only model in our set to be static in its standard version (a dynamic version of GTAP called GDyn exists, cf. Ianchovichina and McDougall, 2000). All other models presented in this paper are recursive-dynamic.

Recursive-dynamic simulations are based on the same principle except that there are several successive time steps in the simulation and for each of them, an equilibrium state is calculated. The value of some parameters is not fixed (though still exogenously defined) over time steps: for the population for example. In CGE models, the Total Factor Productivity (TFP)[13] parameter is usually input in this way. Note that the (re)definition of the TFP is a usual way to input climate change impacts in economic models. The set of parameters trajectories defined in one model is often referred to as the time baseline. Variables are recalculated for each time step, and the values for some of them are expressed as function of their values at the previous step. In CGE models, this is the case for the capital stock for example which is recalculated for each time considering the previous stock and the investment/depreciation mechanism; this is why this type of simulation is recursive dynamic. Note that in both CGE models and PE models, land use redistribution is limited with respect to the previous time step allocation.

Dynamic simulations are able to provide information on intermediate steps. Moreover, endogenising production factor dynamics and distribution across sectors, can potentially make distant time horizon simulations more realistic, as it is difficult and imprecise to make exogenous assumptions for the long-term. Nevertheless, static simulations are generally easier to implement than dynamic simulations since there is no dynamic baseline to calibrate.

The following table sums up the different drivers, outputs and data sources featured by our different models.

[12] Cross entropy methods are based on the combination of different types of input (production data, land cover satellite images, suitability studies, geographical distance to urban centers…). Downscaled data is determined to fit the best all these input sets.

[13] An increase in Total Factor Productivity is an increase in production that is not related to an increase in the use of production factors and intermediate inputs. TFP changes are mainly driven by technological changes.

## Table 2: Main drivers, outputs and data sources of the different models

| Models | | Main exogenous drivers | Main endogenous/output variables | Main data sources used for calibration |
|---|---|---|---|---|
| Computable General Equilibrium models | | Population, TFP, bioenergy demand, (carbon) taxes | Supply (or demand) volumes, prices, capital stock, GDP, GHG emissions | GTAP data base: macroeconomic data<br>IEA[14]: energy data<br>USDA[15]: demand elasticities<br>ILO[16]: (active) population projections<br>FAOSTAT: production data<br>Crop models (cf. 1.4): yield data |
| Partial Equilibrium models | AgLU | Population, GDP, yields, input prices, bioenergy demand (from the energy model included in GCAM), taxes | Land use allocation, supply (or demand) volumes, prices, GHG emissions | FAOSTAT, SPAM: Production data<br>IEA: energy data<br>USDA: demand elasticities<br>IMF: GDP projections<br>ILO: (active) population projections<br>Crop models (cf. 1.4): yield data |
| | GLOBIOM | Population, GDP, input prices, bioenergy demand, taxes, (yields) | Land use allocation, supply (or demand) volumes, prices, GHG emissions | |
| | IMPACT | Population, GDP, input prices, bioenergy demand, yields and areas trends | Supply (or demand) volumes, prices, GHG emissions | |
| | MAgPIE | Population, GDP, input prices, bioenergy demand, yields, taxes | Land use allocation, prices, GHG emissions | |

After this general presentation of driving mechanisms and simulation processes, the following sections go further into detail with respect to the characteristics of land-use representation and allocation in the different models.

# Land-use representation and land allocation mechanisms: top-down vs. bottom-up models

## Two different ways to model land-use allocation

The global land area is divided into different natural and human "uses". In agricultural economics models, this reality is represented in a simplified way and the main categories that are usually included are: cropland, grassland and forests. Each of these categories is generally split into several subcategories, for example between different crops for cropland and

[14] IEA: International Energy Agency

[15] USDA: United States Department of Agriculture

[16] ILO: International Labor Organization

different livestock systems or animal types for grassland. The types of land-uses (i.e. land-based sectors) represented in the models vary across models. The following table presents the sectorial disaggregation featured in the different models:

## Table 3: Sectorial disaggregation of land-based activities in different models

| Model name | Land-based sectors represented in the models |
|---|---|
| Computable General Equilibrium models | |
| AIM (Matsuoka et al. 2001) | Rice, wheat, other grains, other crops, livestock, other agricultural products, forestry |
| CIM-EARTH (Elliott et al. 2010A) | Agriculture & forestry (aggregated as one unique sector) |
| ENVISAGE (Mattoo et al. 2009) | Crops, livestock, forestry |
| EPPA (Gurgel et al. 2007) | Crops, livestock, forestry |
| FARM (Darwin, 2004) | Wheat, other grains, non-grains, livestock, forest products, fish & meat & milk, other processed food |
| GTAP (Golub et al. 2009) | Paddy rice, other grains, other crops, ruminants, non-ruminants, forestry |
| GTEM (Gurney et al. 2009) | Crops, livestock, forestry & fishing |
| LEITAP (IMAGE website) | Vegetable, fruit and nuts; sugarcane and beet; wheat; coarse grains; oilseeds; other crops; cattle; goats; sheep; pigs; poultry. When applicable, meat and milk commodities are differentiated |
| MIRAGE (Bouët et al. 2010) | Rice, wheat, maize, other crops, vegetables & fruits, oilseeds for biodiesel, sugar cane & sugar beet, cattle meat, other animal products, other cattle, forestry |
| Partial Equilibrium models | |
| AgLU (Kyle et al. 2011) | Corn, fibre crop, fodder grass, fodder herb, miscellaneous crops, oil crop, palm fruit, rice, root-tuber, sugar crop, wheat, beef, dairy, pork, poultry, sheep & goat, other meat and fish |
| GLOBIOM (Havlík et al. 2010) | Barley, dry beans, cassava, chick peas, corn, cotton, groundnut, millet, potatoes, rapeseed, rice, soybeans, sorghum, sunflower, sweet potatoes, wheat, oil palm, bovines dairy, bovines others, sheep & goat dairy, sheep & goat others, pigs, poultry broilers, poultry laying hens, poultry mixed |
| IMPACT (Rosegrant et al. 2012) | Cassava, chickpeas, cotton, groundnuts, maize, millet, other grains, palm, pigeon peas, potato, rapeseed, rice, sorghum, soybeans, sugar beets, sugarcane, sunflower, sweet potatoes & yams, temperate fruits, total other oilseeds, tropical & sub-tropical fruits, vegetables, wheat, other crops, Beef, eggs, milk, pork, poultry, sheep & goats |
| MAgPIE (Lotze-Campen et al. 2008) | Temperate cereals, tropical cereals, maize, rice, groundnut, oils palm, rapeseed, soybeans, sunflower, pulses, potatoes, cassava, sugar beets, sugar cane, vegetables/fruits/nuts, two fodder crops, ruminant meat, non-ruminant meat, milk |

The table above shows that land-based activities are not represented with the same level of detail in all the models. This is an important criterion of differentiation between models, which is to be considered carefully when choosing a model to carry out a specific analysis. For example, it is obvious that studies aiming at assessing substitution effects between different types of crops should not be based on ENVISAGE or EPPA which do not differentiate crops but instead work with one crop aggregate. The table also shows that PE models represent land-based activities in a more disaggregated way than CGE models, though the level of disaggregation varies among the latter ones. However, CGE models represent food processing sectors (this is not appearing in the table), which is not the case in PE models.

There are two main approaches to land allocation in the reviewed models. The first approach could qualify as "top-down" and consists of representing land use at a highly aggregated spatial level (i.e. the different macro-regions, countries or groups of countries, defined in the models) and is associated with equation models (i.e. CGE models and the IMPACT model). The second approach can qualify as "bottom-up" and consists of representing land use on a spatially disaggregated level and is associated with GLOBIOM and MAgPIE. Land allocation mechanisms are different across these two types of models.

*Regional land markets and top-down representation of land-use*

In CGE models, land is considered as a production factor where allocation depends on the mechanisms already described in the section about CGEs, the different economic sectors that require land (crop sectors, livestock, forestry) compete on a regional land market to obtain a share of the acreage available in the region. Markets allocate land so that land price is equal to the marginal land productivity (expressed in monetary terms) of all sectors (this is actually not the case). This allocation is optimal, in the sense that it is not possible to increase the global profit generated by all land-based sectors by changing the land allocation.

Climate change will affect the different cropping activities in different ways as species will have different responses to climate variability. This, in turn, will affect land allocation.

The IMPACT model follows a different approach as there are no factor markets in a PE model. However, harvested area for each sector and each region is expressed as a function of output prices (cf. section about PE models) of the sector's commodity itself but also of competing commodities, which enable the representation of substitution effects. From a mathematical perspective, these equations are specified in the same way as in CGEs as they mostly rely on prices - while the major difference is that land price is not explicit in IMPACT.

Another characteristic of CGEs and IMPACT is that these models are all implemented at the regional level, which is why they can be described as top-down. The top-down approach does not allow for an accurate representation of land use and land use allocation. The problem is that land use changes due to climate change are due to changes in agro-climatic conditions that are locally specific.

In order to partly overcome this problem, some models, namely AgLU, FARM, GTAP (in the GTAP-AEZ-GHG version of the model, cf. Golub et al. 2009), GTEM and MIRAGE (in some versions, cf. Bouët et al. 2010) feature an additional disaggregation of land, which accounts for spatial differences in agro-climatic conditions. In these models, the world is indeed divided into Agro-Ecological Zones (AEZs) according to the approach initially developed by FAO (cf. FAO 1996). Concretely, the producer (still defined on the regional level) has the choice between different types of land corresponding to the different AEZs, which present different productivity profiles and different land prices. However, this division is sub-regional, not local. For example, in GTAP-AEZ-GHG, 18 AEZs are distinguished (cf. Golub et al. 2009) that are crossed with regional boundaries.

In order to investigate the link between climate change and land use changes in more detail, other approaches, which can be described as "bottom-up", have been developed.

*Optimization approach and bottom-up representation of land-use*

GLOBIOM and MAgPIE are two canonic examples of a bottom-up approach. In these models, the global land area is divided into "pixels", i.e. small pieces of land. The pixels are small enough to be relatively homogeneous in terms of agro-ecological characteristics. Indeed, in GLOBIOM, the 212,707 pixels (also called Simulation Units in this case, cf. Havlík et al. 2010) are obtained by crossing a spatial disaggregation of land in Homogeneous Response Units (HRU) and a 0.5°*0.5° grid (regional boundaries are considered as well). HRUs are obtained considering criteria of altitude, slope and soil quality. This approach is described in Skalsky et al. (2008). In MAgPIE, the globe is divided into a 3°*3° grid (approx. 300*300km at the Equator) as it is explained in Lotze-Campen et al. (2008), which give a total of 2,178 grid cells. These cells might be too large to be called pixels but the disaggregation is still important when comparing to top-down models.

In these models, land allocation is carried out on the pixel level (or cell level), which explains that this approach is associated with optimization models. It would indeed be difficult to downscale land allocation to this level in CGE models because it would require the specification of thousands of land markets (one for each pixel) and land prices and the integration of these price variables into supply equations. Such models would be extremely heavy to calibrate and to solve. An alternate approach for representing land-use at the pixel level could be to uncouple economic modelling and land-use allocation on the grid-cell level. In the IMAGE framework, for example, the LEITAP model (CGE) is run on the regional level and provides regional shares of land allocated to the different sectors. Then, the land-cover model (cf. Alcamo et al., 1998) generates a land-use map at the pixel level (0.5°*0.5° grid) considering these shares and the differences between pixels in terms of relative productivity.

In order to proceed to land allocation, GLOBIOM and MAgPIE are provided with exogenous agricultural yields and production prices (their determination is enabled by crop models, cf. sections about intensive margin and about climate change impacts modelling) that are pixel (and crop) specific. As a consequence, land allocation is the only endogenous lever left to reach optimality, though in GLOBIOM some switches between different production systems, with different yields and production costs are possible. As exogenous yields and production costs are grid-cell specific, these models are able to establish a link between land productivity and land allocation at the local level. However, in these models, food markets are regional; the aggregated production is equalized to the demand on regional markets.

The AgLU model (encompassed in GCAM) is based on the same logic except that profits instead of yields are considered and that a probabilistic approach is introduced (cf. next section). Moreover, land disaggregation is much less important (cf. Wise and Calvin, 2011). Indeed, there are only 151 AEZ regions defined in AgLU and crop models are not commonly used to determine yields (although they have already been used, cf. Brown et al. 1999). As a consequence, despite many similarities, AgLU cannot be sorted in the exact same category as GLOBIOM and MAgPIE.

## Land types and constraints to land-use change

In both equation and optimization models, driving mechanisms are supposed to lead to an optimal land reallocation for each time step. However, this would assume perfect flexibility in land use changes over time. Yet, in reality land use is not necessarily optimal at every time step due to different reasons, e.g. imperfect information of producers or the fact that land use change is not necessarily free. For example, converting one plot of grassland to cropland requires work and investment. As a consequence, "uncontrolled" land use changes in models could lead to overspecialization in the most profitable crops that would not fit empirical observations. In order to account for these rigidities and avoid unrealistic massive land use changes from one time step to another, some recursive dynamic constraints to land reallocation have been implemented in the models. These constraints allow land rents (i.e. land prices) to differ across uses, which corresponds to a non-optimal land allocation. These constraints differ across models.

In CGE models, except for EPPA, land use changes correspond to "transfers" of land between sectors (i.e. different crops and livestock activities) and are constrained by Constant Elasticity of Transformation[17] (CET, cf. Powell and Gruen 1968) functions. In the same way that a production function relates the production level and quantities of production input, a CET function relates total land area to land areas allocated to each use. The relationship is not linear and ensures that substitutability between the different land uses is not perfect, which results in land reallocation to be sluggish. CET functions are defined specifically (i.e. with specific elasticity of substitution) for each land market, either at regional or at AEZ level, depending on the model.

In EPPA, the approach is a bit different. Five land types are defined: cropland, pasture, harvested forest, natural grassland and natural forest land (cf. Gurgel et al. 2007). Each of these land types is either associated with a given sector (crops, livestock or forestry, which are not further disaggregated in EPPA) or is unmanaged. Conversions between land types are possible but are controlled by land transformation functions. These functions are based on the equalization of the marginal conversion cost of land from one type to another with a difference in value of the types (i.e. the marginal gain from the conversion of land type to another, cf. Gurgel et al. 2007). According to Gurgel et al. (2007), land transformation functions are more adapted to represent the dynamic evolution of transformation elasticities than CET functions.

The division of land into different types in EPPA also has the advantage of representing the specific conversion cost between two given land types. Indeed, conversion costs are differentiated as functions of the types of conversions. For example, conversions between cropland, grassland and forest types require some investment (e.g. cutting trees and soil works to convert forestland to cropland) whereas land-use changes within a same land type (i.e. reallocation of cropland between different crops and of grassland between different livestock

[17] CET functions are similar to CES (Constant Elasticity of Substitution) functions. However, elasticity of transformation replaces elasticity of substitution and is defined as: $\tau = \frac{d(\frac{x1}{x2})}{d(\frac{\partial x1}{\partial x2})}$ ( where $x_1$ and $x_2$ are land areas used in different activities), stated as a constant.

systems - though this is not relevant in EPPA where these uses are not differentiated) do not require such transformation. In order to take differences in flexibility between the different types of land conversion into account, several CGE models rely on "nested" CET functions. For example, in GTAP-AEZ-GHG (cf. Golub et al. 2009) land available is divided into three land types (crops, livestock, forest) by a first CET function with a specific elasticity of substitution and a second CET with a different elasticity that allocates cropland to the different crops. As shown in the Table 4, FARM, GTAP-AEZ-GHG, GTEM, LEITAP and MIRAGE feature nested CET structures for controlling land allocation.

Approaches are different in PE models. In bottom-up models, i.e. GLOBIOM and MAgPIE, several land types are defined (e.g. in GLOBIOM: cropland, grassland, managed forest, short-time tree plantations, pristine forest, and other natural forest) and conversions between these types are possible but limited in two ways. Firstly, conversion costs are accounted for in the objective function (cf. Havlík et al. 2010 for GLOBIOM and Lotze-Campen et al. 2008 for MAgPIE), which endogenously limits land conversions and secondly, conversion rates are limited proportionately for each time step by exogenous coefficients. The reallocation of each land type to different uses is controlled through exogenous coefficients but not through conversion costs. These conversion and reallocation mechanisms are implemented at "pixel" level.

In AgLU, land is allocated in order to maximize the profit of producers as it was previously explained but there is no explicit cost function. However, profit (for a given crop and a given AEZ) is not specified by a unique value but instead by a probabilistic distribution of profits. This feature is associated with a "nested logit architecture" (cf. Wise and Calvin, 2011) used to allocate land among types and uses, allowing to control land use changes and to avoid "winner-takes-it-all" situations.

In IMPACT, there is no endogenous constraint to land-use changes; areas are given by equations which parameters are input exogenously (cf. Rosegrant et al., 2012).

Through all the mechanisms described in this section, most of the models allow for endogenous agricultural land expansion at the expense of natural or managed forest areas. These characteristics and those described in this section are summarized in the following table.

## Table 4: Land use change drivers and constraints

| Models | Land use change driving mechanisms | Land-use change constraints | Endogenous agricultural land expansion possibilities |
|---|---|---|---|
| Computable General Equilibrium models (CGE) | | | |
| AIM (cf. Fujino et al. 2006, Kato et al. 2011) | Regional land markets and profit maximization programs | CET functions between primary land, secondary land (i.e. forests in both cases), cropland, pasture, urban land | Land conversion from primary or secondary land to cropland or pasture |
| CIM-EARTH (cf. Elliott et al., 2010) | | Agriculture and forestry as one sector (no livestock) | Not currently |
| ENVISAGE (cf. Galeotti and Roson, 2011) | | CET functions between three sectors: crops, livestock, forestry | Land conversion from forestry sector to the two other uses |
| EPPA (cf. Gurgel et al. 2007) | | Land transformation functions between 5 land types: cropland, pasture, harvested forest, natural grassland, natural forest land<br>3 land-based activities: crops, livestock, forestry | Transformation between different types |
| FARM (cf. Darwin et al., 1995) | | Nested CET: at AEZ level, 1st level of allocation between crops, livestock and forestry, 2nd level between crops | Land conversion from forestry sector to other uses |
| GTAP (cf. Hertel and Tsigas, Structure of GTAP; cf. Golub et al. 2009) | | CET functions<br>For each AEZ, nested CET functions on the GTAP-AEZ-GHG version (cf. Golub et al. 2009), idem FARM | Land conversion from forestry sector to other uses |
| GTEM (cf. Ahammad et al. 2006) | | For each AEZ, nested CET functions : Idem FARM | Idem FARM |
| LEITAP in the IMAGE framework (cf. IMAGE website) | | Nested CET functions: 3 levels. Field crops and pasture form a single aggregate at the 1st allocation level and are split in the 2nd level. The field crop aggregate is split in the 3rd level.<br>Forest uses do not appear in the nesting | Processed outside of IMAGE:<br>The Land Cover Model (LCM) included in IMAGE computes deforestation and land abandonment<br>Transposed in land supply curves (function of land rent) in LEITAP |
| MIRAGE (Bouët et al., 2010) | | For each AEZ, nested CET functions: 4 levels. Forest and pasture appear in the nest, crops are disaggregated | Managed land can be expanded at the expense of unmanaged land (independent from the nesting structure) |

| Partial Equilibrium models (PE) | | | |
|---|---|---|---|
| AgLU (cf. Wise and Calvin, 2011) | Profit maximization | “Nested logit architecture” (cf. Wise and Calvin, 2011) | Forest extent depends on current and expected prices for land and forest products |
| GLOBIOM (Havlík et al. 2010) | Welfare maximization | 6 land-types: cropland, grassland, managed forest, short rotation tree plantation, others<br>Land-type conversion costs are accounted for in the objective function and there are constraints to a maximum percentage of change for each time step<br>Land use changes in a given land type are also constrained by maximum rates | Land conversions from managed/unmanaged forest land types |
| IMPACT (Rosegrant et al. 2012) | Output and input prices, exogenous trends | No explicit constraints in the program. Areas are expressed in function of economic and water variables | Exogenous |
| MAgPIE (Lotze-Campen et al. 2010) | Cost minimization | 3 land-types: cropland, pasture, non-agricultural land<br>The rest is similar to GLOBIOM | Possible land conversions from non-agricultural land type |

Beyond these issues of land allocation and agricultural land expansion, the other important aspect of land-based activities modelling (especially when dealing with climate change studies) is the determination of the land intensive margin. The intensive margin designates the intensity to which one unit of a given resource (here land) is used. For cropping activities for example, the intensive margin could be measured by crop yields.

## Variations and determination of the land intensive margin

In a long term perspective, agricultural yields can vary because of three main reasons besides the variations in agricultural potential[18] of the land itself: i) the use of other production factors (in particular capital through new investments) and intermediate inputs (fertilisers, …) per unit of land may increase; ii) technological progress increases total factor productivity[19]; and iii) climate change may impact total factor productivity. Yields can also vary in the short term because of weather conditions, pests or diseases that can have significant impact on a given agricultural season. However, these shocks and short-term yield variations more generally are not addressed well by these kinds of economic models. Thus, this review will focus only on long term yield trends.

In CGE models, agricultural yields do not appear explicitly in supply equations, which express sectorial production levels in monetary terms. However, the use of land can be implicitly intensified or extensified by endogenous variations in the use of non-land production factors and intermediate inputs. These variations are mainly determined by price effects. Moreover, the impacts of technological progress or climate change on yields can be input exogenously when calibrating the trajectory of total factor productivity.

In PE models, yields appear explicitly and in physical terms. However, different approaches are possible. In IMPACT, yields are endogenous and given by equations depending on output, input and factor prices, as well as trend terms. These trend terms are calibrated exogenously.

GLOBIOM and MAgPIE are both provided with exogenous grid-cell specific yields projected by crop models, such as EPIC (Environmental Policy Integrated Climate model, cf. Izaurralde et al. 2005) and LPJmL (Lund-Potsdam-Jena managed Land Dynamic Global Vegetation and Water Balance Model, cf. Bondeau et al., 2007), which are biophysically-based models able to project yields on the basis of local agro-climatic conditions. Crop models are further described in the section about impact modelling. Projected yields are associated with grid-cell specific exogenous production costs (cf. Havlík et al. 2010) that are used in the objective function. However, there are two noteworthy differences between GLOBIOM and MAgPIE. In GLOBIOM, for each grid-cell, four different yield levels (along with four different production costs) corresponding to four different representative production systems (i.e. irrigated, high input-rainfed, low input-rainfed and subsistence) are input into the model. This means that yields are to some extent endogenous in GLOBIOM whereas they are strictly exogenous in MAgPIE that does not feature this mechanism. The second notable difference is

[18] i.e. soil type and quality

[19] An increase in Total Factor Productivity is an increase in production that is not related to an increase in the use of production factors. TFP changes are mainly driven by technological changes.

that MAgPIE is the only model presented in this paper computing technological progress endogenously (cf. Lotze-Campen et al. 2008). Indeed, technological progress (i.e. yield increases in MAgPIE) can be bought and costs are accounted for in the objective cost function. In GCAM, yield levels and production costs are also input exogenously but at the AEZ level.

After describing the economic models themselves, the following sections describe how these models are related to climate change issues.

# Climate change and economic modelling

As was explained in the introduction, human activities in general and agricultural and forestry activities in particular are related to climate change in two ways: i) they contribute to climate change through GHG emissions, and ii) they are directly impacted by climate change.

## Accounting for GHG emissions

In order to establish an inventory of GHG emissions in an economic model, it is necessary to link economic variables (quantities of commodities produced or consumed, for example) to GHG emissions levels. Agricultural activities are responsible for direct GHG emissions (i.e. directly related to production processes in the agricultural sector) and for indirect emissions due to land-use change.

### Accounting direct emissions from agricultural activities

Direct emissions from the agricultural sector consist mainly of Carbon Dioxide (CO2), Methane (CH4) and Nitrous Oxide (N2O) emissions. Direct CO2 emissions are mainly due to the use of fossil fuels in agricultural activities; CH4 emissions due to enteric fermentation of ruminants, anaerobic degradation of crop residues in paddy fields and manure degradation; and N2O emissions due to the use (and production) of nitrogenous fertilisers and manure degradation (cf. 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Volume 4).

The accounting of CO2 emissions is relatively straightforward as the quantity of CO2 released for one unit of a given type of fossil fuel used is constant and known. As a consequence, CO2 emissions can be derived from the volume of fossil fuels that is used for agricultural production. This approach can be used in the models in which flows of fossil fuel are represented explicitly. This creates an additional difficulty to overcome in CGE models, because CGE models represent economic flows in monetary terms, not in physical quantities. These flows can vary because of fluctuations in prices even if physical values remain constant, which can lead to a bias in emissions accounting. This is why CGE models' accounting for CO2 emissions has been augmented to keep track of physical quantities in this domain (for example, cf. Paltsev et al. 2005 and Bouët et al. 2010). All the reviewed models but IMPACT are able to account for direct CO2 emissions.

Accounting non-CO2 emissions is more complicated as emission sources are multiple and volumes emitted depend on specific biophysical conditions. For example, CH4 emissions originating from ruminants' enteric fermentation depend not only on the quantity of output produced but also on animals' diet, genetics and other factors.

Emission accounting methods in the reviewed models can be classified according to the IPCC typology[20] in three "tiers" representing different levels of spatial disaggregation for the emissions:

[20] Guidelines for National Greenhouse Gas Inventories, Volume 4, IPCC (2006)

- Tier 1: Emissions are tied to activity data at the national or regional level by multiplying given economic variables (given by the models) by average emission coefficients given by the IPCC guidelines or any other global database. Emissions accounting in ENVISAGE and EPPA is based on this approach (cf. Table 5).
- Tier 2: Similar to Tier 1, but emission factors are based on specific national or subnational data (i.e. not taken from global databases). This is the case for the models using an AEZ approach, i.e. GCAM, GTAP-(AEZ-GHG) and GTEM (cf. Table 5).
- Tier 3: The inventory is based on technical or biophysical considerations (process-based) carried out on a high spatial resolution and based on highly disaggregated activity data. Bottom-up models as well as some CGEs follow this third tier approach. These models are GLOBIOM, IMAGE, AIM and MAgPIE (cf. Table 5).

### Accounting for land use change emissions

Agriculture is also responsible for large amounts of indirect emissions because of the land use changes it implies. Indeed, deforestation and, to a lesser extent, the conversion of grassland to cropland are responsible for a large share of global anthropogenic GHG emissions (about 17% and 14% for direct emissions, IPCC 2007[21]). However, carbon sequestration through afforestation or changes in land management can prove to be an important lever to mitigate GHG emissions.

In the models, the accounting of land use change emissions is based on acreages of land that are converted from one use to another. For CGE models the problem is still the same – in their most basic versions, they do not account for land use acreages but are instead based on a land rent approach (Bouët et al. 2010). Therefore, CGE models that aim at accounting land use change related emissions have been extended to explicitly represent land areas (cf. Paltsev et al. 2005 and Bouët et al. 2010). Table 5 shows that land-use related emissions are accounted in some CGE models, namely AIM, EPPA, GTAP-AEZ-GHG, GTEM, IMAGE and MIRAGE.

The same three tiers (cf. previous section) are applicable. Some models consider land use change through global acreage values at region or country level and apply global emission coefficients. This is the Tier 1 approach that can be found in EPPA. In other models, the AEZ representation of land use and the disaggregation of emission coefficients on the AEZ level correspond to Tier 2. The models applying such an approach are GCAM, MIRAGE (biofuel), GTAP-AEZ-GHG and GTEM. Finally, the models following the Tier 3 approach represent land use changes at the grid level, these models are GLOBIOM, IMAGE, MAgPIE and a recent version of AIM (cf. Kato et al. 2011). In these models, emission coefficients that are spatially specific are derived from the modelling of forest and natural vegetation growth dynamics (possibly biophysically based, e.g. in GLOBIOM, cf. Table 5). The modelling of forest dynamics (on a more macro level) is also carried out in Tier 1 and Tier 2 models, GTAP-AEZ-GHG and in GTEM.

[21] 4th Assessment Report, Synthesis Report, IPCC 2007

Table 5 summarises the different approaches used in the models to account for land activity related GHG emissions.

## Table 5: Direct agricultural emissions accounting in different global economic models

| Models | Accounting approaches for direct agricultural emissions | Accounting approaches for land-use change related emissions |
|---|---|---|
| **AIM** (cf. Jiang et al. 2000, Matsuoka et al. 2001, Kato et al. 2011) | CO2: quantities of fossil fuels<br>CH4: output (from ruminants) and paddy land acreage<br>N2O: use of fertilisers<br>In some versions, spatially explicit approach (technology-based) of Enduse module (Garg et al. 2004). | Deforestation (CO2), Biomass combustion (SO2, NMVOCs), land use changes (CO2, CH4, N2O, NOx, NMVOCs, CO and SO2)<br>Area deforested and emission coefficients.<br>In Kato et al. (2011) there is a model of the terrestrial ecosystem, Vegetation Integrative Simulator for Trace Gases (VISIT). Carbon emissions and sequestration are taken into account |
| **CIM-EARTH** (cf. Elliott et al. 2010A) | CO2: quantities of energy used by producers and consumers | Non-accounting land use change related emissions |
| **ENVISAGE** (cf. van der Mensbrugghe, 2010) | CO2: quantities of fossil fuels<br>CH4: cattle stock and acreage of paddy fields<br>N2O: use of fertilisers | Non-accounting land use change related emissions |
| **EPPA** (cf. Hyman et al. 2003, Reilly et al. 2002) | CO2: quantities of fossil fuels used in agriculture<br>CH4: sectoral (crops, livestock) outputs but substitutions possible (cf. emissions control) | CO2: Area of deforested land and emission coefficients<br>Explicit forests growth dynamics in other versions (Reilly et al. 2002) |
| **FARM (cf. Sands, 2011)** | **CO2: quantities of fossil fuels used in agriculture** | **Non-accounting land use change related emissions** |
| **GCAM** (cf. Wise and Calvin, 2011) | CO2: determined in the energy system (module) and tied to the quantity of fossil fuels<br>CH4, N2O: sectorial output quantities | CO2: land-use change acreage from grassland or forest to cropland. Forest and pasture land sinks are considered (differentiated for carbon content along land classes (AEZ)) |
| **GLOBIOM** (cf. Mosnier et al. 2012) | CO2: quantities of fertilisers<br>CH4 and NO2 emissions due to livestock production are given by the RUMINANT model (Herrero et al. 2008). CH4 and NO2 emissions from crop production are derived from rice acreage and fertiliser application, respectively. Emission savings due to biofuels are taken exogenously and depend on production pathway. | CO2: emissions from deforestation depend on forest characteristics (determined by the G4M module, cf. section about impacts). Emissions from conversion from pasture to cropland. |

| | | |
|---|---|---|
| **GTAP (-AEZ-GHG)** (cf. Golub et al. 2009) | $CH_4$ (from ruminants' fermentation and rice cultivation): economic output<br>$N_2O$: quantities of fertiliser | $CO_2$: Emissions or sequestrations due to forests depend on land use change, aging of timber and on forest management (determined by the "Global Timber Model ", cf. Sohngen and Mendelsohn, 2001) |
| **GTEM (cf. Pant et al. 2002, Ahammad et al. 2005)** | **CO2: quantities of fossil fuel**<br>**CH4 : sectorial output (from ruminants), acreage of paddy land**<br>**N2O: fertiliser use** | **CO2: Similar to GTAP but approach presented in Sohngen and Tennity (2004)** |
| **IMAGE** (cf. IMAGE website[22], PBL Netherlands Environmental Assessment Agency) | CO2: quantities of fossil fuel<br>CH4: livestock production, rice cultivation, manure management, crop residues degradation, N2O: fertiliser use, manure management, crop residues degradation<br>Land use emissions module (technical module): process-based approach and grid cell specific coefficients approach | CO2: carbon sequestration in forests through forest growth modelling (managed land module), emissions from deforestation and changes in natural land cover (Terrestrial Carbon Model)<br>CH4, N2O: from deforestation (land use emissions model) |
| **IMPACT** | **Model non-accounting for emissions** | |
| **MAgPIE (cf. Popp et al. 2010, Popp et al. 2011C)** | **CH4: enteric fermentation, rice production, manure management**<br>**N2O: manure management, soil emissions (use of fertiliser)**<br>**Grid-cell specific coefficients applied to quantities of input and output** | **CO2: Conversion of natural vegetation to cropland (Grid-cell specific coefficients, C stocks in natural vegetation predicted by the Lund Potsdam Jena model, cf. Sitch et al., 2003)** |
| **MIRAGE (cf. Bouët et al. 2010)** | **CO2 (direct emissions savings due to biofuel production): coefficients for various production pathways** | **CO2: indirect emissions from land use change due to biofuel production (AEZ-specific coefficients)** |

22 http://themasites.pbl.nl/en/themasites/image/index.html

The accounting of emissions can be made in order to generate GHG emissions scenarios or to assess mitigation policies, for example.

### Emissions control and mitigation policies

The accounting of GHG emissions allows for the modelling and analysis of mitigation policies. According to the IPCC[23], there are three main types of mitigation options for the agricultural sector: i) reducing emissions (direct and indirect emissions due to agricultural activities), ii) enhancing removals (i.e. carbon sequestration) and iii) displacing emissions (i.e. production of bioenergy).

Economic models can help to determine the potential of mitigation measures as they are able to predict how economic agents are going to react when subjected to given policy instruments (e.g. standards, taxes or cap-and-trade systems). These instruments have been subject of many studies based on economic models (cf. the 3rd part on models uses).

In the models, different endogenous mechanisms can respond to mitigation instruments and can help to mitigate emissions:

- Varying output and input levels: emissions can be reduced by decreasing the level of activity (output) or by reducing the emission intensity per unit of output (by changing the input combination).
- Changing land use patterns: the main lever in some PE models (GCAM, GLOBIOM and MAgPIE).
- Sequestering carbon: possible in many models, cf. Table 6.
- Fostering technological progress: in MAgPIE, technological improvements are endogenous (cf. section on land-use representation and Lotze-Campen et al. 2008).
- Following marginal abatement cost schedules (defined exogenously): this is the case in GCAM (cf. GCAM wiki).
- Developing biofuel production: in order to reduce the use of conventional fuels.

Table 6 presents further details on the mitigation levers as they correspond to each model.

23 4th Assessment Report, Working Group III: Mitigation of Climate Change, chapter 8 (IPCC, 2007)

## Table 6: Main levers used in the models to reduce GHG emissions in the land use sectors

| Models | Direct agricultural emissions control | Carbon sequestration | Biofuel policies |
|---|---|---|---|
| AIM (cf. Jiang et al. 2000, Matsuoka et al. 2001, Kato et al. 2011) | Endogenous output and input levels | Allocation of land to forests | - |
| CIM-EARTH (cf. Elliott et al. 2010) | Endogenous output and input (use of fertiliser) levels | Possibility of afforestation (exogenous cost) | Savings from fuel substitution |
| ENVISAGE (cf. van der Mensbrugghe, 2010) | Endogenous output and input levels | - | Savings from fuel substitution (no effect on oil price) |
| EPPA (cf. Hyman et al. 2003, Reilly et al. 2002) | Emissions linked to endogenous output levels. Substitutions possible between emission "input" and conventional inputs (elasticities of substitution calibrated on bottom-up determined mitigation costs) | Allocation of land to forest. Plantation costs taken into account as well as forests growth dynamics. | Savings from fuel substitution |
| FARM | - | | |
| GCAM (cf. Wise and Calvin, 2011) | CO2: endogenous land use allocation<br>CH4, NO2: Marginal Abatement Cost curves are defined exogenously. | Land allocation to forests (explicit forest dynamics) | Substitution to conventional oil. Emission savings due to fuel displacement are determined in the energy module. |
| GLOBIOM (cf. Mosnier et al. 2012) | Land use allocation and switch between different production systems. | Possible expansion of forestland. Explicit forest growth dynamics. | Savings from fuel substitution (different avoided emissions coefficients for different pathways). |
| GTAP (-AEZ-GHG) (cf. Golub et al. 2009) | Endogenous output and input levels. For each emission driver, substitutions possible with other input to reduce emission intensity (calibrated bottom-up determined mitigation cost curve). | Possibility of increasing forest acreage and stock of carbon in existing forests. | Savings from fuel substitution (different avoided coefficients for different pathways). |
| GTEM (cf. Pant et al. 2002, Ahammad et al. 2005) | Endogenous output and input levels. | Possibility of increasing forest acreage and stock of carbon in existing forests. | - |
| IMAGE (cf. IMAGE website, PBL | Endogenous output and input levels, land | Possibility to plant new forests | Savings from fuel substitution |

| | | | |
|---|---|---|---|
| **Netherlands Environmental Assessment Agency)** | **allocation** | **(explicit dynamics). Land abandonment** | **Demand for, production of and emissions from biofuels are computed jointly by TIMER and LEITAP modules.** |
| **IMPACT** | **-** | | |
| **MAgPIE (cf. Popp et al. 2010, Popp et al. 2011C)** | **Land allocation, endogenous technological change** | **Land allocation to forests (explicit dynamics)** | **Savings from fuel substitution** |
| **MIRAGE (Bouët et al. 2010)** | **Endogenous output and input levels, land allocation** | **Possible avoided deforestation** | **Savings from fuel substitution, coefficients for different pathways** |

## Modelling climate change impacts on land-based activities

According to the IPCC[24], climate change expresses itself through both changes in mean climate features (average temperature, precipitation, sea-level rise) and changes in weather variability, in particular changes in the frequency of extreme events (tropical cyclones and storm surge, extreme rainfall and riverine floods, heat- and cold- waves, drought). However, to date, studies carried out with the reviewed models have focused almost exclusively on impacts due to changes in climate trends. This section describes how these long-term impacts are being assessed by the models.

### Use of biophysical models

These physical impacts can be assessed by biophysical models that predict the long-term evolution of crop yields and, more generally, of biomass production considering physical and technical conditions. However, this "physical" analysis is insufficient to correctly represent the full extent of climate change impacts. Indeed, economic agents, in particular producers, in land-based activities may react by adapting production processes to new climate patterns. Such a response from the producers qualifies as autonomous adaptation[25]. Economic models can account for autonomous adaptation to climate change. As a consequence, the assessment of climate change impacts is carried out in two steps: i) assessment of physical consequences of climate change on agriculture and forest processes and ii) assessment of the economic consequences of these physical impacts.

Within the group of biophysical models, some crop models predict the impact of climate change on crop growth. A typical crop model simulates plant growth on a daily and spatially explicit basis considering (daily and local) weather data, soil data and crop management information (cf. Nelson et al. 2009). These models are run specifically for each crop and determine crop yields. As a result, the effects of a change in climate and in the subsequently derived weather data on crop yields can be assessed. The models AIM, EPPA (IGSM), GLOBIOM, IMAGE and MAgPIE include crop models in their standard version (cf. Table 8). GCAM, IMPACT and MIRAGE have also been coupled with crop models in studies dealing specifically with climate change impacts – e.g. with EPIC[26] in Brown et al. (1999), DSSAT[27] in Nelson et al. (1999) and DSSAT in Laborde (2011). In order to determine the change in yield due to climate change, crop models are usually run to provide a set of yield data for a reference year (i.e. the present time) and another one for a future time horizon, ensuring comparability of the two series of projection. This type of projection is made to determine the trend in yields, it is not meant to assess yield impacts of changes in climate variability.

[24] Working Group II report: "Impacts, Adaptation and Vulnerability" of the IPCC 4th Assessment Report.

[25] Autonomous adaptation: adaptation that does not constitute a conscious response to climatic stimuli but is triggered by ecological changes in natural systems and by market or welfare changes in human systems. IPCC 2007, Working Group II.

[26] EPIC: Environmental Policy Integrated Climate model, cf. Izaurralde et al. 2005

[27] DSSAT: Decision Support System for Agro-technology Transfer, cf. Alexandrov and Hoogenboom, 2000

Once biophysical models are run, simulation results are input in the economic side of the models. There are two main ways to implement this coupling: i) yields can be input directly at the grid level and in absolute value, which is the case in GLOBIOM and MAgPIE (bottom-up PE models). This means that yields are exogenous in these models (although switches between different production systems are possible in GLOBIOM); ii) changes in yields (projected at grid-level) are considered in percentage and aggregated at regional level before being input into the model. In IMPACT, yields are input directly in absolute values. However, in CGE models, i.e. AIM, EPPA, IMAGE and MIRAGE, it is the evolution of yields in percentage between two projection series that is used to recalibrate the agricultural total factor productivity that is exogenously defined in the baseline (for each region). In GCAM, yields projections are made directly at regional level on the basis of representative physical and technical conditions (for example, in GCAM at AEZ level in Brown et al. (1999)).

The use of crop models has enabled all models mentioned in this report to assess climate change impacts on crop production and on the rest of the economy (as far as CGEs are concerned). Some examples include Kainuma et al. (2003) for the AIM model, Reilly et al. (2007B) for EPPA, Brown et al. (1999) for GCAM, Eickhout et al. (2009) for IMAGE, Nelson et al. (2009) for IMPACT, Lotze-Campen et al. (2008) for MAgPIE and Laborde Debucquet (2011) for MIRAGE.

The impact of climate change effects on agricultural activities is not only carried out through yield predictions (cf. Table 7). For example, the geographic distribution of land classes (and subsequently the potential distribution of crop production areas) can be redefined like in FARM (cf. Darwin, 1998) or IMAGE (cf. IMAGE website, PBL Netherlands Environmental Assessment Agency) as explained in Table 7. In ENVISAGE, “damage functions” (cf. van der Mensbrugghe, 2008) are included in the production functions to affect the level of output considering temperature change. These functions are exogenously calibrated thanks to sectorial studies (cf. Galeotti and Roson 2011).

Furthermore, agriculture is not the only sector for which climate change effects are taken into account in the models. Indeed, in some models the impacts on forests (managed/unmanaged) and more generally on natural vegetation are assessed. As shown in Table 7, this assessment is based either on changes in biomass dynamics and or on changes in the spatial distribution of natural vegetation.

The following table summarises how climate change impacts on cropping activities and natural vegetation are taken into account in the different models.

## Table 7: Modelling climate change impacts on land-based ecosystems and activities

| Models | Crop production | Forest and natural cover |
|---|---|---|
| AIM (AIM/Impact module, cf. Matsuoka et al. 2001) | Crop productivity model: crop model provides potential crop productivity, 5 arc-minutes resolution, aggregated at regional level and input in AIM/Emissions (CGE) | Vegetation model: relates spatial distribution of ecosystem to cumulative-temperature and precipitation at grid-level and aggregated to be input in the CGE model. |
| CIM-EARTH | - | - |
| ENVISAGE (cf. Galeotti and Roson 2011, van der Mensbrugghe 2008) | Exogenous variables (e.g. stock of land) or factor (or multi-factor) productivities are impacted directly by changes in temperature through damage functions (calibrated thanks to sectorial studies) | - |
| **EPPA** (in MIT IGSM, Integrated Global Systems Model, cf. Sokolov et al. 2005) | Terrestrial Ecosystem Model (TEM) represents terrestrial ecosystem processes (cycles of C, N and water) and provides yields and net primary productivity effects of climate change at 0.5°*0.5° resolution, aggregated at regional level and input in EPPA. | |
| FARM (cf. Darwin, 1998) | The "GIS Component" of FARM is able to redefine the potential spatial distribution of 6 land classes (defined according to the length of growing season), based on a 0.5°*0.5° resolution<br>Change in productivity due to carbon fertilisation is input exogenously in the CGE | - |
| GCAM (cf. Brown et al. 1999) | Coupled with crop models, e.g. EPIC, determines changes in productivity for each AEZ of each region | - |
| GLOBIOM (Havlík et al. 2010) | The crop model EPIC provides yields at grid level, input directly in the spatially explicit production system | Global Forestry Model (G4M), biophysically determines forests growth |
| GTAP (cf. Lee, 2009) | Changes in productivity are taken from exogenous projections | - |
| GTEM | - | - |

| | | |
|---|---|---|
| IMAGE (cf. IMAGE website[28], PBL Netherlands Environmental Assessment Agency) | Natural Vegetation Model: gives potential distribution of crop (and livestock) production at 0.5°*0.5° resolution<br>Managed Land Module: potential productivity of crops at grid level<br>Sea level rise model<br>Land degradation model | Natural Vegetation Model: gives potential distribution of natural vegetation at 0.5°*0.5° resolution<br>Managed Land Module: forest sinks growth |
| IMPACT (cf. Nelson et al. 2009) | Trend terms in area and yield equations calibrated to account for climate change, projections obtained by DSSAT model | - |
| MAgPIE (cf. Lotze-Campen et al. 2008) | The crop model LPJmL (Lund-Potsdam-Jena managed Land Dynamic Global Vegetation and Water model, cf. Bondeau et al. 2007) provides vegetation growth (including yields) and distribution at grid level for both agricultural and natural ecosystems, input directly in the spatially explicit production system. | |
| MIRAGE (cf. Laborde 2011) | Total factor productivity baseline in agricultural sector is calibrated to take into account climate change. Yield projections obtained from DSSAT crop model | - |

[28] http://themasites.pbl.nl/en/themasites/image/index.html

Along with cropping activities, forest and natural vegetation, the livestock sector can also be impacted by climate change. These impacts can be direct or indirect. Direct impacts are effects climate change could have on animal physiology that can affect productivity. However, livestock production might also be indirectly affected by the impact of climate change on grass and feed production. Moreover, the livestock sector is linked to crop production through land competition. Indirect impacts are taken into account in most models. However, in a more detailed approach GLOBIOM, and in particular the encompassed RUMINANT model (cf. Herrero et al. 2008), proposes a biophysical analysis of production systems (for ruminants' livestock farming). Indeed, the RUMINANT model is a dynamic simulation model of digestion in ruminants, which can predict feed intake, production (both meat and milk), and excretion as well as metabolism end products (e.g. methane). RUMINANT pays particular attention to the representation of the diversity in the types of production systems and it is able to be input with climate change data and to determine climate impacts on the ruminants sector.

### Use of water simulation models

Besides crop, vegetation and livestock models, it is also possible to input climate change impacts through water models. Thus, the Water Simulation Model (WSM, cf. Rosegrant et al. 2012) has been used with IMPACT and GTAP to determine the impacts of water scarcity on crop production. The WSM is a river basin[29] model that calculates the water balance for each river basin, thus determining the volume of water available for irrigation. In IMPACT, this calculated volume is used to calculate "water terms" in area and yield equations for irrigated crops. In GTAP, it is used for the benchmark equilibrium calibration (irrigation water is a production factor in the GTAP-W version of GTAP – see Calzadilla et al. (2009) for further details).

The previous sections outlined emission accounting issues and impacts modelling issues. The next section presents the principle of the integrated assessment approach in which these two issues are combined into one modelling framework.

## Integrated assessment approaches

The integrated assessment approach spans disciplinary borders to study all relevant aspects related to a given global issue within the same framework (here, climate change). Coupling economic and crop modelling is already part of this approach. However, models commonly referred to as integrated assessment models encompass a climate module that is able to derive climate projections from the emission baselines they have themselves generated. Under this definition, AIM, CIM-EARTH (ongoing implementation of the climate module), ENVISAGE, GCAM and IMAGE follow an integrated assessment approach. The MIT Integrated Global System Model (IGSM, cf. Sokolov et al. 2005) encompasses both EPPA and a climate module.

[29] A river basin is the total land area from which water is drained into a given river and its tributaries.

In general, climate modelling is carried out by General Circulation Models (GCMs) to give a physical and chemical representation of the atmosphere and the ocean[30] in three dimensions and with a high spatial resolution. Climate projections used in "non-integrated" economic models are GCM's outputs. However, GCMs are large-scale models that require extensive computational capacities and specialized scientists. Therefore, in integrated models, climate modules consist of "emulators[31]" (cf. Raper and Cubasch, 1996), i.e. simplified climate models able to reproduce the results from GCMs at aggregate level. MAGICC (Model for the Assessment of Greenhouse-gas Induced Climate Change, cf. Wigley and Raper, 1992) used in GCAM and IMAGE is a good example of a climate emulator.

Moreover, some integrated frameworks are built as multidisciplinary clusters of models allowing for endogenous modelling of population dynamics, land degradation, consequences of sea level rise, etc. Among the reviewed models, the IMAGE framework is a good example of this kind of approach. Table 8 presents the structure and different components (i.e. modules) featured by the different models:

## Table 8: Structure and components of the different models

| Model | Modules |
|---|---|
| **AIM** (cf. Matsuoka et al. 2001) | 3 main modules:<br>AIM/Emission: encompasses CGE (top-down), global technology selection module (bottom-up) and land use module (top-down)<br>AIM/Climate: climate model (emulator)<br>AIM/Impact: predicts climate change impacts on the economy through impacts on water resources, agricultural production (crop productivity model), natural ecosystems (vegetation model) and some diseases |
| **CIM-EARTH** (Elliott et al. 2010) | Economic model: CGE<br>Climate model (ongoing implementation) |
| **ENVISAGE** (van der Mensbrugghe, 2008) | Economic model: CGE<br>Climate model (emulator) |
| **EPPA** (cf. Paltsev et al. 2005, Sokolov et al. 2005) | Economic model: CGE<br>Climate model (emulator)<br>Terrestrial Ecosystem Model (TEM): represents terrestrial ecosystem processes (cycles of C, N and water) and provides yields and net primary productivity effects of climate change |
| **FARM** (cf. Darwin 1998) | CGE model<br>"GIS Component": redefines potential spatial distribution of 6 land classes |
| **GCAM** (GCAM wiki, University of Maryland, Brown et al. 1999) | Partial equilibrium model for the energy sector (ERB, Edmonds-Reilly Barnes)<br>Partial equilibrium model for agriculture and Land-Use (AgLU)<br>Climate model (emulator)<br>Occasionally coupled with EPIC: crop model |

[30] A General Circulation Model is a numerical representation of the atmosphere and ocean and its phenomena over the entire Earth, using equations of motion and including radiation, photochemistry, transfer of heat, water vapor, and momentum. (Source: National Ice and Snow Data Center, University of Colorado Boulder)

[31] cf. definition of Raper and Cubasch (1996)

| | |
|---|---|
| **GLOBIOM** (Havlík et al. 2010) | PE model (spatially explicit land-use)<br>EPIC: crop model<br>G4M: Forestry model<br>RUMINANT: livestock model |
| **GTAP** (Calzadilla et al. 2009, Golub et al. 2009) | CGE model<br>GTAP-Water coupled with the Water Simulation Module (WSM)<br>GTAP-AEZ-GHG coupled with modified version of Global Timber Model (GTM) to give forest optimal sequestration |
| **GTEM** (Pant et al. 2002) | CGE model<br>Population module<br>Greenhouse module: tracks GHG emissions |
| **IMAGE** (IMAGE website, PBL Netherlands Environmental Assessment Agency) | Economic modules: world economy model (macro-economic baseline), PE models for energy (TIMER) and agriculture (LEITAP)<br>Population module (PHOENIX)<br>Climate model (emulator)<br>Land-cover model (LCM): determines land-use and land-cover<br>Natural Vegetation Model: gives potential distribution of crop (and livestock) production and natural vegetation<br>Managed Land Module: potential productivity of crops at grid level (crop model) and forest sinks growth<br>Sea level rise model<br>Land degradation model<br>Biodiversity module |
| **IMPACT** (Nelson et al. 2009) | Partial equilibrium model<br>Coupling with crop model (DSSAT) in some versions<br>Coupling with water simulation model (WSM) in some versions |
| **MAGPIE** (cf. Lotze-Campen et al. 2008) | MAgPIE land-use model<br>Crop model: LPJmL (Lund-Potsdam-Jena managed Land Dynamic Global Vegetation and Water Balance Model) |
| **MIRAGE** (Laborde Debucquet, 2011) | CGE model<br>Coupling with crop model (DSSAT) in climate change versions |

Treating economic and climate modelling in the same framework guarantees a certain level of consistency between the extent of GHG emissions on the one hand and the extent of climate change impacts on the other. However, it is more approximate than GCM's results and there is no disaggregation at the local level, which can be a problem for the coupling with crop models.

## Different uses for different types of models

This section presents the main types of climate change studies that have been carried out by the reviewed models. Appendix 4 presents a more comprehensive list of relevant articles involving the models and focusing on climate change and agricultural issues. Table 9 (Appendix 3) categorises the articles and a count of articles for each category. There are three main types of topics investigated: i) Climate change impact assessment; ii) Mitigation policies assessment and iii) Generation of GHG emissions baselines.

### Assessment of the impacts of climate change

There are two main approaches, already described, to analyse climate change impacts: i) the approach that consists of recalibrating TFP (Total Factor Productivity, cf. section about CGEs) trajectories in CGE models and ii) the introduction of yield trajectories that are affected by climate change in bottom-up PE models. Based from these two approaches, several studies have been carried out. Some research topics are recurrent in the literature. The first topic is rather general and deals with climate change impacts on food production (and prices), which is useful to deal with food security issues, for example. This issue is addressed in all types of models, for example in PE (see Nelson et al. (2010) with IMPACT and Lotze-Campen (2008) with MAgPIE); but also in CGE models that enable economy-wide analyses of climate impacts (including other sectors, GDP[32], international trade patterns), e.g. Kainuma et al. (2004) with AIM, van der Mensbrugghe (2009) with ENVISAGE, Reilly et al. (2007B) with EPPA, Darwin et al. (2004) with FARM, Calzadilla et al. (2009) with GTAP and Laborde (2011) with MIRAGE.

Note that some studies particularly focus on the impacts of climate change on land-use change patterns. The two bottom-up PE models GLOBIOM and MAgPIE are based on land-use allocations, therefore they are well adapted to carry out this kind of analysis. This is the case in Lotze-Campen et al. (2008) using MAgPIE. However, some CGE models accompanied by land modules (cf. sections about impacts and about land-use) have been used to investigate climate impacts on land-use, for example in Verburg et al. (2008) and Rounsevell et al. (2006) using the IMAGE model or Darwin et al. (1995) with FARM. Furthermore, it is also possible to address climate impact issues through the perspective of irrigation water scarcity. This has been done in Calzadilla et al. (2009) with GTAP (CGE) and IMPACT (PE).

Lastly, it is worth noting that even though all the economic models considered here represent more or less refined autonomous adaptation mechanisms, only few studies deal explicitly with planned adaptation[33] policies. This is the case in Calzadilla et al. (2009) with GTAP or in Nelson et al. (2009) for example.

[32] In this case, CGE are useful to carry out sensitivity analyses, to compare in relative terms different climate scenarios for examples. However, do not aim to make GDP projections more broadly.

[33] Planned adaptation: adaptation that is the result of a deliberate policy decision, based on awareness that conditions have changed or are about to change and that action is required to return to, maintain, or achieve a desired state.

## Assessment of mitigation policies

The second main category of studies relates to the assessment of mitigation policies. This assessment aims at determining the efficiency of mitigation policies by analysing their economic impacts and costs with respect to their efficiency to mitigate GHG emissions. Many papers deal with this topic, since this is an important concern for policy makers.

Economic models are used to determine impacts of mitigation policies on GHG policies, (food) production and prices, GDP and land-use. Similarly to climate impact studies, CGE models can proceed to economy-wide analyses. Examples of this are Elliott et al. (2010) using CIM-EARTH, van der Mensbrugghe (2010) using ENVISAGE, Paltsev et al. (2009) using EPPA, Morris et al. (2008) using EPPA, Gurney et al. (2009) using GTEM or Edenhofer et al. (2010) using IMAGE among many other examples (cf. Appendix 4). Mitigation policies are, in most cases, input into the models through carbon taxes on GHG emissions that are accounted for (cf. section about emissions accounting), e.g. in Golub et al. (2009) in GTAP-AEZ-GHG. However, cap-and-trade systems have also been analysed, for example in Paltsev et al. (2008) using EPPA. The results obtained from these simulations can be assessed in detail, i.e. sector by sector and variable by variable but it is also possible to gather results by building abatement curves which show global abatement costs in function of global GHG emissions abatement. Golub et al. (2009) based on GTAP-AEZ-GHG features such curves. Although global, these studies focus on the agricultural sector, mostly on cropping activities. Some articles such as Avetisyan et al. (2010) using GTAP-AEZ-GHG focus on impacts of mitigation policies on the livestock sector.

Apart from these studies covering the agricultural sector as a whole or some commodities, a number of studies have dealt with specific levers that can be used to abate emissions. At first, the sequestration of carbon in forests and soils (and/or avoided deforestation) have been addressed in Kato et al. (2011) using AIM, Reilly et al. 2002 using EPPA, Gusti et al. (2009) using GLOBIOM, Golub et al. (2009) using GTAP-AEZ-GHG, Ahammad et al. (2005) using GTEM, Rose et al. (2012) using GTEM or Strengers et al. (2008) using IMAGE. The impact of technological change has been investigated in Garg et al. (2004) using AIM and in Jakeman et al. (2004) using GTEM. Finally, the impacts of a change to less meat-intensive human diets have been considered in Stehfest et al. (2009) using IMAGE and in Popp et al. (2010) using MAgPIE.

Biofuel policies were initially introduced at the political level as mitigation policies and have been subject of an important number of studies. The potential of biofuel production for mitigating GHG emissions has been indeed hotly contested during the last decade because increasing biofuel production has a tremendous impact on the demand for arable land which leads to land-use and in particular to deforestation. And land-use related emissions due to biofuels could outstrip emissions abatement due to the decrease in fossil fuel consumption (Searchinger et al. 2008). Aside from the issue of indirect emissions, the increase in biofuel production has a significant impact on food production and prices and could lead to food security problems. These two aspects of biofuel production have been and are extensively investigated as biofuel policies constitute an important and sensitive political stake.

CGE models have been used to analyse both aspects, indirect land use emissions by Melillo et al. (2009) using EPPA, Lapola et al. (2010) using IMAGE, Bouët et al. (2010) using

MIRAGE and economic impacts by Elliott et al. (2010B) using CIM-EARTH, Britz et al. (2011) using GTAP. Bottom-up PE models are particularly well-suited for analysing land-use emissions due to biofuel policies. This was done for example in Popp et al. (2011A&B) using MAgPIE and in Havlík et al. (2010) with GLOBIOM. IMPACT has been used to deal with food security in many papers, for example Msangi et al. (2007).

### Emissions baselines projections

The third category of studies gathers all articles dealing with the projection of GHG emissions baselines. Indeed, there is a need to translate some socio-economic assumptions (e.g. SRES[34] scenarios) into quantitative economic scenarios and into quantitative baselines for GHG emissions (or even into climate projections). This enables the comparison of different scenarios in terms of climate impacts. IMAGE has been used the most to carry out this type of analyses, for example in Strengers et al. (2004) and Feddema et al. (2005). However, articles involving other models can be found, for example Jiang et al. (2000) with AIM, van der Mensbrugghe et al. (2010) with ENVISAGE or Sokolov et al. (2009) with EPPA.

[34] *Special Report on Emissions Scenarios, IPCC (2000)*

# Concluding remarks

This review of economic models has shown that different ways can be followed to carry out similar types of climate studies. This raises the question of the comparability of model outputs as well as of the robustness of these outputs. Outputs are indeed strongly dependent on the characteristics of the different models and on the input data used in these models. A comparative analysis of these outputs considering differences between the models and between the sets of input data may help to identify the sources of divergence between models and to improve the output homogeneity. The AGMIP project[35] (Agricultural Model Intercomparison and Improvement Project, cf. Rosenzweig et al. 2012) is dedicated to this purpose. It focuses both on the comparison and the improvement of crop models and economic models. The project follows two different "tracks": track 1 consists of comparing model outputs when submitted to historical climate conditions, and track 2 consists of comparing model outputs when submitted to future climate scenarios. As far as economic models are concerned, there is some upstream work to be done on the homogenization of input data. Thus, a specified set of crop model outputs and standardised socio-economic baselines are defined so that economic models themselves can be compared with each other. The AGMIP project is relatively recent and constitutes an interesting example of collaborative work between economic modelling teams. It will reconcile and increase the reliability of economic projections.

Apart from this collaborative work on the reconciliation of models, there are some points concerning agriculture and climate change that need further work. For example, a better representation of the livestock sector, based on biophysical conditions, and with a refined representation of animal diets (in particular concerning the mix pasture/feed crops) would be an interesting research topic. The work that has been done so far in the coupling between GLOBIOM and RUMINANT is an interesting example of this kind of work. Another important question that has been little investigated to date (although a few examples can be found, cf. Fuss et al. 2011) is the analysis of the impacts due to changes in weather variability. This point would require extensive modification of economic models so that short-term responses of producers can be better represented and it might justify the introduction of mechanisms for decision-making under uncertainty.

[35] http://www.agmip.org/

# Appendix 1: Individual presentations of the models

**AIM** (Asia-Pacific Integrated Model) by NIES, Japan

- **Model type:** integrated assessment model including a CGE model
- **Mathematical formulation:** the CGE is an equation model, recursive-dynamic
- **Main exogenous drivers:** population, TFP, bioenergy demand, (carbon) taxes
- **Land use representation:** initially top-down, however in Kato et al. (2011), AIM/CGE is associated with a land use model used for downscaling land-use.
- **Land-based sectors represented:** rice, wheat, other grains, other crops, livestock, other agricultural products, forestry
- **Other modules and particularities:** AIM is an integrated assessment framework based on a CGE model (AIM/CGE). The integrated framework is composed of three main modules:
    - Emission module (AIM/Emission): encompasses a CGE model (AIM/CGE) and a bottom-up type global technology selection model (AIM/Enduse) that is operated for each country specifically. In some studies (Kato et al. 2011), a land-use module is used for downscaling land-use patterns after regional variables determined in the CGE.
    - Several types of simplified climate models (emulators) form the AIM/Climate module, which is aimed at deriving climate projections from emission baselines projected by AIM/Emission.
    - Impact/adaptation model (AIM/IMPACT) that assesses potential impacts of climate change on economic (thanks to a crop productivity sub-module) and natural (thanks o a vegetation sub-module) systems and provides feedback to the emission model. This module is able to represent some adaptation mechanisms.
- **Key references:**
- "Integrated Assessment Model of Climate Change: The AIM Approach", Matsuoka et al. (2001)
- "Long-Term GHG Emission Scenarios for Asia-Pacific and the World, Technological Forecasting and Social Change", Jiang et al. (2000)
- "Development of spatially explicit emission scenario from land-use change and biomass burning for the input data of climate projection", Kato et al. (2011)

**CIM-EARTH** (Community – Integrated Model of Economic and Resource Trajectories for Humankind) by the University of Chicago and the Argonne National Laboratory

- **Model type:** CGE model, ongoing development of an integrated assessment framework
- **Mathematical formulation:** equations model, recursive dynamic
- **Main exogenous drivers:** population, TFP, bioenergy demand, (carbon) taxes
- **Land use representation:** top-down
- **Land-based sectors represented:** agriculture & forestry (aggregated as one unique sector)
- **Other modules and particularities:** CIM-EARTH is a recent integrated framework that is under development. In the future, CIM-EARTH will encompass a climate module.
- **Key references:**

  "CIM-EARTH: Framework and Case Study", Elliott et al. (2010C)

  "CIM-EARTH: Community Integrated Model of Economic and Resource Trajectories for Humankind, Version 0.1", Elliott et al. (2010A)

**ENVISAGE** (ENVironmental Impact and Sustainability Applied General Equilibrium Model) by World Bank and FAO

- **Model type:** integrated assessment model encompassing a CGE model
- **Mathematical formulation:** equations model, recursive-dynamic
- **Main exogenous drivers:** population, TFP, bioenergy demand, (carbon) taxes
- **Land use representation:** top-down
- **Land-based sectors represented:** crops, livestock, forestry
- **Other modules and particularities:** ENVISAGE is an integrated assessment framework encompassing a simplified climate model (emulator). A feedback from climate projections to the CGE is possible and carried out by damage functions included in the model. These functions directly affect output levels in function of changes in temperature, calibrated according to sector studies.
- **Key references:**

  "The Environmental Impact and Sustainability Applied General Equilibrium (ENVISAGE) Model", van der Mensbrugghe (2008)

**EPPA** (Emissions Prediction and Policy Analysis Model) by MIT

- **Model type:** CGE model
- **Mathematical formulation:** equations model, recursive-dynamic
- **Main exogenous drivers:** population, TFP, bioenergy demand, (carbon) taxes
- **Land use representation:** top-down
- **Land-based sectors represented:** crops, livestock, forestry
- **Other modules and particularities:** EPPA was initially designed to generate emission baselines and to assess the efficiency of given mitigation policies. Particular attention is paid to depicting different technologies in the energy and transport sectors. Moreover, EPPA can be coupled with a climate model to form the IGSM (Integrated Global Systems Model, cf. Sokolov et al. 2005). Feedback from these projections to the EPPA model is possible.
- **Key references:**

  "The MIT Emissions Prediction and Policy Analysis (EPPA) Model: Version 4", Paltsev et al. (2005)

**FARM** (Future Agricultural Resources Model) by Future Agricultural Resources Model

- **Model type:** CGE model
- **Mathematical formulation:** equations model, recursive-dynamic
- **Main exogenous drivers:** population, TFP, bioenergy demand, (carbon) taxes
- **Land use representation:** top-down, definition of Agro-Ecological Zones (AEZ)
- **Land-based sectors represented:** wheat, other grains, non-grains, livestock, forest products, fish & meat & milk, other processed food
- **Other modules and particularities:** FARM presents an "AEZ approach" for modelling land-use. 6 land classes (defined according to the length of the growing season) are defined. The "GIS Component" (Geographical Information System) of FARM is able to redefine the potential spatial distribution of the 6 land classes at 0.5°*0.5° resolution. Another important focus is on the energy sector, as six energy generation technologies are defined. This helps to determine biofuel demand.
- **Key references:**

  "World Agriculture and Climate Change: Economic Adaptations", Darwin et al. (1995)

  "FARM: A Global Framework for Integrated Land Use/Cover Modeling", Darwin et al. (1998)

  "The land-use effects of a forest carbon policy in the US", Wong and Alavalapati (2003)

**GCAM** (Global Change Assessment Model) by the University of Maryland

- **Model type:** integrated assessment model encompassing two partial equilibrium models, one for land-based activities (AgLU, Agriculture and Land Use model) and one for the energy sector.
- **Mathematical formulation:** optimization model, recursive-dynamic
- **Main exogenous drivers:** population, GDP, yields, input prices, bioenergy demand (from the energy model included in GCAM), taxes.
- **Land use representation:** top-down, definition of Agro-Ecological Zones (AEZ)
- **Land-based sectors represented:** corn, fibre crop, fodder grass, fodder herb, miscellaneous crops, oil crop, palm fruit, rice, root-tuber, sugar crop, wheat, beef, dairy, pork, poultry, sheep & goat, other meat and fish.
- **Other modules and particularities:** GCAM is an integrated assessment framework and is composed of 4 modules:
  - A simple economic growth model
  - A partial equilibrium model focusing on the energy sector.
  - The agriculture-land-use model (AgLU) that is a partial equilibrium model of the agricultural sector with a particular focus on land-use. Determination of production and prices relies on the land allocation carried out by farmers on the basis of expected profitability.
  - A Model for the Assessment of Greenhouse-gas Induced Climate Change (MAGICC): a set of simple models that uses emission baselines provided by the economic models to provide information successively on GHG concentrations in the atmosphere, on the radiative forcing and on global changes in temperature and sea level.
  - Regional Climate SCENario GENerator (SCENGEN): this climate module operates a downscaling at regional level of the projections made by the MAGICC model.
- **Key references:**

  GCAM is documented in a wiki: http://wiki.umd.edu/gcam/index.php?title=Main_Page

  More details can be found in the following papers: "GCAM 3.0 Agriculture and Land Use: Technical Description of Modeling Approach", Wise and Calvin (2011);"GCAM 3.0 Agriculture and Land Use: Data Sources and Methods", Kyle et al. (2011)

**GLOBIOM** (GLObal BIomass Optimization Model) by the IIASA

- **Model type:** partial equilibrium model
- **Mathematical formulation:** optimization model, maximization of the global welfare, recursive-dynamic
- **Main exogenous drivers:** population, GDP, input prices, bioenergy demand, taxes, (yields)
- **Land use representation:** bottom-up, 212 707 grid-cells
- **Land-based sectors represented:** Barley, dry beans, cassava, chick peas, corn, cotton, groundnut, millet, potatoes, rapeseed, rice, soybeans, sorghum, sunflower, sweet potatoes, wheat, oil palm, bovines dairy, bovines others, sheep & goat dairy, sheep & goat others, pigs, poultry broilers, poultry laying hens, poultry mixed
- **Other modules and particularities:** The supply side of GLOBIOM follows a "bottom-up" approach and is input with exogenous crop yields at pixel level. Yields are determined by the EPIC crop model (Environmental Policy Integrated Climate model). GLOBIOM features 4 types of crop management (irrigated, high input-rainfed, low input-rainfed and subsistence), EPIC projects the yield and the needs for fertilisers and water for each of these models. An endogenous switch between these systems is possible. The forestry and livestock sectors are also based on biophysical models, respectively on the Global Forestry Model (G4M) and the RUMINANT model.
- **Key references:**

  "Global Land-Use Implications of First and Second Generation Biofuel Targets", Havlík et al. (2010)

**GTAP** (Global Trade Analysis Project) by the Purdue University

- **Model type:** CGE model
- **Mathematical formulation:** equations model, static in its standard version but many recursive-dynamic versions (e.g. GTAP-AEZ-GHG, cf. Golub et al. 2009)
- **Main exogenous drivers:** population, TFP, bioenergy demand, (carbon) taxes
- **Land use representation:** top-down, definition of Agro-Ecological Zones (AEZ), in the GTAP-AEZ-GHG version of the model
- **Land-based sectors represented:** paddy rice, other grains, other crops, ruminants, non-ruminants, forestry
- **Other modules and particularities:** GTAP is a static general equilibrium model; but a dynamic recursive version of GTAP called GDyn exists (cf. Ianchovichina and McDougall, 2000). GTAP has been declined in several versions including two versions that are particularly well-adapted to climate studies. These versions are GTAP-W (GTAP-Water) and GTAP-AEZ-GHG (GTAP-Agro-Ecological Zones-GreenHouse Gases). In GTAP-W, the production technology structure is reorganized to focus on irrigation and water issues. GTAP-W is coupled with the Water Simulation Module (WSM, also used in IMPACT), which predicts water availability for agricultural purposes taking some constraints such as climate change into account. GTAP-AEZ-GHG features an AEZ (Agro-Ecological Zones) based disaggregation of land.
- **Key references:**

  "Structure of GTAP", Hertel and Tsigas (2000, updated in 2010, draft version)

  "The opportunity cost of land use and the global potential for greenhouse gas mitigation in agriculture and forestry", Golub et al. (2009)

**GTEM** (Global Trade and Environment Model) by the Australian Bureau of Agricultural and Resource Economics and Sciences

- **Model type:** CGE model
- **Mathematical formulation:** equations model, recursive-dynamic
- **Main exogenous drivers:** population, TFP, bioenergy demand, (carbon) taxes
- **Land use representation:** top-down, definition of Agro-Ecological Zones (AEZ)
- **Land-based sectors represented:** crops, livestock, forestry & fishing
- **Other modules and particularities:** in GTEM, a population module determines population dynamics endogenously as function of the progression of each country along a development pathway. A second notable particularity is that productivity changes are endogenous for the infant electric power generation sectors and the mining sector.
- **Key references:**

  "The Global Trade and Environment Model: A Projection of Non-Steady State Data Using Intertemporal GTEM", Pant et al. (2002)

**IMAGE** (Integrated Model to Assess the Global Environment) by PBL Netherlands Environmental Assessment Agency

- **Model type:** integrated assessment model, encompassing a CGE model: LEITAP.

- **Mathematical formulation:** LEITAP is an equations model, recursive-dynamic

- **Main exogenous drivers:** LEITAP as a CGE is mainly driven by the population, TFP, bioenergy demand, (carbon) taxes

- **Land use representation:** top-down in LEITAP but downscaled by Land-Cover Model

- **Land-based sectors represented:** Vegetable, fruit and nuts; sugarcane and beet; wheat; coarse grains; oilseeds; other crops; cattle; goats; sheep; pigs; poultry. When applicable, meat and milk commodities are differentiated.

- **Other modules and particularities:** IMAGE is an integrated modelling framework with many different modules, including:
  - World economy module determines the evolution of important macroeconomic variables, such as GDP.
  - TIMER model (The IMAGE Energy Regional Model) is a global energy model that determines the long-term evolution in energy demand and efficiency as well as the possible transition towards renewable energy sources.
  - LEITAP model is used to model the agricultural sector. LEITAP is a modified version of GTAP that gathers some characteristics of GTAP-Agr (Keeney and Hertel, 2005), GTAP-E (Burniaux and Truong, 2002) and GTAP-Dyn (Ianchovichina and McDougall, 2000).
  - Natural Vegetation Model (NVM) determines the potential geographical distribution of different types of natural vegetation and crops (on the pixel level) according to climate data.
  - Land Cover Model (LCM) re-calculates the land-use map at pixel level according to regional land use data provided by LEITAP.
  - Managed land module contains a crop model that calculates potential crop productivity. Potential productivities are input in the land cover module which is then able to determine land allocation.
  - A few models simulate gas cycles using emission baselines generated by the economic models. They provide data to the climate model.
  - Climate model generates climate projections.
  - Complementary modules: sea-level rise, biodiversity, land degradation.

- **Key references:**

  IMAGE is described in detail on the website of the PBL:

  http://themasites.pbl.nl/tridion/en/themasites/image/

**IMPACT** (International Model for Policy Analysis of Agricultural Commodities and Trade)

- **Model type:** partial equilibrium model
- **Mathematical formulation:** equations model, recursive dynamic
- **Main exogenous drivers:** population, GDP, input prices, bioenergy demand, yields and areas trends
- **Land use representation:** top-down,
- **Land-based sectors represented:** cassava, chickpeas, cotton, groundnuts, maize, millet, other grains, palm, pigeon pea, potato, rapeseed, rice, sorghum, soybean, sugar beets, sugarcane, sunflower, sweet potatoes & yams, temperate fruits, total other oilseeds, tropical & sub-tropical fruits, vegetables, wheat, other crops, beef, eggs, milk, pork, poultry, sheep & goats
- **Other modules and particularities:** Production in each sector is calculated as multiplication of area and yield. In both equations there is a trend term. In the yield equation, this yield trend can be recalibrated according to the projections of a crop model (DSSAT in this case, Decision Support System for Agrotechnology Transfer, cf. Hoogenboom et al. 2010). In both equations, there is also a water stress term that reduces area and yield according to water scarcity. Water scarcity for irrigation purposes is determined by the Water Simulation Model (WSM, cf. Rosegrant et al. 2012).
- **Key references:**

  "International Model for Policy Analysis of Agricultural Commodities and

  Trade (IMPACT): Model Description", Rosegrant et al. (2012)

**MAgPIE** (Model of Agricultural Production and its Impact on the Environment) by the Potsdam Institute for Climate Impact Research

- **Model type:** partial equilibrium model
- **Mathematical formulation:** optimization model, minimization of the global cost, recursive-dynamic
- **Main exogenous drivers:** population, GDP, input prices, bioenergy demand, yields, taxes
- **Land use representation:** bottom-up, 2178 grid-cells
- **Land-based sectors represented:** temperate cereals, tropical cereals, maize, rice, groundnut, oils palm, rapeseed, soybeans, sunflower, pulses, potatoes, cassava, sugar beets, sugar cane, vegetables/fruits/nuts, two fodder crops, ruminant meat, non-ruminant meat, milk
- **Other modules and particularities:** MAgPIE follows a bottom-up approach and is input with exogenous yields at grid-cell level. These yields are determined by the Lund-Potsdam-Jena (LPJmL, cf. Bondeau et al. 2007) crop model. In contrast to other models presented in this review, MAgPIE features an endogenous technical change which cost is accounted for in the objective function.
- **Key references:**


- "Integrated Assessment Model of Climate Change: The AIM Approach", Matsuoka et al. (2001)
- "Long-Term GHG Emission Scenarios for Asia-Pacific and the World, Technological Forecasting and Social Change", Jiang et al. (2000)
- "Development of spatially explicit emission scenario from land-use change and biomass burning for the input data of climate projection", Kato et al. (2011)

**MIRAGE** (Modeling International Relationships in Applied general Equilibrium) by CEPII and IFPRI

- **Model type:** CGE model
- **Mathematical formulation:** equations model, recursive-dynamic
- **Main exogenous drivers:** population, TFP, bioenergy demand, (carbon) taxes
- **Land use representation:** top-down, definition of Agro-Ecological Zones (AEZ) in some versions of MIRAGE (cf. Bouët et al. 2010)
- **Land-based sectors represented:** rice, wheat, maize, other crops, vegetables & fruits, oilseeds for biodiesel, sugar cane & sugar beet, cattle meat, other animal products, other cattle, forestry
- **Other modules and particularities:** In order to study climate change effects, the total factor productivity baseline in MIRAGE can be recalibrated according to the yield projections carried out by the DSSAT crop model (Decision Support for Agrotechnology Transfer, cf. Hoogenboom et al. 2010).
- **Key references:**

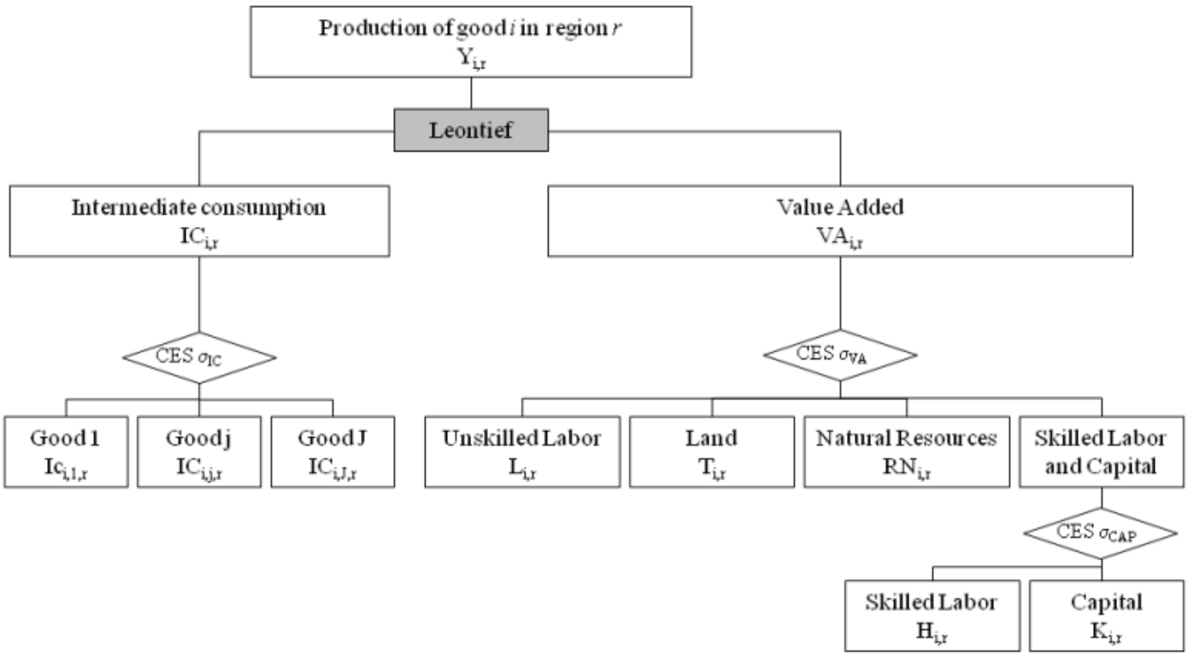
  The MIRAGE model is documented in a wiki: http://www.mirage-model.eu/miragewiki/index.php/Main_Page

  "Modeling the global trade and environmental impacts of biofuel policies", Bouët et al. (2010)

# Appendix 2: The production function in MIRAGE

Figure 1 shows the production function used in the MIRAGE model:

### Figure 1: Structure of the production technology in the MIRAGE model (source: MIRAGE wiki)




In this figure, the respective aggregations of intermediate inputs and factors (the aggregate is often called value added) are operated by Constant Elasticity of Substitution (CES) production functions that enable substitutions[36] between inputs. However, the aggregation of the intermediate input aggregate and value added is made by a Leontief[37] function with which no substitutions are possible.

[36] Substitutions are possible when for a given level of output different combinations of production inputs can be used.

[37] A Leontief function can be written as follows: $Q = Min(\frac{z_1}{a}; \frac{z_2}{b})$, in which Q is the quantity of output produced, $z_1$ and $z_2$ the quantity of inputs or factors that are used and a and b two parameters.

# Appendix 3: Research topics addressed in the articles used for this review

**Table 9: Mapping of the different research topics found in the literature review (No. of articles found on Google Scholar / No. of articles found on Scopus)**

| Models | Climate change impacts assessment | | | Mitigation policies assessment : impacts on the economy and on emissions abatement | | | | | | | | Emissions projections (incl. land use related emissions) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Economy-wide impacts (GDP, international trade) | Impacts on land-based sectors (incl. on land-use patterns) | Impacts on poverty, on distributional aspects | Mitigation impacts and costs | | Analysis of specific policy instruments | | Specific sectoral studies | | Biofuels studies | | |
| | | | | Determination of mitigation costs | Impacts on the economy (incl. on land-use) | Economic instruments : incl. Carbon taxes, Cap-and-Trade Systems | Kyoto Protocol | Role of the livestock sector, incl. diet shifts | Deforestation / Carbon sequestration (in forests and soils) | Impacts of biofuel policies on GHG emissions | Impacts of biofuel policies on the economy and on land-use change | |
| AIM | 1 / 1 | 1 / 1 | | 2 / 2 | 1 / 1 | | 1 / 1 | | | | | 5 / 5 (incl. / 1) |
| CIM-EARTH | | | | | 1 / 1 | 1 / 1 | | | | | 2 / | |
| ENVISAGE | 7 / | 7 / | 3 / | 1 / | 2 / | 3 / | | | | | 1 / | |
| EPPA | 2 / 2 | 3 / 3 | | 14 / 12 | 5 / 5 | 6 / 5 | 4 / 4 | 1 / 1 | 2 / 2 | 1 / 1 | 2 / 2 | 5 / 5 ( incl. 1 / 1) |
| FARM | 7 / 4 | 7 / 4 ( incl. 2/) | | | 1 / 1 | | | | 1 / 1 | | | |
| GCAM | | 1 / 1 | | 2 / 2 | 2 / 2 (incl. 1 / 1) | 1 / 1 | | | | | 2 / 2 | 1 / 1 |
| GLOBIOM | | | | 2 / | | | | | 2 / | 3 / 2 | 3 / 2 | 3 / 2 |
| GTAP | 8 / 5 | 8 / 5 ( incl. 1 / 1) | 2 / 1 | 1 / 1 | 3 / 1 ( incl. 1 / | | | 3 / 1 | 1 / 1 | 2 / 3 | 5 / 6 | 4 / 3 (incl. 4 / 3) |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | 1) | | | | | | | |
| GTEM | | | | 5 / 3 | 7 / 3 | | 4 / 2 | | 2 / 1 | | | 2 / 1 |
| IMAGE | 4 / 3 | 11 / 10 ( incl. 5 / 5) | | 6 / 6 | 5 / 5 ( incl. 1 / 1) | | | 1 / 1 | 1 / 1 | 2 / 3 | 2 / 3 | 13 / 11 (incl. 6 / 5) |
| IMPACT | | 3 / 2 ( incl. / 1) | 1 / | | 1 / | | | | | 1 / 1 | 3 / 2 | |
| MAgPIE | | 2 / 2 ( incl. 2 / 2) | | 2 / 2 | 1 / 1 ( incl. 1 / 1) | | | 1 / 1 | | 2 / 2 | 5 / 4 | 3 / 3 (incl. 3 / 3) |
| MIRAGE | 1 / | 1 / | | | | | | | | 5 / | 5 / | 5/ (incl. 5 /) |

# Appendix 4: Complete list of references and associated topics

G: Reference found in Google Scholar

S: Reference found in Scopus

**AIM:**

Fujino J, Nair R, Kainuma M, Masui T, Matsuoka Y. 2006. Multi-gas mitigation analysis on stabilization scenarios using AIM global model. The Energy Journal 2006;3 Special Issue:343353. **G** **S**

Garg A, Shukla P.R, Ghosh D, Kapshe M, Rajesh N. 2003. Future greenhouse gas and local pollutant emissions for India: Policy links and disjoints. Mitigation and Adaptation Strategies for Global Change, 8 (1), pp. 71-92. Emissions predictions **G** **S**

Garg A, Shukla P.R, Kapshe M, Menon D. 2004. Indian methane and nitrous oxide emissions and mitigation flexibility. Atmospheric Environment, 38 (13), pp. 1965-1977. **Mitigation policies-Emissions predictions** **G** **S**

Jiang K, Masui T, Morita T, Matsuoka Y. 2000. Long-term GHG emission scenarios for Asia-Pacific and the world. Technological Forecasting and Social Change, 63 (2-3), pp. 207-229.**Emissions predictions** **G** **S**

Kainuma M, Matsuoka Y, Morita T. 1999. Analysis of post-Kyoto scenarios: The Asian-pacific integrated model. Energy Journal, 20 (SPEC. ISS.), pp. 207-220. **Mitigation costs-Kyoto protocol-Emissions trading scheme-Impacts of mitigation policies** **G** **S**

Kainuma M, Matsuoka Y, Morita T, Masui T, Takahashi K. 2004. Analysis of global warming stabilization scenarios: The Asian-Pacific Integrated Model. Energy Economics, 26 (4), pp. 709-719.**Impacts of climate change- Carbon tax** **G** **S**

Kato E, Kawamiya M, Kinoshita T, Ito A. 2011. Development of spatially explicit emission scenario from land-use change and biomass burning for the input data of climate projection. Procedia Environmental Sciences, 6, pp. 146-152. Emissions predictions-land use change-deforestation **G** **S**

Matsuoka Y, Morita T, Kainuma M. 2001. Integrated Assessment Model of Climate Change: the AIM approach. Present and Future of Modeling Global Environmental Change: Toward Integrated Modeling, Eds., T. Matsuno and H. Kida, pp. 339–361. **G**

Sharma M, Sharma C, Qaiyum A. 2012. Impacts of future Indian greenhouse gas emission scenarios on projected climate change parameters deduced from MAGICC model. Climatic Change, 111 (2), pp. 425-443. **Emissions and climate predictions** **S**

**CIM-EARTH:**

Elliott J, Foster I, Judd K, Moyer E, Munson T. 2010A. CIM-EARTH: Community Integrated Model of Economic and Resource Trajectories for Humankind, Version 0.1. Argonne National Laboratory Technical Memorandum ANL/MCS-TM-307.

Elliott J, Kotamarthi V.R, Drewniak B, Franklin M, Foster I, Munson T, Doctor R, Wang M. 2010B. Some economic and societal implications of a biofuel based economy: Results from CIM- EARTH, a new integrated assessment model. American Meteorological Society Fifth Symposium on Policy and Socio-Economic Research, January 2010. **Biofuels-Economic and societal consequences** **G**

Elliott J, Foster I, Judd K, Moyer E, Munson T. 2010C. CIM-EARTH: Framework and Case Study. The B.E. Journal of Economic Analysis & Policy, July 2010. **Carbon tax impacts on international trade** **G** **S**

Elliott J, Foster I, Loudermilk M, Munson T. 2011. **Impact of Eliminating Biofuels Production on US Gasoline Prices: An Equilibrium Analysis.** Preprint ANL/MCS-P1983-1111, N. **Economic impacts of biofuels** **G**

**ENVISAGE:**

Bussolo M, De Hoyos R, Medvedev D, van der Mensbrugghe D. (2008). **Global Climate Change and its Distributional Impacts. Conference paper,** Future of the Global Economy, 11th Annual Conference on Global Economic Analysis, Helsinki, 12-14 June, 2008. **Impacts of climate change** **G**

Cororaton C.B, Timilsina G.R, Mevel S. 2010. Impacts of Large Scale Expansion of Biofuels on Global Poverty and Income Distribution. Proceedings Issues, 2010: Climate Change in World Agriculture: Mitigation, Adaptation, Trade and Food Security, June 2010, Stuttgart-

Hohenheim, Germany 91279, International Agricultural Trade Research Consortium. **Biofuels-Economic impacts of biofuel policies G**

Galeotti M, Roson R. 2011. Economic Impacts of Climate Change in Italy and the Mediterranean, Updating the Evidence. Center for Research on Energy and Environmental Economics and Policy, Working Paper n°45. **Economic impacts of climate change G**

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