Centro Euro-Mediterraneo
sui Cambiamenti Climatici

Research Papers
Issue RP0133
June 2012

Division: Climate Impacts and Policies. An Economic Assessment

Modelling Land use, Land-Use Change, and Forestry in Climate Change: A Review of major Approaches

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SUMMARY The rapid development of climate policies and the need to understand the dynamics of climate change have highlighted and shaped the role of land use, land-use change and forestry dynamics (LULUCF), making it an issue of global importance. As a consequence, LULUCF has become a central topic in economic theory and in environmental sciences. The attention is focused on creating and expanding comprehensive global land-use datasets and on improving the modelling strategies allowing for an extensive representation of the land-use system. However, this is a relatively new research field and the development of this challenging process is likely to require greater effort in the years to come. By adopting a straightforward model classification, this paper provides a broad, but detailed, overview of the most representative methods and models developed to date. This summary will guide a following critical discussion on relevant methodological aspects related to the global modelling of land use and its changes. An additional focus is placed on the representation of forest-carbon sequestration within climate mitigation, which represents one of the most demanding issues from a modelling perspective.

Keywords: land, land-use change modelling, agriculture, forestry

JEL: Q23, Q24, Q51, Q54

I am grateful to Ramiro Parrado and Renato Rosa for their suggestions

Contents

Introduction and Motivation

The land-use system represents a very important link between the biosphere and the economy. Human action is directly mapped into the biosphere through this link. Management practices in agriculture and forestry have a crucial impact on natural cycles, which in turn, affect land productivity and production levels for food and wood as well as ecosystems' dynamics (Foley *et al.*, 2005).

Despite this, there are not many examples of global models with a comprehensive representation of land use and its changes. A complex design of the land-use system, which includes both forestry and agriculture sectors at the global scale, has been hindered by a number of technical and data-related issues. First, land use has been mostly considered from either an economic (WATSIM by Kuhn, 2003; IMPACT-Water by Rosegrant *et al.*, 2005) or a geographical/biophysical standpoint (CLUE by Veldkamp and Fresco, 1996), and rarely as a multiple-sided issue. As a result, important interactions and feedbacks between and from the economic and physical spheres have often been left outside the scope of most analyses. Second, the lack of land information for many variables and parameters, and for many regions of the world has confined research on land use to geographically restricted areas, so that a good number of existing analyses and models focus on specific zones (SALU by Stephenne and Lambin, 2001, 2004; CLUE by Veldkamp and Fresco, 1996).

Only recently, land use, land-use change, and forestry dynamics (LULUCF) have become central topics in economic theory (Hertel *et al.*, 2009). Moreover, the development in international agreements on climate and climate policy has been shaping their role, making LULUCF an issue of global importance. Consequently, researchers are becoming increasingly eager to develop sophisticated modelling strategies to i) join together economics with physical and spatial characteristics; ii) represent the global dimension of land use, iii) assess its impacts on climate mitigation.

In this direction moves the development of i) new large-scale datasets for land use (GTAP-AEZ by Lee 2004, Lee *et al.*, 2009; USEPA, 2006) and ii) new approaches combining strengths of different models. Spatial considerations have been embedded in climatic-economic models or some economic concepts have been incorporated in geophysical analysis (KLUM@GTAP, IMAGE-LEITAP, etc.). In line with this, more structured and very complex integrated assessments have come into development (IMAGE, AIM, etc). However, a realistic and complete representation of the land system, which links environmental and economic sciences, represents a new and multifaceted research field which is likely to require more effort in the next future.

In the light of the aforementioned, this article attempts to summarise state-of-the-art in LULUCF modelling and. This overview helps to provide a following critical discussion on key aspects which are challenging researchers who are eager to progress in this direction. Compared with the majority of existing reviews, mainly focused on specific types of models, this paper provides a broad, updated, and comprehensive picture of existing frameworks in LULUCF modelling, by critically comparing characteristics, strengths and limits of most used approaches. This is intended to provide stimulus for further advancing the debate on land-use modelling strategies. In addition, within the context of this thesis, this first chapter provides the reader with useful knowledge to enable a better understanding of the empirical applications offered in chapter 2 and 3.

Clearly, this paper does not have the ambition of exhaustively describing the complete sample of existing land-use models or methodologies rooted in a vast number of disciplines.[1] This would require the development of a much extended research, going beyond the constrained length appropriately required for a scientific article. The focus is mainly placed on those frameworks assessing the problem from a global perspective. The attention is restricted to agriculture and forestry, the two land covers to which almost one-third of global GHG emissions can be associated (Hertel, 2012).

The structure of this work is organised as follows. Section 1 briefly introduces the concept of land-use in climate mitigation and adaptation, focusing on its importance and drivers. Section 2 draws a straightforward model categorisation which guides transverse considerations on major features, strengths, and concerns of existing frameworks. A critical review of the most relevant geographical, economical, and integrated assessment frameworks is then provided in sections 3, 4, and 5. Drawing from these sections, the 6th one summarises and reviews the following key methodological issues regarding the development of a comprehensive land-use modelling:

i) The level of the analysis and the spatial dimension,
ii) Land heterogeneity representation,
iii) Data limitation and harmonisation,
iv) Forestry design within global climate change modelling.

The final section concludes providing hints for further research, future improvements, and messages for policy considerations. Given the relevance of the forest sector representation within environmental economics Appendix 1.1 offers an overview of its forest role and development within international negotiations. Appendix 1.2 provides a schematic summary of the majority of the models analysed, while Appendix 1.3 reports acronyms and abbreviations used within the text as well as extended names of cited models.

1. Relevance and drivers of LULUCF

The most important land-using activities at the global scale refer to agriculture and forestlands (Heirstermann *et al*., 2006). Forestry and agriculture together are broadly acknowledged to offer considerable potential for greenhouse gases (GHG) mitigation (IPCC, 2007 4AR) and represent cost-effective stabilisation strategies especially in a short-run perspective (EMF21, 2008).

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[1] Readers interested in developing their knowledge on other models or model classifications are invited to refer to the following: Van Ittersu *et al.* (1998) for exploratory land-use studies and their role in policy; Kaimowitz and Angelsen (1998; 1999) for land use related to economic-based deforestation; Briassoulis (2000) for a general review; Bockstael and Irwin (2000) for land-use models based on economic theory; Irwin and Geoghegan, (2001) for spatial and economic classifications of models; Lambin (2000) and Veldkam and Lambin (2001), for models of agricultural intensity; Agarwal *et al*. (2002), for spatial, temporal, and human decision-making dimensions; Parker *et al.* (2002) for Agent-Based Systems, Verburg *et al.* (2004) for mainly descriptive models; Balkhausen and Banse (2004), for partial and general equilibrium models focused on global land use and trade; Heistermann *et al*., (2006), for continental and global land use models; or Palatnik and Roson, (2009), for the modelling of agriculture in general equilibrium analysis.

Forestlands may crucially contribute to gain valuable time before implementing other mitigation measures (Tavoni *et al*., 2007). Total carbon content in world forests accounts for 283 Giga tonnes (Gt) in forest vegetation, 38 Gt in dead wood, and 317 Gt in soils and litter, while its totality exceeds the amount existing in the atmosphere (IPCC, 2007 4AR). From an economic standpoint, forest-based mitigation has been recognised as a cost-efficient, and a possibly optimal, abatement strategy within climate stabilisation policies (Richard and Stokes, 2004; van Kooten, 2007). On the other hand, activities in agriculture (cropland and livestock) account for approximately 50% of global anthropogenic CH_4 emissions and 85 % of global N_2O emissions (Scheehle and Kruger, 2006).

Due to their natural ability to remove GHGs from the atmosphere, the forestry and agriculture sectors have been receiving increased attention. For example, in 1997, the Kyoto Protocol stipulated the possibility to include removals and emissions deriving from land-use change and forestry activities (LULUCF) as of 1990. Since then, Annex I countries have been permitted to use forest-carbon sequestration to meet their commitment targets in emissions reduction.[2] Nevertheless, under certain circumstances, these sectors may also turn out to be important carbon sources releasing significant amounts of GHGs. This circumstance is due to forest disturbances, tropical deforestation, or unsustainable agricultural and forest management, among other factors.

These arguments highlight the relevance of investigating future pathways of the economic and natural environments, by developing a good representation of land use and land-use change at the global level. Since the land-use system is a many-sided subject, its realistic representation involves defining and characterising the wide range of factors influencing its path. In doing so, some of the most challenging issues are that i) drivers are numerous, of different nature, and often closely interlinked with one another; ii) the relevance of those factors changes according to the spatial scale of the analysis; ii) they produce different impacts either on agriculture or forestry or on both of them simultaneously (Heistermann *et al.,* 2006).

The different nature of these factors is normally embedded into a three-tiered structure distinguishing amongst biophysical/geographical, economic, and socio-cultural drivers. The first class of biophysical/geographical factors refers to the impacts of climate (Ogallo *et al*., 2000), the availability of water, (Rosegrant *et al*., 2002), and soil conditions (Lal, 2003), among others. The second class of economic variables mainly considers income, rents, and prices (Delgado, 2003). The third class of cultural or political factors includes issues such as law enforcement and land tenure conditions (Rockwell, 1994; Pfaff, 1999; Müller, 2004).

Accounting for all these aspects and their interlinked effects in the same land-use analysis is extremely complex, especially when dealing with a global representation of the phenomenon under study. For example, global models of LULUCF normally neglect the effects and feedbacks of socio-cultural drivers (CLUE, KLUM, etc.) while a few of them integrate economic and geographical information (e.g., IMAGE with LEITAP). The tradition, which normally disregards cultural or

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[2] See Appendix 1.1 for more information on land-use and forestry activities within international negotiations.

political factors, views decisions on agriculture and forestland uses as modelled either from a geographical or an economic perspective. A recent modelling strategy has attempted to integrate the two spheres by complementing information and combining the strengths of existing methods while reducing their limitations (Heistermann *et al.,* 2006).

The following sections describe a selected sample of standalone models for LULUCF, and provide examples of recent approaches pursuing such integration. Specifically, soft and hard links, model couplings, as well as integrated assessments represent the most recent scheme to deal with the complex matter of representing the land-use system overall.

2. Modelling LULUCF: Different approaches to deal with the same problem.

The complexity of modelling LULUCF has brought a broad variety of approaches into production. Most models are different in terms of methodologies, purposes, assumptions, geographic areas of the analysis, and both the source and type of data used. The objective of integrating the socio-economic and the spatial dimension of LULUCF, often implying developing combinations of dissimilar models used simultaneously, have further complicated the overall picture.

As a result of the aforementioned, restraining models in a rigid classification would not reflect the numerous dimensions normally characterising most of them (purpose, type of data, regional aggregation, etc.). For example, one model can be global, economic, statistical, prescriptive, etc., at the same time. However, it is useful to consider some classifications to guide a more organized discussion on the modelling aspects of major interest. For this reason three broad categories are identified. The first one involves geographical models which mostly focus on biophysical characteristics. The second one encompasses different approaches developed with economical-oriented models. A third category considers the interaction of the previous classes highlighting the role of each model either as a standalone solution or as part of an integrated assessment. The following list clarifies the classification structure used in this paper:

A. Geographical models
    a. *Statistical models*
    b. *Rule-based models*
B. Economic models
    a. *Econometric models*
    b. *Partial equilibrium models*
    c. *General equilibrium models*
C. Standalone versus Linked or Integrated models

The categorization used in the following sections offers a summary description of each of the classes introducing examples of selected models. By reporting major strengths and limitations of the broader model groups, Table 1 below serves to introduce a following description of major characteristics of these classes and examples of corresponding models. Table 2 condenses the analysis in a schematic distinction between strengths and limitations for sub-model categories considered in sections 3 and 4 (belonging to economic and geographic frameworks), while Table 3, in section 5, places the attention on the link-type underlying Integrated Assessment Approaches. Appendix 1.2 offers more specific information for each single model considered.

Table 1: Main Characteristics of the broad modeling categories

	STRENGHTS	LIMITATIONS
GEOGRAPHIC MODELS	Spatial dimension of land use change; Biophysical constraints on land-use change.	No endogenous economics; No endogenous land use change; No global analysis.
ECONOMIC MODELS	Based on economic theory; Endogenous land allocation; Opportunity costs explicitly considered; Consideration of markets interactions.	No spatial assessment; No physical constraints or biophysical land characteristics; Market structure completely drives land-use allocation.
LINKED OR INTEGRATED ASSESSMENT MODELS	Economy linked with biosphere & atmosphere in a unique framework; Synergies and trade-offs of different policy strategies; Long-time scale analysis.	High complexity & demanding for computer power; Sacrifices a detailed representation of land processes; Linking models maintain details but require much harmonization to reach convergence; Difficult to perform uncertainty analysis.

Source: Own Elaboration

3. The Geographic/Spatial Framework

Broadly speaking, geographic analyses have been supported by the rapid improvement of remote sensing and Geographic Information Systems (GIS). They focus their attention to the spatial dimension and the properties of land use. Land suitability and land-use allocation derive from either empirical or statistical verification. Alternatively, they are based on decision rules, resulting from other studies or deriving from reasonable, yet sometimes subjective, judgments. These models do not provide support to assess endogenously interactions between supply, demand and trade. In other words, economic driving factors are typically ignored. Regional or large-scale assessments represent the majority of existing exercises.

3.1 Statistical Models

Statistical representation makes use of statistical techniques to model spatial change in land. Land allocation is assumed to result from different forces, or driving factors (socio-economic, environmental, and other factors), assumed exogenous to the land-use system. In particular, a system of equations is used to represent the relation between land demand or supply, and its determinants. This relation, expressed by the coefficients in the system, is normally obtained implementing multiple or multivariate regression techniques. The empirical analysis is supported by some rules, which concur to control the land competition among different uses. These approaches, simple to apply and manage, lack an endogenous categorisation of land-use economics and normally do not foresee a role for feedback effects.

Structured frameworks based on statistical techniques are CLUE (Veldkamp and Fresco, 1996) and ELPEN-System (Wright *et al.*, 1999). CLUE is a geographic model of land use, which simulates recent and future changes in land-use patterns through a multiple regression approach supported by transition rules of different nature.[3] Multiple land-use categories are accounted for in addition to agriculture and forests. The land spatial allocation procedure combines empirical analysis with scenario-specific decisions-rules and neighbouring characteristics. Allocation is limited by the demand for land cover at the national level, which sometimes overrules constraining conditions on local suitability. Natural vegetation dynamics are governed by conversion elasticities changing in successive stages. Conversion costs as well as local policies may prevent or limit the transformation of forestland into agriculture. Although CLUE has been used for large-scale analysis, it is not globally extended. Regional applications include the areas of Ecuador (De Koning *et al.*, 1999), China (Verburg *et al.*, 1999a), Indonesia (Verburg *et al.*, 1999b), Central America (Kok and Veldkamp, 2001), Vietnam (Castella *et al.*, 2006), and Neotropics (Wassenaar *et al.*, 2007). Spatial resolution depends on the individual analysis but ranges between 7 and 32 km due to the large extent of the areas under assessment and the lack of more detailed data. More recently, Verburg and Overmars (2009) improved the CLUE model by developing Dyna-CLUE which integrates local-specific and large-scale dimensions of land use in Europe at 1x1 km grid cells. In this context land allocation is the result of a combination between a top-down approach, where land use mostly depends on exogenous macroeconomic factors, and a bottom-up approach based on locally specific processes of vegetation dynamics. Despite the effort, the model structure remains that of a geographic model, where land-use economics are not endogenously integrated in the system.

Likewise the previous model, ELPEN-System is an example of a statistically oriented model where multiple linear regressions techniques are implemented to assess policy impacts on the livestock sector in Europe. It is based on both statistical and geographical data and in opposition to CLUE, which consists of multiple land-use types, and focuses only on the livestock sector.[4] Both CLUE and ELPEN do not explicitly address the interaction of land-use processes and driving factors, which is conversely, what is pursued by Rule-based models.

3.2 Rule-based Models

Compared with statistical frameworks, rule-based models try to replicate land-use processes addressing more explicitly the interactions between such processes and driving factors. They can capture the effects of new land-use policies and can incorporate different factors for future land prediction. Nevertheless, with statistical models they share the lack of endogeneity of land competition.

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[3] For more information on the CLUE model see the its webpage at: http://www.ivm.vu.nl/en/Organisation/departments/spatial-analysis-decision-support/Clue/index.asp

[4] For more information on ELPEN see : http://www.macaulay.ac.uk/elpen/docs/ELPEN_final_report.ppt

The rules governing the land ranking can be of different types (physical suitability, market rules, etc). In IMAGE (Alcamo *et al.*, 1998; IMAGE, 2001; MNP, 2006)[5] and SALU (Stephenne and Lambin, 2001, 2004) the expansion of agricultural land is driven by demand and is estimated on the basis of a suitability ranking involving climatic, physical aspects and sometimes some underlying economics. In particular, SALU is used to formulate endogenous agricultural intensification, resulting after a certain level of agricultural land expansion has been achieved at the most extensive level of technology. IMAGE, assumes basic drivers for demographics and economic development, production and consumption of energy, agricultural demand, trade, and production. Conversely to SALU, which is limited to the Sahel area, IMAGE is global and accounts for agriculture as well as for managed and unmanaged forests.[6] Furthermore, IMAGE is one of the few existing models accounting for agricultural soil carbon fluxes.

A specific rule-based model for forestry dynamics is EFISCEN (Schelhaas *et al.*, 2007), which focuses on managed and even-aged forests in Europe. It works at the provincial level and is mostly used to compare different forest-management scenarios. It can be used to explore the plausibility of a scenario based on certain levels of a specific forest-related variable, such as harvest or forest expansion rates. The model allows for long-term projections on area, growing stocks and harvest rates, wood production possibilities, climate change impacts, natural disturbances, carbon budgets and related dynamics for biomass and soil. The detail that can be reached depends on data availability for the initial matrix, which requires data for each forest type on area and average standing volume per age class; growing stock volumes; information on natural mortality per age class, on thinning and final felling regime; etc. At the current state, the model distinguishes, for each forest type, among 60 age classes and 10 volume classes, in addition to tree species, owner, and the administrative unit in which the forest is located. Transition matrices define land allocation over time. More specifically, aging, growth, thinning, felling, and natural mortality are simulated by moving in/out areas within the cells of the matrix. A carbon module is then used to convert model outputs into carbon stocks. Similarly to SALU, this model limits the analysis to a restricted environment and is not suitable to assess dynamics in uneven-aged or unmanaged forests. Finally, it cannot simulate fast growing forests with a rotation period shorter than 5 years (time step of EFISCEN).

An additional version of rule-based approach derives such rules from expert judgements (e.g., van Delden and Luja, 2007). Nevertheless, the extent to which this expert considerations can be extended to large areas remains arguable.

Finally, ACCELERATES (Rounsevell *et al.*, 2003) and KLUM (Ronneberger *et al.*, 2005) offer a variant to SALU and IMAGE, deriving decisions rules from agents' profit maximisation. Due to this characteristic, they might be considered similar to the economic-based optimisation frameworks described below. However, their main focus remains biophysical, which explains why they are generally grouped within the geographical model category. Both ACCELERATES and

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[5] For more information on IMAGE see its webpage at: http://themasites.pbl.nl/en/themasites/image/index.html

[6] In addition to be a geographic model IMAGE represents an example of Integrated Assessment Model. For this reason more details are given in the IAM section below.

KLUM replicate major characteristics of crop allocation to establish a relation between economy and vegetation. Agricultural land area is allocated among different uses assigning to each spatial unit the use with the highest expected profit per hectare, adjusted for a risk aversion factor calibrated to observed data. Landowners choose the most profitable land allocation over a certain area extension. The overall optimal allocation is assured, as the sum of local optima equals the global optimum.

Overall, geographical frameworks do not account for the underlying economic aspects of land use, nor do they involve responses of consumption and production to changes in prices. The following sections present models that deal more specifically with the economics of land-use.

4. The Economic Framework

Conversely to land-use models, economic models are based on the traditional economic theory. They generally aim at explaining changes in land-use patterns with changes in economic variables such as production and consumption of food and products prices. In doing so, they assume functional forms for utility, production, demand, and structure of population, if endogenous. They may be focused either on land-intensive sectors or on the economy as a whole. The market structure completely drives land-use allocation while geographical or biophysical factors are normally vaguely represented. Economic frameworks can be further classified into i) Econometric models and Ricardian Analysis; ii) Optimization and Equilibrium models.

4.1 Econometric Models and Ricardian Analysis

Econometric models specifically focusing on land-use change and its drivers seek to estimate the opportunity cost of land and carbon-sequestration costs by analysing landowners' historical decisions - revealed preferences – on land-use allocation. This allows investigating the relation between choices on land allocation between forestry and agriculture and market prices differentials (for instance, for crops and timber products). By deriving a response function this approach allows simulating how landowners would react under similar or different policy scenarios (such as a governmental subsidy to forest-carbon sequestration).

In general, the interest in the econometric approach lies, among other things, on its flexibility and relatively simple way in which it is possible to account for a variety of factors affecting land opportunity costs, or in which it incorporates changes in land quality and landowners' preferences.
At the same time, however, this methodology is susceptible of some critiques. First, it normally neglects the role of technology and, in some cases, of climate variability too. Secondly, the assumption that driving factors are exogenous is sometimes odd. As a result, problems of endogeneity, collinearity, and reverse-causality of the relation often arise with respect to many explanatory variables (population growth, prices in the long-run, etc.), undermining the unbiasedness or the efficiency of the model estimates (see Chomitz and Gray, 1996; Pfaff, 1999; Mertens and Lambin, 2000, etc.). Third, this approach is often developed within a short-run analysis and small sample sizes, which results in a low degree of explanation (Verburg *et al.*, 2004). Furthermore, the regression techniques typically implemented leave no scope for a comprehensive

understanding of the interactions between underlying drivers, processes and their relations, which are frequently considered constant in time. These aspects call for a careful analysis of the results, especially for long-run simulations (Heistermann *et al.*, 2006).

A parallel method is the so-called "Ricardian approach" (Mendelsohn *et al.* 1994, Darwin 1999, etc.). It is generally presented in the form of a cross-sectional analysis, which aims to measure the impacts of a changing climate on landowners' choices. Despite its greater focus on climate variability with respect to traditional econometric approaches, a one-year data analysis is likely to produce unstable results (Deschenes and Greenstone, 2007). In addition, inter-annual changes in weather, normally used as a proxy for intertemporal climate variation, is unlikely to be forecasted by farmers and therefore results in a poor surrogate for climate change, to which landowners can better adapt (Massetti and Mendelsohn, 2011). As a result, the latest development of this methodology intends to enhance the cross-sectional approach with a panel study analysis, more appropriate to register farmers' choices on land-use in time. Despite the answers given to these concerns, the Ricardian approach as well as the traditional econometric approach can still be claimed to develop a regional rather than a global analysis, which makes it difficult to scale-up resulting outcomes.

Examples of econometric approaches to land-use change are provided by Stavins (1999), Plantinga and Mauldin (2001), and Lubowski *et al.* (2006). More recent applications are Pfaff *et al.* (2007) who evaluate implications of the Clean Development Mechanism under the Kyoto Protocol, by Munroe and Muller (2007), presenting an exercise related to Vietnam and Honduras. As for the Ricardian technique, it has been successfully applied since the early 90's. Recent applications include, among others, Sanghi and Mendelsohn (2008) and Mendelsohn and Dinar (2009).

4.2 Optimisation and Equilibrium Approaches

By means of mathematical programming or alternative optimisation techniques, optimisation models maximise individual/regional welfare or firms' profits under some constraints on budget, natural resources or technology. Functional forms are assumed for preferences, production, and other variables. Within the representation of the economic system, land is normally conceived as one input of production for land-using sectors. It can be assumed as either fixed or extendable in quantity.

A variant of the optimisation framework is characterised by equilibrium models, where the solution derives from equating demand and supply for either the land-using sectors (partial equilibrium models), or the economy as a whole (general equilibrium models). They solve a set of nonlinear equations that include zero-profit conditions, market clearing conditions, and income balance equations. The equilibrium of the system, characterising this approach, can be either static, dynamic as well as competitive, or non-competitive. More specifically dynamic frameworks can be distinguished into recursively-dynamic and forward-looking models, depending on the type of equilibria and assumptions on agents' expectations. In addition, a competitive economy is generally assumed, although market imperfections may also be taken into account (for an analysis of the techniques to include imperfect competition in equilibrium models see for examples Joseph, 1998).

Parameters and coefficients in the models are calibrated with either mathematical or statistical methods, or are alternatively derived from econometric estimations external to the models.

These models are powerful tools for land-use impact assessments in climate change. One of the most important advantages is their ability to capture price dynamics in time and numerous economic interactions among sectors or regions. Compared with econometric models, the existing applications, especially for equilibrium frameworks, often involve global-scale investigations. The economical side of the land system is derived endogenously and in dynamical exercises some feedbacks might also be assessed. For these reasons, these approaches are very frequently used to produce future scenarios on land-use patterns and allocation or to evaluate the impact of different policies on land use and other variables.

Nevertheless, their outcomes should be interpreted with care, given their dependence on parameters and functional forms assumptions. In this respect, model validation, that can be developed by using these models in historical counterfactual analysis to reproduce real data, can help to provide support to the robustness of results (Ronneberger *et al.*, 2008; Beckman *et al.*, 2011). Another limitation relates to people's behavioural modelling: individuals and firms are representative agents respectively, within one region and one market sector. Unless an assortment of different representative households and firms is modelled, this implies assuming the same preferences within regions and sectors. Finally, collective dynamics or strategic behaviours are normally left aside of the analysis.

4.2.1 Partial Equilibrium Models (PEMs)

In Partial Equilibrium models (PEMs) production and consumption respond to price variations, which adjust to achieve the equilibrium between demand and supply for land-using commodities only. Being normally bottom-up approaches, they have the advantage of describing land management and its changes with a good level of detail, allowing an in-depth analysis of the land-use markets. It is precisely their detailed specification along with their simple market structure, which make these models particularly attractive to be combined with other optimisation or equilibrium approaches (e.g., general equilibrium models). Similarly, they are sometimes included in the larger structure of an Integrated Assessment Model (IAM).

Nevertheless, by only representing land-using sectors, they disregard all the feedbacks deriving from the rest of the economy. Effects of trade on food and timber markets are therefore limited, as goods are implicitly assumed homogeneous and bilateral or intra-industrial flows cannot be represented (Heistermann, 2006). Some examples of partial equilibrium models are provided below.

With a focus on the agriculture sector CAPRI (Britz *et al.*, 2008) evaluates regional and aggregated impacts of the cap and trade policies in Europe. The economic module sequentially links non-linear regional programming models with a global agricultural trade model. Capri-Spat (Leip *et al.*, 2008) extends this original version from EU15 to EU27 and provides a more detailed analysis for 270 European regions. Similarly, IMPACT-Water (Rosegrant *et al.*, 2005) generates projections on both global and regional food demand and supply for 32 agricultural commodities for the years 2020, 2025 and 2050. Water is fully integrated into the model as represented regions and countries are spatially traversed by 126 river basins. In the same way WATSIM (Kuhn, 2003), expresses agricultural land changes as a function of own and cross-prices other than trends in other variables assumed exogenous to the model. Conversely to CAPRI and IMPACT, WATSIM has a global coverage and countries are allowed to trade a wide number of agricultural products. Also, while CAPRI and IMPACT allow comparative static analysis, WATSIM is a quasi-dynamic model where economic agents have adaptive expectations on prices.

In addition to agricultural land effects, AgLU and FASOM can assess the impacts in the forest sector as well. AgLU2 (Sands and Edmonds, 2005) is a revised version of the AgLU1 model (Sands and Leimbach, 2003) where a single composite crop was differentiated into four crop-types for the US region. It currently assesses, at the global level, the impact of climate change or a change in climate policy on land use, carbon emissions, crops and bio-fuels production. Likewise previous models, the relative economic return of each type of land use is at the base of the land allocation mechanism among crops, pasture, forests, and commercial biomass growth. Differently from the economic models described above, AgLU focuses more on land allocation than on the market structure to derive production of land-using crops and land-use emissions. Allocation of land across different uses is governed by a joint probability distribution over yields. A Gumbel distribution is assumed for profit rates. For each geographic location considered, a different Gumbel distribution exists, implicitly capturing variations in climatic variables. The biggest portion of land is assigned to the use entailing the highest average-profits rate, which depend on the average of land yields across geographical locations. Demand for food consumption depends on the minimum level of kilocalories needed per person per day, while yields for cropland are derived as units of giga-calories per hectare. Importantly, through the use of calories, AgLU2 builds a link between physical and economical aspects of land use . By using carbon intensities, the stock of carbon between each time step, whose difference represents carbon sequestration, can be calculated for the land-use system. The inclusion of an exogenous price introduces incentives to employ land to grow biomass from corn and sugar cane. Crops for food and for biomass growth compete therefore directly. As regards forest products, demands for fuel and industrial wood mainly depend on population, income, other than prices. Their supplies are derived by multiplying land allocated for forestry production with the average yield. At each model time step (15 years) forests are characterised by previously planted trees (for which a portion of land is already committed) and new planted trees for biomass growth or industrial wood production, to which corresponds a certain amount of land newly allocated to forestry. The time lag between planting and harvesting is assumed fixed and constant for 45 years (3 model time steps). In turn, wood supply results fixed as well and corresponds, at each time step, to the quantity of wood grown in 45 years. A clearing price brings global demand and fixed supply for the two markets of fuel and industrial wood in equilibrium. In AgLU2x, Sands and Kim (2008) improve previous versions of the model by more realistically representing forestry dynamics and bio-fuels response to carbon incentives. AgLU2 is then transformed into a general equilibrium framework that will be described in the section below. Despite the additional effort of Sands and Kim (2008), this probabilistic approach does not represent explicitly changes in yield as a function of soil and productivity variations. Therefore, land variability is not truly captured. Additionally, no spatial dimension is included in the land-use analysis. It can be noted that when assuming a fat-tailed probability distribution, such as a Gumbel, implies attributing a certain probability to the occurrence of extremely high crop yields, which is small but not zero.

Similarly to AgLU, the FASOM model (Adams *et al.*, 1996; McCarl, 2004; USEPA, 2005) also assesses welfare and market impacts of climate change and policies of different nature (timber harvest policy, farm program policy, biofuel policies, among others) affecting both agriculture and forestry in US. The most advanced version, FASOMGHG, is an intertemporal-perfect foresight PEM solved for 100-year period on a 5 to 10 year time-step basis. It produces results on land competition, GHGs emissions (CO_2, CH_4, N_2O), welfare, agricultural and forest production and prices, harvest levels, and more in general, timber management investment decisions.

Similarly to FASOMGHG the GTM model (Sohngen *et al.*, 1999; Sohngen and Mendelsohn, 2007) derives forest area from optimising welfare and profits. In addition, it entails a global representation of the forestry sector. Including incentives to store carbon, resulting land-rental functions allow accounting for land competition between agriculture and forestry. The extended version of the model entails 146 distinct timber types in 13 regions, each of which can be allocated into three kinds of forest stocks: i) moderately valued forests managed in optimal rotations, located primarily in temperate regions; ii) intensively managed Subtropical plantations, highly-valued; iii) low-valued forests, managed lightly if at all, mainly located in inaccessible regions of the boreal and tropical forests.

Another global model entailing a level of detail for the forestry sector as explicit as in GTM is GLOBIOM (Havlìk *et al.*, 2010). GLOBIOM is still a dynamic model, although with no perfect agents' foresights, with the specific aim of running global policy analysis on land-use competition among land-based sectors. In a bottom-up fashion it accounts for forestry, agriculture and bioenergy production, and several land cover types (cropland, managed forest, areas suitable for short rotation tree species, unmanaged forest, grassland, other natural vegetation). Cropland is represented by 31 crops that may be grown for food consumption, livestock and biofuel production. Ethanol and biodiesel, first-generation bio-fuels, can be produced from respectively sugar cane and corn, rape seed and soybeans. Demand for crop consumption is modelled by constant elasticity of transformation (CET) functions, parameterised using FAOSTAT data on prices and quantities, and own price elasticities. The feed crops requirements for the livestock sector, calculated from FAOSTAT, constitute the link between livestock production and cropland. Wood products are represented by saw logs, pulp and other industrial logs, traditional fuel wood, and biomass for second-generation energy production. Main exogenous drivers influencing the model outputs are bio-energy demand, technological change, GDP, and population. The latter two replicate the IPCC-B2 scenario. GLOBIOM allows for the accounting, and eventually taxing, of major greenhouse gas emissions/sinks related to agriculture and forestry. Sequestration or emissions released into the atmosphere due to land-use change are calculated as the difference in carbon contents between the initial and the new land cover classes. It is assumed that agricultural practices do not have an impact on soil carbon emissions, while in the case of deforestation, defined as expansion of cropland into the forest, the total carbon contained in above and below ground living biomass is emitted. Finally, a land supply function is introduced to enable land expansion into inaccessible, marginal areas. To allow for a spatial representation of land use this model has been linked to the Global Forestry

Model (G4M), which geographically allocates land use decisions (this link is detailed in following sections). Other attempts have also successfully linked GLOBIOM with other models. Hence, although it has been included under the class of PEMs, GLOBIOM is often considered as an IAM.

4.2.2 General Equilibrium Models (GEMs)

Compared with the partial equilibrium models, general equilibrium frameworks (CGE) are suited to represent the overall economic system, not only land-using sectors, providing a more comprehensive analysis of the dynamics of production and prices. They can be used to evaluate the opportunity costs of different mitigation options and are specifically suited to assess policy impacts on the economy as well as other scenario simulations in the short and medium run.[7] The economy is represented in a Walrasian style, where a vector of equilibrium prices makes all markets in equilibrium at the same time implying efficient allocation of resources. The general equilibrium between demand and supply across the interconnected markets is attained through endogenous adjustments in relative prices. This framework belongs to the category of micro-founded macroeconomic models as all the behavioural equations are derived from economic theory. This aspect represents one of their most important strengths as it generates internal consistency and allows for the assessment of feedback mechanisms among all markets.

In general, among the most popular critiques, it is often argued that by assuming the optimal equilibrium of the economy underestimates the potential for win-win situations (Tol, 2000). In fact, stating that markets operate efficiently in the absence of policy, naturally implies that any shock necessarily entails economic costs. The assumptions of perfect competition and constant returns to scale represent a further concern given their relevant implications. More specifically, the nature of climate change, which is expected to require great changes in investments, infrastructure, and networks, should be represented with the discontinuity of the structure of production (Barker, 2004).

As regards land allocation, CGEs are acknowledged as important tools to evaluate the trade-offs amongst the opportunity costs of alternative land-based mitigation strategies. All is based on representative landowners', consumers', and firms' optimal decisions, which respond to changes in domestic and foreign prices and rents. It is not rare that existing frameworks only adopt a local rather than a global perspective to model land competition and related GHGs sinks or sources (Hertel *et al*., 2009). In addition, land, normally treated as a regional and non-tradable endowment is considered fixed or not extendable to economically inaccessible areas. Finally, since CGEs are top-down rather than bottom-up approaches, they do not share with sectoral models (or PEMs) a detailed representation of the supply side. For these reasons they are sometimes linked to sectoral models or to the more complex structure of IAMs. Some examples of CGE models are delineated below.

G-cubed (McKibbin and Wilcoxen, 1998), is an example of model where land is introduced as a non-tradable endowment for production. It was primarily developed to investigate the impact of

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[7] For an outline on CGE models in environmental economics see, among others, Conrad (1999), Balkhausen-Banse (2004), Wing (2005), and Palatik-Roson (2009).

climate change on the economy and later extended to analyse the effects of trade liberalisation by including a more detailed representation of US agricultural markets. It results from the combination of an intertemporal-perfect foresight general equilibrium model for the U.S. economy (Jorgenson and Wilcoxen, 1990) and a macroeconomic model (McKibbin and Sachs, 1991). It only focuses on agricultural land in addition to considering land endowment as homogeneous in terms of biophysical/climatic factors across sectors and regions.

Examples of global rather than large-scale land representation retaining, however, the assumption of homogeneity of the land input are provided by GTAPE-L, GTAPEM, and GTAP-AGR. They are extensions of the original GTAP framework (Hertel *et al.*, 1997), where land can be transformed via a "nested" Constant Elasticity of Transformation function (CET) into cropland and pastureland, or into different crop-types, regardless of climatic or soil constraints. The associated elasticity parameters, calibrated or estimated with econometric techniques, govern the response of the land supply to changes in relative prices and rents. GTAPE-L (Burniaux, 2002; Burniaux and Lee, 2003) investigates economic impacts of GHGs (CH_4, CO_2, and N_2O) and climate change. It explicitly introduces land competition among different crops by making use of a land transition matrix derived by the IMAGE model version 2.2 (IMAGE, 2001) tracking changes in land and emissions amounts among different land uses in time under a specific socio-economic scenario. This approach requires a good amount of information at the regional level; unfortunately land-based data was very elementary at that time. A most refined land structure is developed in GTAPEM (Hsin *et al.*, 2004; Brooks and Dewbre, 2006), built to assess the impacts of OECD agricultural policies on developing countries. Land endowment is distinguished into pasture, rice, field crops, and miscellaneous agricultural land. Finally, Keeney and Hertel (2005) develop the GTAP-AGR model, which among other improvements, introduces explicit substitution among feedstuffs used in the livestock sector.

The land treatment of all these models, with the exception of GTAP-L, has the disadvantage of measuring land changes as the value-added to production rather than in physical units of area (Heistermann *et al.*, 2006). This turns any attempt to give a spatial dimension to land-use change into a very hard task. Also, land heterogeneity resulting from climate and biophysical considerations is not accounted for and results in no impact on land differences and productivity. In addition, only one homogeneous land type, completely characterised by the agricultural sector, is in use. Indeed, a common weakness of previous GTAP-based models is that they normally do not represent the forestlands, but only the timber industry. The forest sector is assumed to require no land for timber maturation and production. As a consequence, forest growth dynamics are not captured, neither greenhouse gas sinks nor sources in the forest sector.

Indeed, a realistic representation of the land system in global CGEs requires relaxing the traditional assumption that land is homogeneous and perfectly substitutable among different uses and sectors (Heistermann *et al.*, 2006). In this respect FARM (Darwin *et al.,* 1995) represents a first effort to model 6 land classes distinguished depending on the length of growing seasons resulting from a spatially-explicit bioclimatic model. Built to evaluate effects of global climate change on the world's agricultural system it has been used, to assess climate change effects, impacts of nature conservation (Darwin *et al.*, 1996), and of sea level rise (Darwin and Tol, 2001). D-FARM (Ianchovichina *et al.*, 2001; Wong and Alavalapati, 2003) improves the original version of the model turning it into a recursive-dynamic CGE. With FARM and D-FARM, the concept of dividing land into agro-ecological-zoning is beginning to be explored within CGE models. However, in both settings changes in land demands do not result from agents' optimising behaviours, but are derived on the basis of the bioclimatic-model rules. Therefore, land economics and physical-geographical aspects are not fully integrated into the CGE.

GTAP-AEZ (Lee, 2004; Lee *et al.*, 2005; Lee *et al.*, 2009) continues along the FARM line attempting to bring more biophysical realism into the economics of land use . It extends the original model GTAP (Hertel, 1997), and relies on a very consistent and comprehensive dataset for land-use emissions and forest-carbon sequestration at the global scale. Land is differentiated in agro-ecological zones (AEZ), and each of them implies a different land type in terms of climatic conditions and soil characteristics. The concept of agro-ecological zoning (FAO, 2000 and IIASA; Fischer *et al.*, 2002) is used to design both land heterogeneity and mobility among agriculture, pastureland, and forestry, although not across AEZs. In this manner, taking advantage of the AEZ land distribution, different and imperfectly substitutable land inputs are combined by means of the CET approach for producing land-using commodities.

The initial version of the GTAP-AEZ model (Lee, 2004; Lee *et al.*, 2005), involved 6 AEZs, ranging over a different length of growing periods (LGP) each of them having homogeneous agronomical features. A different production function for each of the land-based sectors is assumed, which requires a significant amount of data on cost and input shares within AEZs, for each region of the world that was distinguished (US, China, and Rest of the World). The most recent version (Lee *et al.*, 2009) revises this postulation by assuming a unique regional production function for each land-using commodity. This revision, which allows overcoming data limitations, enables a bigger disaggregation of the world. However, it is based on strong assumptions not yet tested. For example, it is assumed that the same land-using commodity produced within a region but in different AEZs has the same qualities and characteristics and therefore the same price.

The GTAP-AEZ model bases on a global AEZ-database, which results from a merging of different sources and authors' contributions. It accounts for agriculture, pasture, and forestland. Data on agriculture relates to arable land and permanent crops and is detailed for the benchmark years of 2001 and 2004. It entails information on 175 crops for 226 countries in the world and 18 agro-ecological zones (Ramankutty *et al.*, 2008; Monfreda *et al.*, 2008). Similarly, the final global database on forestry for the years of 2001 and 2004 (Sohngen *et al.*, 2009) relates to managed forests differentiated into 3 tree species, 14 management types, 10 age classes, and 18 AEZs. Physical and economic data, such as land hectares, land rents for forestry, agriculture, and livestock are allocated into AEZs to build a globally consistent dataset for CGE analysis (Lee *et al.*, 2009). As soon as this new comprehensive and global AEZ-database was produced, a number of land-use analyses have been performed within the CGE modelling. For example, extending the work of Lee (2004) and Lee *et al.*, (2005), Hertel *et al.* (2008) and Golub *et al.* (2009), GTAP-AEZ-GHG is used to assess the global mitigation potential of CO_2 and non-CO_2 land-based emissions (agriculture, livestock, and forestry) and agents' abatement responses under different emissions taxation policies. These responses in land allocation are calibrated to engineering information for agriculture (USEPA, 2006) and to the GTM (Sohngen and Mendelsohn, 2003) sectoral model for forestry, by running the CGE model in partial equilibrium mode. Interestingly, for the forest sector, both intensification (timber management) and extensification (land-use change) are explicitly modelled, allowing disentangling mitigation potentials. Agricultural emissions and mitigation opportunities are associated with the use of intermediate inputs (N_2O from fertiliser use in crops), of primary factors (CH_4 from paddy rice), and of sector output (CH_4 from agricultural residue burning). Compared with the initial version of the GTAP-AEZ model, assuming a very high elasticity parameter across AEZs, substitution is allowed not only within, but also across AEZs for both agricultural and forest products. On the other hand, as in Lee (2004) and Lee *et al.* (2005) this analysis still divides the globe into only 3 regions, grouping most of the countries' flows into the vast area of the "rest of the world". In line with this, yet with a more specific focus on the livestock sector, Golub *et al.* (2010) extend the analysis of Golub *et al.* (2009) and allow for a representation of a 19-regions world.

These investigations have the static nature of the GTAP-based framework in common, which only consents a short/medium run analysis. To the aim of investigating global land-use change in the long-run (1997-2025) and related GHGs emissions Golub *et al.* (2008) turns the standard GTAP-AEZ into a recursive-dynamic model. They expand the GTAP-Dyn (Ianchovichina and McDougall, 2001), a dynamic general equilibrium model for the global economy, by changing both the land demand and supply structures. The modelling of land mobility across uses, on the supply side, finds the implementation of successively more sophisticated models of land supply, where the final representation concerns a nested CET function accounting for land competition among forestry, grazing, cropland, and within crops. Initial baseline results on land rental changes for livestock and forestry appear unrealistically high and are explained by the authors with the absence of unmanaged land representation, along with the fact that forestry growth does not depend on input-augmenting productivity. They attempt to solve for these lacks by modelling investment decisions on unmanaged lands. However, the absence of short-run constraints leads to very high access rates which guide the authors towards adopting a complementary approach to access cost functions, for instance, to develop a coupling exercise with the GTM model of Sohngen and Mendelsohn (2007).
Both the attractiveness and disadvantage of most of the analysed approaches lie within the nested CET function for land supply. It allows for flexibility and tractability of the land heterogeneity modelling, while creating a rigid land transformation scheme, which is difficult to validate against real data (Hertel *et al.*, 2009; Hertel, 2012). Furthermore, the implicitly assumed land transition matrix, governing the land disaggregation according to the agro ecological zoning, is not permitted to vary. In other words, the distinction of the regional land aggregate in different land quality types, reflecting differences in climate, soil conditions, length of growing periods, and therefore productivity, is maintained constant in time. This postulation, which is reasonable for a short-run analysis, could be an argument of concern in medium-long run projections.

Sands and Kim (2008) provide an approach alternative to Agro Ecological Zoning by enhancing the AgLU model described in earlier sections. With the new version, AgLU2x, they turn the original framework into a multi-sectoral general equilibrium model for US, divided into 18 watersheds at 2-digit level of classification. The advantage of using watersheds is twofold. Since they are expressed in physical units and are fixed in location, they can be spatially mapped to soil and give an important indication on land productivity. As for forestry, a forward market is created as the intersection of a supply curve of existing trees and a wood demand at the time of harvesting. To allow the rotation period to vary as well as resulting forest-carbon at each carbon price, they construct a steady-state version of the forestry sector, for instance, forest driving variables are in steady-state equilibrium. Therefore, forestry dynamics are not the result of an intertemporal optimisation problem where landowners' decisions are made optimally, but are rather the algebraic solution to a problem which is outside the optimisation framework. Despite these advancements, similarly to previous CGE models, forestry remains to be a subject, which has not been fully addressed. The same can be said for land-use change in cropland and pastureland, which does not result in any spatial illustration.

It can be summarised that, unless improved or integrated with other approaches, economic models normally tell only a part of the story. The same is true for geographical frameworks (see Table 3 for main features of economical and geographical model). A bigger effort in complementing economic with more biophysical information, or the reverse, has recently been acknowledged by a number of studies. The IAM models reported below represent perhaps the most advanced level of analysis on LULUCF, bridging economic and geographic grounds together.

Table 2: Geographic and Economic sub-categories: major models features

			STRENGHTS	**LIMITATIONS**		**Examples**
GEOGRAPHIC MODELS	*Statistical models*		Multiple land use drivers considered; Multiple land cover types considered.	Driving factors assumed exogenous; Not endogenous land allocation; Very limited feedback effects, if any.	Normally short-run and local analysis.	CLUE and Dyna-CLUE, ELPEN
	Rule-based models		More explicit assessment of land processes & drivers interactions w.r.t. Statistical Models; Multiple rules considered; Multiple land-cover types considered.		Rules based on subjective judgements.	IMAGE°, SALU, EFISCEN, ACCELETATES*, KLUM*
ECONOMIC MODELS	*Econometric models*	*Econometric*	Multiple land use drivers; Multiple land-cover types considered; Agents' reactions under similar or different policy scenarios.		Technology and climate variability not always considered; Need to deal with problems of endogeneity and reverse causality; normally short-run, local and small sample analysis.	Stavins (1999), Plantinga and Mauldin (2001), Lubowski et al. (2006), Pfaff et al. (2007), Munroe and Muller (2007)
		Ricardian Analysis	Multiple land use drivers; Multiple land-cover types considered; Greater focus on climate variability w.r.t. Econometric Models; Recently extended to panel-data analysis.	Ignore technology; No global analysis; Very limited feedback effects.		Sanghi and Mendelsohn (2008), Mendelsohn and Dinar (2009)
	Optimization and Equilibrium Approaches	*Partial equilibrium models*	Multiple land use drivers; Agents' reactions under similar or different policy scenarios; Good detail in land-using markets; Land allocation endogenously derived w.r.t. Econometric & Ricardian Analysis; Often global and forward looking models.	Only a part of the economy is modelled and represented; Models not frequently validated; Agents' preferences on land allocation assumed to be the same; Climate and biophysics have normally no impact on land differences and productivity.		CAPRI, IMPACT-Water, WATSIM, AgLU, FASOM, GTM, GLOBIOM°
		General equilibrium models	Agents' reactions under similar or different policy scenarios; Compared with Econometric and Ricardian Analysis, land allocation among land covers endogenously derived; Compared with Partial Equilibrium Models all the economy is considered; Global scale investigations.	Land exclusive input for agriculture, represented as value added to production; Normally, only currently managed land is represented: land is not allowed to expand; Less detailed production description compared with Partial Equilibrium models; Identical agents' preferences on land allocation within regions and sectors; Climate and biophysics have normally no impact on land differences and productivity.		G-cubed, GTAPE-L, GTAPEM, GTAP-AGR, FARM, GTAP-AEZ, GTAP-Dyn, AgLU2x

Source: Own Elaboration
°Also IAM model
**Geographic model with economic considerations*

5. Model Linking and Integrated Assessment

Thus far, models used independently to develop LULUCF analysis have been described. As previously illustrated they are either economic or geographical models and normally do not dynamically integrate spatial information with prices and rents, nor do, they fully account for biophysical factors. However, recent studies acknowledge that both land use (Brovkin *et al.*, 2006) and its feedbacks (Strengers *et al.*, 2004) must be represented in the future development of the carbon cycle. This discussion calls for the use of a multitude of approaches, data, and disciplines if one wants to provide a good and complete representation of LULUCF. Recently a new modelling strategy has emerged, which allows complementing different information sources and combining the strengths of existing approaches (Heistermann *et al.,* 2006). Given that this strategy is founded on model linkages, combinations, and integrations, this section is devoted to provide some recent examples of coupling exercises, which are interesting from a modelling perspective.

The literature offers an array of different definitions for "integrated assessment model" (IAM). In the context of this article all the applications aiming to describe the land-use system by using more than one model are broadly defined as such. Strictly speaking, however, the most advanced IAMs are interdisciplinary settings where major features of society and economy are consistently linked with the biosphere and the atmosphere, in a unique framework. They are normally composed of sub-modules, communicating through the exchange of data and results. The sub-models, can be added or removed from the integrated framework depending on the specific research question that needs to be tackled. Among their most relevant strengths it can be mentioned the ability of addressing the synergies and trade-offs of different policy strategies, to develop investigations with a global coverage, and the opportunity to run long-time scale analysis. On the other hand, they entail a big degree of complexity and are high demanding for computer power. Such complexity and inter-linkages among different models also make the analysis of uncertainty very difficult. Finally, it has to be noticed that the development of global land use assessment within IAMs remains an on-going process still seeking to fully address methodological barriers faced by standalone models.

5.1 A general classification of model linkages

A general classification of IAMs relates to the underlying connections among models. According to their different degree of coupling complexity it is possible to distinguish among *Off-line runs*, *Soft-link*, *Hard-link* models.

Off-line runs are perhaps the most simple link type, as the output of one model is used as an input to a second model. Examples are Michetti and Rosa (2012), and Bosello *et al.* (2010), which are described in the following paragraph. These approaches allow exploring interesting short-time questions in only one direction of the effect under study. Model harmonisation is not required, nor are the changes in either of the two models. Only some effort is needed to translate the output of one model into an input for the subsequent model. On the other hand, these approaches do not leave room for feedback effects between the two or more models combined, which therefore remain unexplored.

Conversely, the *soft-link* approaches account for feedback effects by implementing the same process than in o*ff-line runs* but iterated until simultaneous convergence between the two models is reached. These links are slightly more complex and convergence is not assured. In addition, they are more time consuming, requiring the transmission of data across modellers to guaranty the harmonisation of basic modelling assumptions and characteristics. Examples are provided by Golub *et al*. (2009), Tavoni *et al.* (2007), Bosetti *et al.* (2011), AIM, and the link between IMAGE and LEITAP. This frameworks are all sketched in the paragraph below.

A most refined coupling strategy is represented by *hard-links.* They use reduced-form models, embedded in a more detailed, and usually a more aggregated, model. This approach assures long-trend and consistent dynamics with immediate feedbacks. Although with this set-up convergence is a much less problematic issue, a larger effort is required to build reduced forms of sub-models to be linked. Examples are offered within the integrated assessment of the LUC Programme at IIASA. Another is provided with the dynamic integration between EPPA (Paltsev *et al*., 2005) and the land-system model of the MIT Integrated Global Systems Model, or IGSM (Sokolov *et al*., 2005).

Table 3: IAMs according to linkages complexity

		STRENGHTS	***LIMITATIONS***	***Examples***
LINKED OR INTEGRATED	*Off-line runs*	Model harmonization is not required	Short-time questions; Only one direction of the analysis; No model feedbacks.	Michetti and Rosa (2012), Bosello *et al.* (2010)
	Soft-links	Compared with off-line runs some feedback effects are accounted for;	Compared with off-line runs these links require some model harmonization and are slightly more complex; Simultaneous model convergence is not assured;	Golub *et al*. (2009), Bosetti *et al.* (2011), Tavoni *et al.* (2007), AIM, IMAGE + LEITAP
	Hard-links	Compared with previous categories provide long-term analysis and consistent dynamics with feedbacks; Compared with Soft-links convergence less problematic	Large effort required to build reduced forms of sub-models to be linked.	EPPA, IGSM

Source: Own Elaboration

5.2 Detailed description of some IAMs

A more straightforward classification of IAMs entails analysing how they make use of information coming from land-sector models (for agriculture or forestry), on which most of them rely. More specifically, they can be broadly distinguished into two approaches. The first one is characterised by the fact that it implements, or mostly relies on, mitigation response curves derived from sectoral agriculture or forestry models. The next two categories entail effectively linking or iterating land sector models into IAMs. According to the complexity of the overall framework under analysis, the second category include less elaborated model linkages while the third one accounts for more structured frameworks. This simple three-tiered classification strategy is followed below.

Within the first category, Jakeman and Fisher (2006) introduce sequestration supply curves from Sohngen and Sedjo (2006) into the GTEM-CGE model generating fully endogenous mitigation costs for agriculture, leaving forestry mitigation as exogenous. Bosello *et al.* (2010), drawing from the IIASA-Cluster model (Gusti *et al.*, 2008) include regional emissions reductions from avoided deforestation within the ICES-CGE framework. The same CGE structure has served Michetti and Rosa (2012) to assess the role of carbon sequestration from afforestation and forest management in temperate regions by relying on forest-carbon supply curves derived from the GTM of Sohngen and Sedjo (2005). Differently from previous approaches, van Vuuren *et al.* (2007) do not make use of a sectoral model, however they still rely on afforestation supply curves within an integrated assessment framework. They work out plantations marginal abatement costs from IMAGE calculations, as described in Strengers *et al.*, (2008). They only focus on grid cells corresponding to land abandoned by agriculture where potential carbon uptake is higher than natural vegetation uptake. For these grid cells, for which they assume that carbon plantations are harvested at regular intervals, they derive carbon sequestration supply curves by adding land and establishment costs. The developing of such exogenous land competition analysis (based on IMAGE) leads the authors to restrict the focus on abandoned agricultural areas that do not impact food production. As a result, land competition effects on agricultural production are not considered.

Within the second category, Sands and Leimbach (2003) iterate the ICLIPS integrated assessment (Toth *et al.*, 2003) with the AgLU sectoral model already described. ICLIPS provides AgLU with data on GDP growth by region - one of the main drivers of demand for agricultural products - and the time path of the global carbon price. In AgLU, the global carbon price influences the biomass price and, in turn, the biomass produced from land-use change. Information on land-based emissions is sent back to the ICLIPS model, where the carbon price will be adjusted to meet a climate protection strategy. Rao and Riahi (2006) introduce forest carbon sinks in their analysis iterating the Energy model MESSAGE (Messner and Strubegger, 1995) with the GTM model of Sohngen and Sedjo (2005).[8] The shadow prices from MESSAGE are used as an input to the forest model, which then estimates the corresponding potential mitigation capacity from forests biomes. Regarding mitigation from the livestock and agriculture sectors they directly implement the marginal abatement cost curve from DeAngelo *et al.*, (2006). In a similar way, Tavoni *et al.* (2007) develop a link between the integrated assessment, WITCH (Bosetti *et al.*, 2006) with GTM (Sohngen and Mendelsohn, 2007), to the aim of evaluating the potential role of forestry in achieving a moderate CO_2 climate stabilisation of 550 ppmv, by 2100. Bosetti *et al.*, (2011), analyse the effects of introducing credits for emissions reduction from tropical deforestation. They

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[8] MESSAGE (Messner and Strubegger, 1995; Riahi and Nakicenovic, 2007) is a bottom-up engineering optimisation model used for long-term projections (1990-2100 in ten year time-step). Currently, it accounts for CO_2 and non-CO_2 emissions, covers all six Kyoto GHGs, and embodies all the emissive and abatement sectors (energy, industrial, agriculture, forestry, and biomass). Biomass abatement is distinguished into biomass sequestration and “BECS”, the biomass energy, which is combined with CO_2 capture and storage. Compared with models that specifically address land-based emissions, it does not directly deal with land use.

present a link between WITCH (Bosetti *et al.*, 2006) and three alternative models from which they derive forestry mitigation supply curves. The three sources are i) the analysis carried out at the WHRC (Nepstad *et al.*, 2007) and the estimates on the global forestry mitigation potential derived from ii) the GTM model of Sohngen and Mendelsohn (2007), and iii) the IIASA model cluster of Gusti *et al.* (2008) which is itself an IAM (see its description below). Although not within a structured IAM, a similar iterative approach has been undertaken by Sohngen and Mendelsohn (2003) and Golub *et al.* (2009). Sohngen and Mendelsohn (2003) link a forestry model to the global climate–economic model DICE (Nordhaus and Boyer, 2000) where the world is represented by a unique aggregate region. Golub *et al.* (2009) couple the GTM model version of Sohngen and Mendelsohn (2007) complementing the GTAP-Dyn forestry dynamics with a forward-looking approach. The rate of unmanaged forest access, predicted by GTM, is used to introduce the possibility of converting unmanaged forests into agriculture and commercial timber area.

Within the third category more complex IAMs are included. They normally incorporate a land-use model within a structured integrated framework. In the specific examples provided below, attempts to consistently link major features of the economy with the land-use system are developed.

AIM (Matsuoka *et al.*, 2001) is an IAM for the Asian-Pacific region, which puts together bottom-up national modules with top-down global modules. It specifically integrates a land-use model with a module on GHGs emissions, on global climate change and further modules assessing impacts on natural environment and economy. It uses the Geographic Information System to map the distribution of impacts. However, rather than for the treatment of land, it is mostly popular for involving a very detailed technology selection module, which serves for assessing the effects of introducing advanced technologies. Moreover, the overall structure lacks a behavioural representation of the economy.

The ObjECTS-GCAM (Kim *et al.*, 2006) links in a unique framework a number of energy supply technologies with the agriculture-land use model, AgLU, and a reduced-form climate model. Based on agro-ecological zoning, AgLU breaks down land into 12 land cover types. Arable land is distinguished into non-commercial forests, grassland and commercial forests, and cropland. Land implied for biomass production competes with land for food and fibres uses. The link between land uses and land cover changes determine stocks and flows of terrestrial carbon. Markets are defined for biomass, carbon and agricultural products, among others.

Ronneberger *et al.* (2008) develop KLUM@GTAP, a coupled system between KLUM sectoral model for agriculture (described above) and the global CGE GTAP-EFL (Bosello *et al.*, 2006, 2007). The task of allocating land is performed by KLUM as described in section 2.1.2. To the aim of making the regional land endowment extendable, which is assumed fixed in the standard GTAP framework, they make the sectoral land allocation in GTAP-EFL exogenous. KLUM land allocation, which is introduced into GTAP-EFL induces variations in crop prices and management yield. Although KLUM has been used at 0.5x0.5 degree grid to spatially allocate land (Ronneberger *et al.*, 2008) within this coupling exercise, the model is calibrated to country-level data, a larger aggregation compared to AEZs. On the other hand, KLUM@GTAP tracks actual area and land is not classified by a rigid "space-less" scheme of productivity differentials; instead it depends on productivities continuously varying over space. Finally, land-use decisions are limited to crops, while livestock and forestry are excluded from this allocation mechanism.

A comparable method has been used in the EURURALIS project (Verburg *et al.*, 2008) where an extended version of the GTAP model (van Meijl *et al.*, 2006), with partial equilibrium detail for the land sector, has been integrated with IMAGE (Alcamo *et al.*, 1998; IMAGE, 2001; MNP, 2006) and final land allocation is translated into land-use patters at 1 km^2 resolution by using a variant of the CLUE model. IMAGE (Alcamo *et al.*, 1998; IMAGE, 2001; MNP, 2006) is a global dynamic, long-term IAM. In the last version available, among others, a Terrestrial Environment System (TES), a Terrestrial Vegetation Model (TVM), and a Land Cover Model (LCM) are integrated. On the basis of regional food consumption, animal feed and timber production TES, calculates changes in land use, while TVM spatially simulates the distribution of crops, crop productivity, and natural vegetation according to grid-specific conditions on climate and soil. Crop productivities are then used in the LCM, which allocates the overall cropland in different crop types, and at 0.5-degree resolution, simulates the land use and land cover change by merging regional land demands with global land supply. The effects of land mobility across different uses are also captured by a geographically-explicit terrestrial-carbon cycle model. This module simulates carbon pools and fluxes in natural vegetation and carbon plantations, distinguished amongst 6 types. Management practices represented allow either letting plantations grow at a stable rate or harvesting at the maximum carbon sequestration level. A significant advantage of the IMAGE framework is that it allows the display of emissions, land use, and certain impacts on global maps. In fact, although this framework has the same demand structure of most described models where consumer preferences and income impact agricultural demand, on the supply side, its grid-cell land-use assessment reaches a very good level of geographical detail. On the other hand, IMAGE lacks a comprehensive macroeconomic representation. As a result, within EURURALIS it is not possible to endogenously derive whether demand for will be fulfilled by the extension of agricultural area rather than intensification. To further improve the economic representation Eickhout *et al.*, (2008) have further integrated IMAGE with an adjusted version of GTAP, the LEITAP CGE model. The demand structure of the original GTAP model (Hertel *et al.*, 1997) is changed to account for different degrees of substitutability across land types, while a land supply curve is introduced to allow for land conversion and land abandonment representation. The terrestrial vegetation model and the land cover model in IMAGE are coupled via a link with LEITAP. Specifically, the rule-based land cover model allocates land in grid cells according to biophysical rules such as crop productivity, distance to water, etc., and from changes in food and feed demands derived from LEITAP. IMAGE computes yields, regional land demand for agriculture and pasture, and climatic consequences on crop productivity. The deviations in crop production between the two models are interpreted as yield changes resulting from climatic change and from changes in the extent of used land. These yield changes are fed back to LEITAP. In the case in which a convergence is achieved, the iteration procedure ends when projections on arable land in both models are similar. The iteration procedure is provided only for crops, while the economics of the forestry sector does not play any role in this integration.

The LUC Programme at IIASA has been directly aimed to develop enhanced methodologies to derive spatial explicit data and provide better integration between biophysical and socio-economic analysis. In this respect, with the collaboration of FAO, IIASA structured the IIASA-FAO AEZ spatial analysis system, enabling rational land-use planning based on land resources constraints and land production potential. Statistics on agricultural production are spatially downscaled to produce a gridded analysis of agricultural yields, land productivity, and production. This system, therefore, is able to spatially distribute biophysical and socio-economic datasets and simulate land resources availability and use in time, as a function of climate change and environmental constraints. The land-resource assessment has been linked further with the CGE Basic Linked System (BLS) agro-economic model for trade to compute actual regional and global production and consumption of food. The BLS model (Fischer *et al*., 1988) is a recursively dynamic system implied for analysing the world food structure, which make national agriculture (9 agricultural sectors) and 34 national economies interact at the international level through a world market. Precisely by merging the AEZ-based system with the BLS trade model, Tubiello and Fischer (2007) analyse climate change impacts on the productivity of the agriculture sector and related GHGs mitigation for the period 1990–2080, under a CO_2 non-mitigation scenario (800 ppm) and a CO_2 stabilisation scenario (550 ppm). The estimated changes in productivity and projected climate influence BLS. Final land availability is expressed therefore as a function of climate and agronomic conditions.

Successively, the IIASA model cluster (Gusti *et al*., 2008) combines the sectoral model GLOBIOM with the G4M model. The result is a recursive-dynamic, spatial and partial equilibrium model, with the maximisation of social welfare. Specifically, G4M (Benitez *et al*., 2004; Benitez and Obersteiner, 2006; Rokitiansky *et al*., 2007; Kindermann *et al*., 2006, 2008) is a geographically explicit agent-based model built to the aim of investigating land-use change decision-making. It is driven by exogenous assumptions on economic variables such as market prices for land and commodities. Decisions on land allocation, modelled comparing the relative net present values of the different land-use decisions, are spatially derived for approximately 50 km^2 grid. The current version of the model allows accounting for avoided deforestation, afforestation and forest management decision-making, involving emissions from belowground biomass, dead trees, litter and organic soil carbon. Deforestation is geographically expanded if net present value of the benefits coming from agricultural activities or sustainably managing forestry is lower than the one that would derive from selling wood from forest clearing. Deforestation cannot occur in protected areas. Similarly, afforestation competes with agriculture and geographically takes place if environmental conditions allow. Decisions on land allocation also reflect endogenous calibration parameters, which have the objective of controlling agents' choices to calibrate predictions to FAO and IPCC values. Additionally, other two country-specific coefficients, endogenously derived, adjust changes in deforested and afforested land. The forestry model, informs GLOBIOM on the biophysics of forest growth and on the costs of potential forest managements alternatives. Making use of this information, GLOBIOM endogenously derives commodity and land prices for different land uses, which are in turn, considered as exogenous factors in G4M and spatially allocated.

Finally, the MIT Integrated Global System Model (IGSM), is a popular and perhaps one of the most complex integrated assessments designed to investigate human-driven global environmental changes and their effects on economy.[9] It consists of an economic model, a coupled atmosphere-

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[9] Details of the MIT integrated assessment model can be found at http://globalchange.mit.edu/igsm/

ocean-land surface model, and natural ecosystems models. EPPA is the economic module characterised by a long-term, global recursive-dynamic framework. It simulates economic dynamics to the aim of projecting GHGs gases, aerosol, and other air pollutants. EPPA shares the structure of the GTAP model (Hertel *et al*., 1997), and improves the representation of alternative energy supply technologies by adopting bottom-up engineering approaches. The land-based sector is broken down into food crops, bioenergy crops, livestock, and forestry. Land-GHGs emissions and mitigation potential also depend on the climate change effects resulting from the Global Land System framework (Schlosser *et al*., 2007) of IGSM. The Global Land System framework dynamically integrates the Community Land Model (which calculate global terrestrial balances for water and energy) with the Terrestrial Ecosystems Model (simulating carbon-equivalent contents in vegetation and soils) and with the Natural Emissions Model (which computes fluxes of CH_4 and N_2O). This system, which develops the graphical distribution of land cover and plant "biodiversity" throughout the entire world, is linked with the EPPA model via the Terrestrial Ecosystems Model component.

6. Methodological Issues of Modelling Land-use

Despite the recent efforts, the process of improving the LULUCF assessment at the global scale both from a modelling perspective and from a dataset construction is on-going. There are several key methodological challenges, to which there is significant room for improvement. In the following, drawing from the information given in previous paragraphs, an overview of the critical dimensions is given to summarise state-of-the-art modelling.

6.1 The Level of the Analysis and the Spatial Dimension: Going Global

The global dimension of the land-use system modelling is a relevant aspect for more than one reason. Causes and consequences of LULUCF are often of a global extension and processes happening in one region of the world can affect events outside the boundaries of that country on either a biophysical or an economic ground. For example, bordering regions often compete for the same water resources, in addition to be subject to similar weather and to trade similar products.

However, land-use change is difficult to be modelled explicitly at the global scale (Geist and Lambin, 2004). Progress in global land-use modelling for both geographical and economical approaches has been delayed in time due to several difficulties.

Economic studies modelling agents' optimising behaviour assume a unique representative agent for each region (GTAP, FARM, GTAPE-L, etc.). Assuming the same preferences within regions, and sometimes across land-using sectors, may generate wrong approximations in terms of results. As for geographical approaches, it is clear that dissimilar regions are characterised by different climates, soil conditions, and other biophysical aspects. In addition such land-use drivers vary across areas and time. These two reasons notably complicate a global geographical assessment of the land system given that local representation cannot be scaled up. As a result, geographic models only develop local analysis.

The biggest challenge to be pursued for a global oriented analysis is the linking of geographical and physical factors with economic drivers into a unique framework, which finds a balance with bottom-up and top-down model characteristics. While geographic models are locally restricted, most of the existing global economic models do not include any biophysics in the analysis (e.g., GTAP), conceive biophysics as external and exogenous, or maintain it constant in time while accounting for it (e.g., GTAP-AEZ). On these grounds, IAMs move a step forward by including specific models to address these issues (e.g., IMAGE, AIM), and by extending the analysis to the world region. On the other hand, despite their global coverage IAMs, sometimes lack agents' behavioural responses (e.g., IMAGE).

It is also worth mentioning the necessity of providing quantitative and spatial dimension to global land use. Such a comprehensive representation has been slowed down in time by data limitations (see the following section) for a number of regions of the world (Heistermann *et al.*, 2006). As a result, most of the existing models, especially economically oriented, do not present spatial illustration of land disaggregation (e.g., BLS, FARM, D-FARM, GTAP). First attempts in this direction were made by Nordhaus (2006), Asadoorian (2005) and Grübler *et al.*, (2007). However, the spatial down-scaling techniques were not so refined. Now that new databases have been made available (e.g., GTAP-AEZ, FAO-IIASA AEZ, USEPA), gridded or spatially explicit economic data representations have increased. However, current global models still operate at a rather low-resolution level (0.5 degree grid cell), in line with the aggregation of statistics on economic variables (see for example Monfreda *et al.*, 2008). Results on land allocation are often shown only at the country level since a more detailed assessment would imply the estimation of data on input usage and output at the spatial unit (Hertel *et al.*, 2009). This is the case of the MIT-EPPA model (Paltsev *et al.*, 2005), KLUM (Ronneberger *et al.*, 2005), and KLUM@GTAP (Ronneberger *et al.*, 2008). Exceptions for global models are provided, for example, by IMAGE (Alcamo *et al.*, 1998; IMAGE, 2001; MNP, 2006), and GTAP-AEZ (Lee 2004; Lee *et al.*, 2009) which produces analysis at the Agro-Ecological Zone (AEZ) level.

A further aspect relates to the description of multiple land uses and associated mitigation potentials. Climate mitigation with land-using activities should include agricultural reductions in emissions of non-CO_2 GHGs, production of bio-fuels, afforestation and avoided deforestation, as well as changes in forest management. However, especially in energy-economic-models, adding terrestrial mitigation options generates problems in terms of conceptual development and data requirements (Sands and Kim, 2008). This assertion is particularly true for forestry mitigation, as illustrated in the following sections. Consequently, most of existing global energy-economic-models develop a detailed mitigation ability especially for agriculture (AgLU2x, G-cubed, FARM, among others). Exceptions are provided by GLOBIOM and GTM.

While it is reasonable to envision significant room for improvement in land-use representation within global economic models in the near future, today researchers still have to face significant challenges to realistically describe global land-based emissions from sinks and sources. Modelling land heterogeneity, overcoming data limitations, and including a detailed forest sector are still demanding aspects. More on this can be read in the following.

6.2 Land Heterogeneity Representation and Product Differentiation

A crucial point for a global assessment of land use is to represent land heterogeneity replicating production differentiation in forestry and agriculture. From a modelling perspective, this is not a simple task, especially for economically-oriented models. The latter models have been developed different approaches to deal with this aspect.

In KLUM (Ronneberg *et al.*, 2005) a geographic framework based on profit maximisation, land heterogeneity is modelled with a risk-based approach. Returns on different crops are assumed uncertain and the expected utility is maximised by risk-averse producers. However, since risk aversion is an agent-based issue, at the regional rather than at the producer level, this choice-under-risk approach loses its attraction. A large-scale diversification should rather reflect differences in types of the land and climatic endowments (Hertel *et al.*, 2009).

Economic models typically express land heterogeneity as a function of own and cross prices. Land allocation is therefore the result of an agents' comparison among relative economic returns for different uses of land, without considering different land qualities (e.g., GTAP and GTAP-based models). Exceptionally, GTAPE-L (Burniaux, 2002; Burniaux and Lee, 2003) makes use of a land transition matrix derived by IMAGE (IMAGE, 2001). AgLU (Sands and Leimbach, 2003) mimics production differentiation (in a given AEZ) by assuming a Log-Gumbel probability distribution over land yields, while FARM (Darwin *et al.*, 1995) represents a first attempt to derive land heterogeneity from a spatially explicit bioclimatic model.

GTAP-AEZ (Lee 2004; Lee *et al.*, 2009) presents perhaps the most advanced production differentiation in standalone global models. It is more valuable to grow different crops, or different tree types, in areas presenting heterogeneous climatic and physical characteristics. However, land distribution based on these characteristics remains exogenous and constant in time, rather than being an endogenous evolution of biophysical features. Land separability is normally achieved by using Constant Elasticity of Transformation (CET) functions. An aggregated land endowment is then ramified in different uses (forestry, agriculture, grazing), according to a calibrated elasticity of transformation (ET) governing the sensitivity of land supply reactions to changes in relative yields. This approach, within CGE frameworks, has been in use since the first time Hertel and Tsigas used it in 1988. Afterwards, it was included in the traditional version of the GTAP model (Hertel, 1997). More recently, Hertel *et al*. (2008), Eickhout *et al.* (2008) implemented the approach in LEITAP, Golub *et al.* (2008) in GTAP-Dyn, and Havlik, *et al*., (2010) in GLOBIOM.

The CET is a very flexible approach and fits well within CGE frameworks. It translates into a restriction on the cross-elasticities of land supply between different nests, and can therefore be tested with econometrical techniques. Nevertheless, it is discussed on more than one ground (Hertel *et al.* 2009; Hertel 2012). First, it does not capture the amount of land which is neither attributable to one land-use nor to another, but to both uses at the same time. In other words, it disregards the land allocated "across" agricultural or forest activities. Secondly, model validation proves to be difficult, given the absence of a specific relation between land heterogeneity and land yields. Finally, Golub *et al.* (2008), argue that the employed nesting game can have significant consequences in the long-run for both land rents and the allocation of land supply among different uses.

6.3 Data Limitations and data Harmonisation

Although land use should be represented as a global phenomenon, there are not many global models. One of the limits obstructing further progress in this direction is the lack of data. A detailed representation of LULUCF strictly depends on data availability, which governs the spatial description of land-use aggregation, socio-economic data, and land-use types.

To integrate economic with spatial information, down-scaling techniques have been notably refined in recent years. A rapid improvement is also expected in the near future. However, although the resolution of existing spatial models has recently increased, the level of aggregation of economic data, normally does not allow a very detailed analysis, especially for global economic-climatic representations. The spatial resolution of economic data is constrained by administrative boundaries, which is the level of detail required for economical or policy analysis, not always suitable for environmental variables (Briassoulis, 2000).

On the other hand, there are still issues concerning the integration of spatial biophysical aspects with spatial economic information. The temporal dimension of the economic system is usually not consistent with the timing of natural cycles in continuous change. Assuming specific or rigid aggregations or disaggregations for economic variables may generate inconsistency between these two types of information. The same could be argued for geo-referenced (and longitudinal) data, which are associated with precise points in time. In addition, the fact that a global economic database is already a combination of different datasets and regional sources can also generate inconsistencies. The final outcome typically derives from a mixture of maps, historical data, census, and discrete data from aerial photographs and satellites.

Assuming that these inconsistencies are solved, and that theoretically speaking, a high level of disaggregation is achieved in both spatial depiction and economic data, in practice the detail of the analysis also depends on other factors. If we consider optimisation models, for example, a higher level of specification would normally call for greater computational power and more time is needed for simulation exercises, especially for dynamic assessments. Additionally, this higher complexity could also imply an increasingly intricate interpretation of results and a lower capacity to critically process information by the human mind (Briassoulis, 2000). Therefore, even though a very disaggregated model offers higher flexibility in terms of possible analysis to be run, this positive aspect should be conceived in a trade-off perspective with the increasing complexity of the problem.

6.4 Inclusion of the Forestry Sector in Land-Use modelling

Including forestry representation into the land-use system is one of the most challenging, though attractive, issues of this field. This explains why several land-use studies have focused on agricultural activities rather than forestry and its mitigation potential (KLUM, ACCELERATES, ELPEN, SALU, WATSIM, IMPACT, CAPRI, GTAP, FARM, GTAPEM, etc.).

Temporal dimension is especially relevant in this context. Growing new forests, increasing forest stock, or accumulating forest carbon may require more than one decade (Hertel *et al.*, 2009). As a result, short time analyses are not fully able to capture the long-run features of the forest sector.

Furthermore, these processes are inherently dynamic, requiring a more sophisticated investigation than static comparative exercises. Indeed, investment decisions on forestry must take into account long-run agents' expectations. However, the few global economic models, which examine forestry, often have a static nature (GTAP-AEZ, GTAP-L, AgLU, etc.). Among the few, including some dynamics, the bigger sample is represented by recursive-dynamic frameworks, implicitly assuming agents with myopic expectations (GLOBIOM, BSL-IIASA, GTAP-Dyn, etc.). Only a minority is characterised by perfect foresight (e.g., GTM, and FASOM-GHG which is not global). In this respect IAMs typically built as long-term dynamic models can better address these issues.

Another aspect worth mentioning is that the forest processes are strictly influenced by locally-dependent factors and characteristics. For example, forest type and age, forest management, climate patterns, disturbances, and other variables have a great ability of controlling forests growth and sequestration capacity. This renders the representation of forest processes at the global level a difficult task, requiring biophysical factors to play their role. Furthermore, economic models accounting for investment decisions on forestland and timber production normally do not address directly biophysical aspects; nor do they illustrate global forestland distribution with a spatially consistent framework (AgLU, GTAPE-L). By explicitly incorporating terrestrial vegetation models, land cover models, and climate modules, IAMs, can help to overcome these concerns.

The problem of forest-carbon non-permanence is connected to biophysical characteristics (see Marland *et al.*, 2001; McCarl, 2005 for a discussion on this issue). For example, new forest plantations can accumulate carbon up to the so-called saturation point while its storage is achieved unless subsequent clearing activities or forest disturbances (pests, wild fires, heat waves, etc.) take place. These aspects are rarely taken into account in the calculation of forest sequestration potential or costs. An exception is provided by Tavoni *et al.* (2007) and the GTM model (Sohngen *et al.*, 1999; Sohngen and Mendelsohn, 2007) where the land-rental functions introduced for each timber type imply that carbon sequestration is only paid while carbon is really stored.

Another critical issue relates to the modelling of new land access, namely forests, which at current conditions are not economically accessible. Most of the existing models disregard this possibility considering land as a fixed endowment, or restraining the attention of the analysis to managed land. This is for example the case of GTAP-based and GTAP-AEZ models. With this modelling structure it is impossible to track forest carbon resulting from deforesting new lands, or carbon sequestration

coming from deforestation slowdown, resulting from the introduction of forest sequestration incentives. Similarly, the increase in timber supply derived from new lands brought into production would have no impacts on the economics of the forest sector. This problem is especially relevant for those countries having tropical old-growth forests.
In this respect, Sohngen and Mendelsohn (2007) introduce a supply function for currently inaccessible lands, which have an impact on forest carbon accumulation. Gouel and Hertel (2006), attempt to incorporate forest access-cost functions in general equilibrium models. The solution takes the form of an investment decision problem, in which the discounted payback flows of accessing marginal hectares of forestlands are equated to the marginal access cost. Following Gouel and Hertel (2006), Golub *et al*. (2008), the model investment decisions on unmanaged lands in a recursive-dynamic CGE model. They acknowledge that the inclusion of unmanageable lands generate significantly different results in terms of long-term land availability, timber production, and carbon accumulation. Ronneberger *et al.* (2008) with the KLUM@GTAP coupling also allow regional land endowment to expand beyond the hectares, otherwise assumed fixed in the standard GTAP framework. However, this is done at the expenses of sectoral land allocation, which is set as exogenous in the GTAP-based model.

Finally, the majority of models accounting, to some extent, for forestry mitigation potential, only include a limited set of forest-related abatement options (EMF21, 2008). Some of them only focus on afforestation strategies (e.g., van Vuuren *et al*., 2007), while others focus only on avoided deforestation contribution (Tavoni *et al*., 2007; Bosetti *et al*., 2011, etc.). Only a few also include management options (Golub *et al*., 2010; GTM, FASOM).

7. Conclusion

Today, it is widely acknowledged the relevant role detained by land in long-term climate stabilisation. Agriculture and forestry mitigation represent an important part of a cost-effective mitigation strategy, mostly in a short-run perspective (EMF21, 2008). This concept has been confirmed by the progressively greater weight attached to the debate on agro-forestry activities potential within international negotiations on climate change.

The land-use system has a global dimension, which involves the continuous evolution of a wide number of multi-sided and interlinked processes. Additionally, agricultural and forestry mitigation portfolios vary across regions depending on resources endowments and opportunity costs. A realistic representation of LULUCF calls, therefore, for the use of a spatial and global framework, which dynamically integrates the environment, economics, and biophysics.

However, the development of such a comprehensive structure has been obstructed by its underlying complexity, in addition to the lack of consistent large-scale datasets. As a result, economic models have been generally opposed to geographical or spatial representations where biophysical aspects were often disregarded.

Only recently, due to the development of GIS methods and to the evolution in datasets and modelling strategies, land use and its change have been embedded in a global climate mitigation analysis. Today integrated assessments represent the most advanced modelling strategy to deal with the complexity of the land-use system. Within one comprehensive global and long-term framework they have the ability to employ advantages of both geographic and economic models, while including biophysical considerations.

Despite this progress, more effort is required within IAMs to render the integration of those interactive spheres more transparent and to allow for the inclusion of more feedback effects, especially between economy and environment.

Concerning forestry, a future challenge for integrated assessment models will be to improve the endogenous modelling of future biophysical and economic implications of current decisions on forestland as well as consequences on future mitigation paths. Finally, more effort should be put on modelling forestry intensification separately from extensification.

As for agriculture, among other aspects, IAMs normally do not model soil carbon abatement options, and the implications of fertiliser use. In addition, potential mitigation of the livestock sector should also be taken into account more extensively.

Biomass production is a promising sector competing for land with agriculture and forestry. Its recent development entails the lack of historical data. Current studies can only poorly represent competition for land between food, biomass, and timber production. In years to come economic-climate models must attempt to improve these aspects, for example, calibrating mitigation responses to estimates derived from progressively available econometric applications.

Finally, an improvement is also required in the identification and evaluation of the most important sources of uncertainty permeating IAMs within and across integrated modules. For example, incorporated energy-economic models, not precisely developed for land-use analysis, should confine uncertainty in parameters by using available econometric estimates or by calibrating outcomes to bottom-up approaches. In addition, uncertainty in fire incidences, pests and diseases in agro-forestry sector would deserve more attention given their impacts on production, costs, and natural sequestration capacity.

Accounting for these issues in new generation IAMs models would significantly enhance future land demand and supply projections under baseline or under climate stabilisation scenarios. This would result in a better estimation of mitigation amounts and costs, for both agriculture and forestry land-mitigation opportunities.

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Appendix 1.1 LULUCF activities under the Kyoto Protocol and in climate negotiations

In 1997, the Kyoto Protocol stipulated the possibility to include carbon sinks deriving from land-use change and forestry activities (LULUCF). Annex I countries, within the period 2008-2012, have been permitted to use forest-carbon sequestration to meet their commitment targets in emissions reduction.[10]

Contemplated changes in carbon stocks involved the activities of afforestation/reforestation (AR) and avoided deforestation (AD) in managed forests developed since1990. Forest management, cropland management, and grazing land management where described as *additional* activities, and were also eligible to be included in the emissions total balance, under specific conditions.[11]

By setting rules for the land use land change and forestry (LULUCF) activities, it was only during the seventh Conference of Parties (COP), held in Marrakesh in 2001, that members of the UN Framework Convention on Climate Change (UNFCCC) actually agreed to include land-based carbon sequestration in their 2008-2012 emissions reduction targets. In 2003, the COP held in Milan, reached a consensus on the regulations to account for LULUCF practices between 2008-2012, within the Clean Development Mechanism (CDM).[12] Only afforestation and reforestation were confirmed as activities that could get involved in the accumulation of carbon credits under the CDM, while reduced emissions from avoided deforestation and other management practices were set aside due to related uncertainties on methodologies and data. The inclusion of avoided deforestation within a coordinated climate abatement strategy would have required addressing concerns such as additionality, uncertainty in forest-carbon estimates, forest saturation, forest-leakage, and non-permanence of carbon.[13] Within communities involved in forest mitigation activities, legacy rights also arise for land tenure and carbon ownership, which imply the entitlement of the project revenues.

The concept of reducing emissions from deforestation (RED) raised again during the UNFCCC COP-11 in Montreal (2005) while at COP-13 in Bali (2007), Parties agreed to address emissions from forest degradation in the developing world (REDD), estimated to be even larger than those from deforestations for several regions. In this occasion, the COP adopted a decision to support the role of conservation, forests sustainable management, and forest carbon stocks enhancement in developing countries (REDD+). The Bali Conference also centred its aim at the creation of a post-Kyoto "Road map". Aware of the drivers moving deforestation and forest degradation, it encouraged all Parties, in particular Annex II, to strengthen voluntary financing, technology transfers, and all possible actions toward developing Countries to protect wood and forests and

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[10] For additional information on the Kyoto Protocol see http://unfccc.int, while for a specification of the countries involved in Annex I see the Glossary.

[11] See the Glossary for a more detailed definition of the mentioned forestry activities.

[12] The Clean Development Mechanism is defined in Article 12 of the Kyoto Protocol and allows an Annex B Party to implement a project in developing countries to achieve its emission reduction target. Such projects gives the Party the right to gain certified emission reduction (CER) credits, each equivalent to one tonne of CO2. See the UNFCCC website for more information at: http://unfccc.int

[13] See the glossary for more details on additionality, forest saturation and leakage, and carbon non-permanence.

enhance carbon stocks with sustainable management of forests (see Decision 2/CP.13).[14] This need was also pointed out by Stern (2008) who claimed that developed countries must "*demonstrate that they can achieve low-carbon growth, transfer resources and technologies to developing countries, before developing countries take on binding national targets of their own by 2020".* Regarding the COP-15 held in Copenhagen (2009) and COP-16 in Cancún (2010) they adopted decisions to support the implementation of concrete actions involving all forest practices. Two specific bodies were recognised under the UNFCCC to carry out REDD+, LULUCF, and CDM related matters. These are the Long-term Cooperative Action (AWG-LCA) and the Working Group on Further Commitments for Annex I Parties (AWG-KP), which will continue to handle the building blocks emerged from the Bali Conference and to tackle problems related to the REDD+ also after 2012, when the 1st commitment period of the KP runs out. Finally, the Subsidiary Body for Scientific and Technological advice (SBSTA) has been called in Cancún to work on some technical characteristics such as sequestration monitoring, verification, reporting, and safeguards issues.

Despite these advancements a better understanding on the current levels of forest management is required to move further the discussion on REDD+, after the KP expires. In this direction, the UNFCCC secretariat has recently developed a synthesis report containing all the 38 individual Parties reference levels (for the period 2013-2020), which was intended to guide the dialogue during the COP session held in Durban (South Africa), last December 2011.[15]

Clearly, although REDD+ has increasingly drawn the attention of governments around the world, negotiations on LULUCF are still underway and a comprehensive formal agreement on forest-carbon mitigation has not yet been sealed. Crucial issues remain to be defined, such as deciding whether market-based rather than fund-based financing mechanisms are to be preferred to reward forest practices implementation.

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[14] See the Glossary for a specification of the countries involved in Annex II.

[15] For more information on the upcoming events and on REDD+ see the UNFCCC press release at: http://unfccc.int/press/news_room/newsletter/items/6161.php#1

Appendix 1.2 Major characteristics of analysed models

Model Name	Type of model	Nature of Model	Land use type	Geographic Scale	Dynamics-technique	Temporal dimension	Original Reference	Further applications/model extensions
KLUM	Optimization model/Rule-based model	Geographic model where allocation rules are based on profit maximization	Agriculture	Global	Static	Base year 1997; Analysis 1997-2050	Ronneberg et al., (2005)	
ACCELERATES	Optimization model-Rule based model-IAM	Geographic model where allocation rules are based on profit maximization	Mainly agriculture	Macro-Regional or other local areas	Comparative static	Analysis 2000-2050	Rounsevell et al., (2003)	
CLUE	Statistical/Simulation Model	Geographic model	Multiple land use types	Regional areas	Systems dynamics model-statistical techniques	Several decades analysis-20-40 years. Time step: 1yr	Veldkamp and Fresco (1996)	De Koning et al. (1999); Verburg et al., (1999a,b); Kok and Veldkamp (2001); Castella et al., (2006); Wassenaar et al. (2007).
ELPEN-System	Statistical/Simulation Model	Geographic model	Agriculture-Livestock sector	Europe	multiple linear regression model	Base year: 1997 and 2000	Wright et al. (1999)	Final Version-2003-(www.macaulay.ac.uk /elpen/docs/ ELPEN_final_report.ppt)
SALU	Rule-based model	Geographic model	Agriculture	Sahel area	Dynamic simulation model	Up to some decades of analysis	Stephenne and Lambin, (2001, 2004)	
FASOM-GHG	PEM-Optimization model	Economic model	Agriculture, Forestry, Grazing. Good treatment of forestry	USA in 11 regions	Dynamic-perfect foresight, non linear programming	Base year:2000. 10yrs time step. 100 years analysis	Adams et al., (1996)	McCarl (2004); USEPA (2005); Szulczyk and McCarl (2010)
WATSIM	PEM-Optimization model	Economic model	Agriculture	Global: 9 regions	Quasi dynamic model. No price expectations	Base year: 2000 5yrs time step	Kuhn, (2003)	Kuhn and Wehrheim (2002)
GTM	PEM-Optimization model	Economic model	Timber sector	Global: 12 regions	Intertemporal optimization with perfect foresight	1-year time step; Analysis 1990-2140	Sohngen et al. (1999)	Sohngrn and Mendelsohn (2003, 2007)

Model Name	Type of model	Nature of Model	Land use type	Geographic Scale	Dynamics-technique	Temporal dimension	Original Reference	Further applications/model extensions
IMPACT-Water	PEM-Optimization model	Economic model	Agriculture	Global: 36 regions	Comparative static	Base year: 2000. Annual time step. Analysis in 2020 / 2025 / 2050	Rosegrant et al., (2005)	
AgLU	PEM-Optimization model	Economic model with focus on land use	Agriculture, Forestry, Grazing	Global: 11 regions	Comparative static	Base year: 1990. 15-year time steps to 2096	Sands and Leimbach, (2003); Sands and Edmonds, (2005)	Sands and Kim (2008), develop AgLU 2x with forestry dynamics for US
CAPRI and CAPRI-DynaSpat	PEM-Optimization model	Economic model	Agriculture	EU15-EU27	Comparative static, solved by iterating supply and market modules	Base year: 2002. 5-10 yrs analysis. Specific cases of 20 yrs analysis scenario	Britz et al., (2008)	
GLOBIOM	PEM-Optimization model	Economic model, good focus on land use	Agriculture, Forestry, Livestock, Bioenergy production	Global: 11 or 27 regions	Recursive Dynamic	Base year: 2000; Analysis up to 2030, 2050. Time step: 10 yrs	Havlik, P., et al., (2010)	
GTAP	CGE-Optimization model	Economic model	Agriculture	Global: latest version (GTAP7) accounts for 113 regions	Comparative static	Max 50 yrs projections	Hertel (1997)	
G-cubed	CGE-Optimization model	Economic model	Agriculture	Global:12 regions	Dynamic	Analysis 1993-2070 in 1-year time step	McKibbin and Wang (1998)	
FARM	CGE-Optimization model. A first attempt of IAM	Economic model integrating environmental information from spatial model	Mostly Agriculture	Global: 8 regions	Comparative static	Analysis: 1990-2090	Darwin et al., (1995)	Darwin et al., (1996); Darwin and Tol, (2001)
D-FARM	CGE-Optimization model		Mostly Agriculture	Global: 12 regions	Recursive Dynamic	Analysis: 1997-2007/2020	Ianchovichina et al. (2001), Wong et al., (2003).	

Model Name	Type of model	Nature of Model	Land use type	Geographic Scale	Dynamics-technique	Temporal dimension	Original Reference	Further applications/model extensions
GTAPE-L	CGE-Optimization model	Economic model	Competition among different land uses: agriculture, forestry and other sectors	Global: 5 regions	Comparative static	Base year: 1997	Burniaux, (2002); Burniaux and Lee, (2003)	
GTAPEM	CGE-Optimization model	Economic model	Agriculture	Global: 7 regions	Comparative static	Base year: 2001. Analysis: 2001-2020	Hsin et al. (2004); Brooks and Dewbre (2006)	
GTAP-AGR	CGE-Optimization model	Economic model	Agriculture + explicit substitution amongst feedstuff in livestock	Global: 23 regions	Comparative static	Base-year 1997	Keeney and Hertel (2005)	
BLS-IIASA	CGE-Optimization model	Economic model	Focus on agriculture and pastureland	Global: 34 regions	Recursive Dynamic	Base-year 2000. 1yr time step	Fischer et al., (1988)	
GTAP-AEZ	CGE-Optimization model	Economic model	Agriculture, Forestry, Grazing	Global: 3 regions	Comparative static	Base year: 2001. Max 50 yrs projections	Lee (2004); Lee et al. (2009)	Hertel et al. (2008)
GTAP-Dyn	CGE-Optimization model	Economic model	Agriculture, Forestry, Livestock	Global: 11 regions	Recursive Dynamic	Base year: 1997; Analysis: 1997-2025.	Ianchovichina and McDougall, (2001)	Golub et al., (2006, 2008)
AgLU2x	CGE-Optimization model	Economic model + mapped watersheds	Agriculture, Forestry, Grazing	USA in 18 regions	steady-state comparisons consistent with an intertemporal model for forestry	Base year: 1990 Model in steady state	Sands and Kim (2008)	

Model Name	Type of model	Nature of Model	Land use type	Geographic Scale	Dynamics-technique	Temporal dimension	Original Reference	Further applications/model extensions
KLUM@GTAP	IAM	Link between KLUM and GTAP-EFL	Focus on Agriculture	Global: 16 regions	Comparative static	Base-year 1997; Analysis 1997-2050	Ronneberg et al., (2008)	
EPPA-MIT	IAM	GTAP-based CGE model + hybrid economic and physical accounting model	Focus on Agriculture	Global: 16 regions	Recursive Dynamic	Base year: 1997; 1997-2100; 5yrs time step	Paltsev et al., (2005)	
IGSM-MIT	IAM	Economic module (EPPA) linked with biophysical and terrestrial global models.	Food crops, bioenergy crops, Forestry, Grazing	Global: 16 regions	Dynamic model	Analysis from 1990 up to 2250	Sokolov et al., (2005)	
IIASA-LUC	IAM	CGE (BLS) + Agro ecological system	Focus on agriculture and pastureland	Global: 34 regions grouped in 11	Dynamic model	Base year: 2000; Analysis 1990-2080. Time step: 10 yrs	Tubiello and Fisher (2005)	Tubiello and Fisher (2007)
IIASA model CLUSTER	IAM	PEM (GLOBIOM) + geographically explicit agent-based model (G4M)	Multiple land use types	Global: 11 regions	Dynamic model	Base year: 2000; Analysis up to 2030, 2050. Time step: 10 yrs		Gusti et al. (2008)
IMAGE	IAM	Geographic model-Links between climatic and biophysical models	Multiple land use types	Global: 26 regions	Dynamic model	Projections up to 2100	Alcamo et al, (1998); IMAGE (2001); MNP, (2006).	
IMAGE-LEITAP	Link between modified GTAP-CGE model + IAM	CGE economic model + IAM	Multiple land use types, but economics focused on agriculture sector	Global: 26 regions	Static model	Projections up to 2050	Eickhout et al., (2008)	

AIM	IAM	Climatic + geographic/ biophysical models	Multiple land use types	Focus on Asia Pacific Region	Dynamic model	Projections up to 2100	Matsuoka et al., (2001)	
WITCH-GTM	IAM	Integrated/Hybrid model and Optimization model & Partial Equilibrium model for forestry (2 economic models)	Focus on forestry	Global: 12 regions	Dynamic model	Projections up to 2100. 10 yrs time step	Tavoni et al. (2007)	
ObjECTS-GCAM	IAM	Economic model + agriculture and land-use model (AgLU) + reduced-form climate model		Global: 14 regions	Recursive Dynamic	Base year: 1990. Analysis 1990 – 2095 in 5-year time step.	Edmonds and Reilly (1983)	Kim et al. (2006)

Source: Own Elaboration

Appendix 1.3 Acronyms and Abbreviations

AEZ	Agro-Ecological Zoning
AgLU Model	Agriculture and Land Use model
AIM	Asian-Pacific Integrated Model
BLS	Basic Linked System
CAPRI	Common Agricultural Policy Regionalised Impact
CET	Constant Elasticity of Transformation
CLUE Model	Conversion of Land Use and its Effects Model
CGE	Computable General Equilibrium Model
D-FARM	Dynamic-Future Agricultural Resources Model
EFISCEN	European Forest Information Scenario Model
EPPA Model	Emissions Prediction and Policy Analysis Model
EU	European Union
FAO	Food and Agriculture Organization
FARM	Future Agricultural Resources Model
FASOM	Forest and Agriculture Sector Optimization Model
FASOMGHG	Forest and Agriculture Sector Optimization Model with Greenhouse Gases
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GIS	Geographic Information System
GLOBIOM	The Global Biomass Optimization Model
GTAP-AGR	Global Trade Analysis Project-Agriculture
GTAPEM	Global Trade Analysis Project – Policy Evaluation Mode
GTM	Global Timber model
IAM	Integrated Assessment Model
ICES	Intertemporal Computable Equilibrium System
ICLIPS	Integrated Assessment of Climate Protection Strategies
IIASA	International Institute for Applied Systems Analysis
IMAGE	Integrated Model to Assess the Global Environment
IPCC	Intergovernmental Panel on Climate Change
KLUM	Kleines Land Use Model
LULUCF	Land Use, Land Use Cover, and Forestry
MESSAGE	Model for Energy Supply Strategy Alternatives and their General Environmental Impacts
PEM	Partial Equilibrium Model
ppmv	Parts Per Million by Volume
SALU Model	Sudano-sahelian countries of Africa model
USEPA	U.S. Environmental Protection Agency
WATSIM	World Agricultural Trade Simulation Model
WITCH	World Induced Technical Change Hybrid Model
WHRC	Wood Hole Research Centre

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