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Climate change and agriculture in computable general equilibrium models: alternative modeling strategies and data needs

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Abstract Agricultural sectors play a key role in the economics of climate change. Land as an input to agricultural production is one of the most important links between economy and the biosphere, representing a direct projection of human action on the natural environment. Agricultural management practices and cropping patterns exert an enormous effect on biogeochemical cycles, freshwater availability and soil quality. Agriculture also plays an important role in emitting and storing greenhouse gases. To consistently investigate climate policy and future pathways for the economic and natural environment, a realistic representation of agricultural land use is essential. Top—down Computable General Equilibrium (CGE) models have increasingly been used for this purpose. CGE models simulate the simultaneous equilibrium in a set of interdependent markets, and are especially suited to analyze agricultural markets from a global perspective. However, modeling agricultural sectors in CGE models is not a trivial task, mainly because of differences in temporal and geographic aggregation scales. This study surveys some proposed modeling strategies and highlights different tradeoffs involved in the various approaches. Coupling of

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top-down and bottom-up models is found to be the most applicable for comprehensive analysis of agriculture in prism of climate change. However, linking interdisciplinary data, methods and outputs is still the major obstacle to be solved for wide-scale implementation.

1 Introduction

Relationships between greenhouse effects and agricultural activity are usually and primarily considered in terms of the impact of climate change on agriculture. Food production will be particularly sensitive to climate change, because crop yields largely depend on prevailing climate conditions (temperature and rainfall patterns).

Agriculture currently accounts for 24% of world output, employs 22% of the global population, and occupies 40% of the land area. 75% of the poorest people in the world (the one billion people who live on less than $1 a day) live in rural areas and rely on agriculture for their livelihood (Bruinsma 2003). Forecasts predict that agriculture in higher-latitude developed countries is likely to benefit from moderate warming (2–3°C). However, even small amounts of climate change in tropical regions will lead to declines in yield. The agricultural sector is one of those most vulnerable to the damaging impacts of climate change in developing countries (Stern 2006).

Agricultural emissions mainly come from a large number of small emitters (farms), over three quarters of which are in developing and transition economies. In its climate-change report on mitigation, the Intergovernmental Panel on Climate Change (IPCC 2001) clearly assesses that transport and energy production industries constitute the main anthropogenic GHG sources, while “agriculture contributes only about 4% of global [i.e. worldwide] carbon emissions from energy use, but over 20% of anthropogenic GHG emissions in terms of MtC-eq/yr,[1] mainly from methane (55–60% of total CH_4 emissions) and nitrous oxide (65–80% of total N_2O emissions) as well as carbon from land clearing”. The IPCC (2007) report states that “the largest growth in global GHG emissions between 1970 and 2004 has come from the energy supply sector (an increase of 145%). The growth in direct emissions in this period from transport was 120%, industry 65% and land use, land use change, and forestry (LULUCF) 40%. Between 1970 and 1990 direct emissions from agriculture grew by 27%”.

Emissions from agriculture and land use occur through different processes (IPCC 1997; Alcamo et al. 1998): enteric fermentation and animal waste disposal and fermentation, anaerobic processes in rice-growing, nitrification and de-nitrification linked with fertilization, and also land clearing and burning of biomass, fuel wood, agricultural waste, and savannah. Non-CO_2 emissions from agriculture amount to 14% of total GHG emissions. Of this, fertilizer use and livestock each account for one third of emissions. Over half of GHG emissions are from developing countries. Agriculture is also indirectly responsible for emissions from land-use change (agriculture is a key driver of deforestation), industry (in the production of fertilizer), and transport (in the movement of goods). Increasing demand for agricultural products, due to rising population and income per capita, is expected to lead to continued rises in emissions from this source. Total non-CO_2 emissions are expected to double in the period 2000–2050 (Stern 2006).

Nevertheless, agriculture can contribute to GHG sequestration and abatement, mainly through reforestation, forest management, bio-fuels and soil carbon stocking,[2] changes in

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[1] MtC-eq/yr are millions of tons of carbon equivalent GHG per year, with global warming potentials of methane, nitrous oxide and other GHG other than carbon dioxide, used as conversion coefficients for non-CO_2 gases.

[2] For a review of carbon sequestration in terrestrial ecosystems, see http://csite.esd.ornl.gov.

practices and land uses. Farmers and herders may also react directly to climate policies, imposing a carbon price to GHG-emitting activities.

The potential role of emitting sectors for mitigation, abatement or sequestration options is currently being debated. This study surveys some modeling approaches that have been proposed to address the following questions: Why is agriculture so critical in the assessment of climate change impact and policies? Why climate change assessment requires changes in the structure of the models? How the different model structures score in terms of assessment potential?

We distinguish partial equilibrium (PE) from computable general equilibrium (CGE) models. PE models are classified as bottom-up models that depict markets for a selected set of products. Implicitly, they consider these markets as not affecting the rest of the economy, which is accordingly treated as exogenous. They can provide much product detail and are flexible in representing complex agricultural policy instruments and specific characteristics of agricultural markets. CGE (top-down) models, by contrast, operate at a higher aggregation in terms of industries and products, but they can capture the implications of international trade for the economy as a whole, covering the circular flow of income and expenditure and depicting inter-industry relations. CGE models are therefore well suited to portray the manifold interactions between agriculture and other sectors in the economy.

Moreover, PE modeling has not yet been able fully to account for the opportunity costs of alternative agriculture and land-based mitigation strategies, which are determined by heterogeneous and dynamic environmental and economic conditions of land[3] and economy-wide feedbacks that reallocate inputs, international production, and consumers' budgets. CGE economic models are well suited to evaluate these kinds of tradeoff (Hertel et al. 2009a, b).

Research on GHG abatement or sequestration options in agriculture employing CGE models stems from a need to evaluate and compare net abatement options of all emitting sectors. However, the general equilibrium approach carries disadvantages also. Critics argue that the CGE models are overly simplistic and omit many important characteristics of the agricultural economy. They also argue that the CGE parameters need more solid econometric foundations.

Clearly, an accurate analysis of climate change aspects and agriculture needs a reliable representation of both economic and ecological patterns. A CGE modeler normally needs to choose between two main alternatives: to couple a top-down CGE model with a bottom-up PE agricultural land-use model, or to improve the relevant functional structure inside the CGE model itself. Each possibility has its own advantages and drawbacks in terms of data requirements, computational practices and accuracy. This review compares several approaches proposed in the literature, possibly providing guidelines for modelers in this field.

Section 2 of the paper overviews some approaches adopted to refine the modeling of agricultural and other land-using sectors in CGE models. Section 3 illustrates the development of enhancing land-related economic behavior in CGE models. Models accounting for ecological aspects of land heterogeneity are presented in Section 4. Section 5 introduces the coupling approach. Section 6 outlines some major achievements, potentials and difficulties of the reviewed studies. The last section draws some conclusions and discusses directions for future development.

2 Overview of agriculture and land-use modeling approaches

This survey focuses on CGE modeling related to agricultural and climate-change assessment. The CGE approach offers several important advantages over PE models,

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[3] See Hubacek and van den Bergh (2006) for a review of changing concepts of land in economic theory.

even though the latter are able to include detailed biophysical land use characteristics and to capture better some local environmental and economic effects. Traditional agricultural PE economic analysis has tended to focus on commodities and associated factor returns. By contrast, welfare in a CGE model is computed directly in terms of household utility and not by some abstract summation of producer, consumer and taxpayer surpluses. Additionally, a CGE model insures for finite resources and accounting consistency by relying on Social Accounting Matrices (SAM). This allows capturing inter-industry linkages between agricultural and non-agricultural sectors of economy and provides an economy-wide perspective of analysis, which is especially important in the context of climate change.

In the last decade especially, different attempts have been made to extend top-down CGE models to allow for more detailed analyses of agricultural industries. Two broad approaches have been adopted. The first is to improve the modeling of land within the CGE framework, mainly the transition of land among different uses, like crop production, livestock and forestry. In Section 3 we present several studies that take this direction. Another step is to distinguish various land classes that have different characteristics and productivities and are only suitable for some uses. Some models adopting this strategy, which requires a high level of informational detail, are discussed in Section 4.

The other approach is to link a macro-economic CGE model with a detailed, sectoral model of agricultural land use. Some examples in this area are discussed in Section 5.

Table 1 lists the studies presented in this review.

3 Refined CGE models

Conceivably the simplest method of introducing endogenous land-use allocation in a CGE model is to constrain industrial land stock through a Constant Elasticity of Transformation (CET) function, by which an aggregate endowment of land is transformed across alternative uses, subject to some transformation parameters, determining the responsiveness of land supply to changes in relative yields. Land owners rent out land to uses that give the highest return, under the CET constraint. Perfect competition on input and output markets assures that all markets, including that of land, clear. This way, a land supply elasticity of each type is implied by the elasticity of substitution and implicitly reflects some underlying variation in suitability of each land type for different uses and the cost to or willingness of owners to switch land to another use.

In general, CET functions are often used in CGE models to account for imperfect primary factor mobility. In the case of agricultural land, CETs are used to assign land endowments to different crops or industries, on the basis of relative prices (land rents).

A CET for land use transformation is implicitly defined by a relationship like:

$$TL^{\frac{1-\sigma}{\sigma}} = \sum_i \phi_i L_i^{\frac{1-\sigma}{\sigma}} \tag{1}$$

Where: TL stands for total available land, L for land assigned to crop/industry i, ϕ_i are share parameters and σ is the (constant) elasticity of transformation.

Maximization of the total value of land (sum of products of industry land *Li* by price (rent) *Pi*, subject to (1), gives raise to first order conditions like:

$$\frac{L_i}{L_j} = \left(\frac{\phi_j}{\phi_i}\frac{P_i}{P_j}\right)^{\sigma} \tag{2}$$

Table 1 CGE models covered in the review

Modeling framework	Reference	Temporal resolution and coverage	Spatial resolution and coverage	Motivation
1. CGE models extended for land-use analyses				
CGE for USA	Hertel and Tsigas (1988)	Comparative static; base-year 1977	7 agricultural sectors, USA	Analyze effects of eliminating farm and food tax preferences in 1977.
GTAP	Hertel (1997)	Comparative static; base-year 2004	Latest available version GTAP7 allows for 113 regional and 57 sectors, global	Evaluate effects of agricultural policies on commodity markets and trade.
GTAPE-L	Burniaux and Lee (2003)	Comparative static; base-year 1997	5 regions, global	Exemplify the incorporation of land/land use in GTAP; assess GHG mitigation policies with focus on land-use impacts
GTAP-AGR	Keeney and Hertel (2005)	Comparative static; base-year 1997	23 regions, global; 5 agricultural sectors	Assess the implications of multilateral changes in agricultural policies
G-Cubed (Agriculture)	McKibbin and Wang (1998)	Dynamic, 1-year step; 1993-2070	12 regions, global; 4 agricultural out of 12 total sectors	Explore the impact of international and domestic stocks like trade liberalization on US agriculture
CGE for Canada	Robidoux et al. (1989)	Comparative static	Canada	Analyze Canadian farm policies
CGE for Philippines	Abdula (2005)	Comparative static	Small open economy, Philippines	Study the conflict between food and bio-fuel production
GTAP-based CGE for Poland	Ignaciuk (2006, chapter 5)	Comparative static 1997	Small open economy, Poland	Explore the potential of biomass as a source of energy
GTAPEM	Hsin et al. (2004); Brooks and Dewbre (2006)	Comparative static; 2001-2020	7 regions, global; 8 agricultural sectors	Analyze the impact of agriculture and non-agriculture reform, with particular focus on the effects of OECD agricultural policy on developing countries
GTAP/Supply Curve	Baltzer and Kløverpris (2008)	Comparative static; 2001	22 regions, global; 15 economic sectors	Analyze changes in global wheat supply and consequences for agricultural land use caused by an increase in US household demand for wheat
EPPA	Gurgel et al. (2007)	Recursive-dynamic; 1997	16 regions, global; 21 sectors	Investigate the potential production and implications of a global biofuels industry
FARM	Darwin et al. (1996)	Comparative static; 1990-2090	Multi-scale: 8 world regions, 0.5 lon/lat	Integrate explicit land and water assessment into CGE, environmental focus on climate change
D-FARM	Ianchovichina et al. (2001); Wong et al. (2003)	Recursive dynamic 1997-2007/2020	Multi-scale: 12 world regions	Analyze resource use and technological progress in agriculture
GTAP-AEZ	Lee (2004); Lee et al. (2009)	Comparative static, 2001	8 agricultural sectors+forestry, 3 world regions	Investigate the role of global land use in determining greenhouse gases mitigation costs

Table 1 (continued)

Modeling framework	Reference	Temporal resolution and coverage	Spatial resolution and coverage	Motivation
GTAP-Dyn/AEZ modified for land-use analyses	Golub et al. (2006)	Recursive dynamic 1997-2025	11 regions, global	Analyze GHG emissions driven by land use and land-use changes on the global scale.
GTAP-Dyn and Global Timber Model	Golub et al. (2009)	Recursive dynamic 1997-2025	11 regions, global	Enhance understanding of land-use related GHG emissions
2. Coupled top-down bottom-up models				
GTAP-LEI/IMAGE coupling within EURURALIS	Klijn et al. (2005)	10-year steps; 2001-2030	Multi-scale: national level, sub-national level (NUTS2), grid level; global with focus on EU15	Evaluate impacts of different policies on land use in Europe
GCM-GTAP	Bosello and Zhang (2005)	Comparative static; 1997-2010-2030-2050	8 regions, global; 4 agricultural out of total 17 sectors	Estimate economy-wide implications of climate change on agricultural sectors
KLUM@GTAP	Ronneberger et al. (2009)	Comparative static; 1997-2050	16 regions, global; 4 agricultural out of total 17 sectors.	Assess integrated impacts of climate change on global cropland allocation and its implications for economic development

When there are n industries, parameters ϕ_i can be calibrated by taking as given the elasticity of substitution σ, and solving the n-1 conditions (2) and the (1), on the basis of observed industrial land L, total land TL and prices P.

This was the approach taken by Hertel and Tsigas (1988). Given a specific elasticity of transformation σ1 (Fig. 1), rental rates differ across uses, and acreage response may be calibrated to econometrically estimated values. The Global Trade Analysis Project (GTAP) (Hertel 1997) also follows this approach, defining the land input as an imperfectly substitutable factor among different crops or land uses (Li-Ln).

GTAP is currently one of the most employed CGE models. However, when a CGE modeler focuses her analysis on agricultural sectors like in case of climate change assessment, this structure is found to be over simplified as it assumes land to be equally easily transformable[4] between e.g. rice, grassland, cotton and vegetables.

A bunch of studies motivated by the need to more accurately model land use decisions, and to be consistent with the supply response tackled this problem introducing "nested" CET function. For example, The Global Trade Analysis Project, Energy—Land model (GTAPE-L) (Burniaux 2002; Burniaux and Lee 2003) extends the standard GTAP model to track inter-sectoral land transitions to estimate emissions Greenhouse gas emissions (GHGs): CH4, CO2 and N2O. To get land emission rates, a land transition matrix (which shows changes of land status over a given period of time) is derived from the IMAGE 2.2 model (IMAGE 2001), based on 1995 net carbon emissions estimates (tons of carbon equivalents). By multiplying the land emission rates with the simulated land-use changes, one can estimate the implied variation in GHG emissions due to changes in land use.

Keeney and Hertel (2005) offer another special-purpose version of the GTAP model for agriculture, called GTAP-AGR. The study focuses on factor markets, which play a critical role in determining the incidence of producer subsidies, by modifying both the factor supply and derived demand equations. The authors also modify the specification of consumer demand, assuming separability of food from non-food commodities. Finally, they introduce substitution possibilities amongst feedstuffs used in the livestock industry.

The G-CUBED (Agriculture) model (McKibbin and Wang 1998) is an extension and variant of the G-CUBED model, developed by McKibbin and Wilcoxen (1998), which includes relatively detailed agricultural sectors and a country disaggregation relevant to US agricultural markets. The G-CUBED model combines the disaggregated, econometrically estimated, intertemporal CGE model of the US economy of Jorgenson and Wilcoxen (1990) with the macroeconomic model of McKibbin and Sachs (1991). The G-CUBED (Agriculture) model was primarily designed to analyze impacts of international and domestic shocks on US agriculture, like the APEC trade liberalization and the Asian economic crisis. However, the model treats land as homogeneous. A specific feature of the model is the imposition of intertemporal optimization under perfect foresight for households and governments in consumption and investment decisions.

The studies above exemplify the foremost attempts to deal with agriculture and land in CGE models. Their range of applicability is limited by the way land is represented, as the latter is treated as homogeneous and space-less, with disregard of biophysical characteristics and spatial interactions. To overcome these limitations, a distinction between land types and land uses must be introduced, which implies a significant increase in the models' complexity.

For example, in their CGE model for Canada, Robidoux et al. (1989) specify Constant Elasticity of Substitution (CES) aggregator functions that combine three land types, each of

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[4] In standard GTAP model CET of land transformation equals −1.

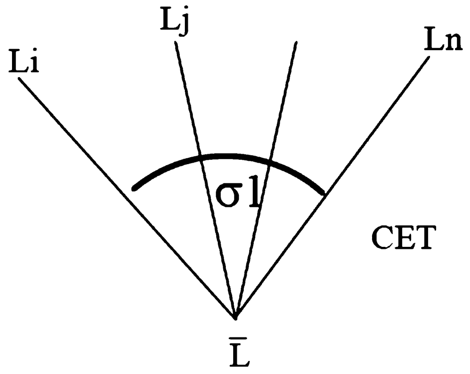

Fig. 1 Land allocation tree for standard GTAP

which is used—to some degree—in the production of six different farm products. Their approach is original in the way they estimate benchmark equilibrium rental rates, differentiated by land type. These are obtained by regressing total land rents in each sector on the observed quantity of each land type used in that sector. The basic assumption is that in equilibrium the land-specific rental rate (i.e., the coefficient on acreage) must be equal across uses.

In general, when multiple land types are considered within the agricultural production processes, a nested production function of the CES class is typically adopted to combine land factors into a land composite. A CES function has the same formulation as a CET Eq. 1 where, however, the elasticity takes a negative value.

The corresponding first order conditions are, in this case, more conveniently formulated as:

$$\frac{L_i}{L_j} = \left(\frac{\phi_i}{\phi_j}\frac{P_j}{P_i}\right)^{|\sigma|} \tag{3}$$

CES and CET function can be usefully combined. For example, a CES function may control the substitution process among land types within single industries, whereas a CET may allocate a specific land type among alternative uses.

Abdula (2005) and Ignaciuk (2006, chapter 5) also follow this approach. Abdula uses a static CGE model for the Philippines and enlarges it with a bio-fuels sector, to study the conflict between food and bio-fuels production. Since both activities use scarce land, subsidizing bio-fuels may induce farmers to move away from food production to the production of inputs for the bio-fuel industry. Land is treated as a heterogeneous factor, including three land types (cropland, pasture and forest, all in fixed supply), some of which are only suitable for particular uses. Ignaciuk (ibid.) considers land contaminated by heavy metals, e.g., through mining and industrial activities in the past, in a GTAP-based CGE model for the Polish economy. Contaminated land can only be used for bio-fuels production, so it is excluded from producing food. Therefore, land is treated explicitly as a heterogeneous input.

GTAPEM (Hsin et al. 2004; Brooks and Dewbre 2006) is a specially tailored version of GTAP that inherits some of the features of GTAP-AGR, utilizing domestic support data (PSE) from the OECD. GTAPEM augments GTAP-AGR by distinguishing land in the production structure of agricultural sectors into miscellaneous agricultural land, rice, and the group field crops and pastures. For these land types, three different elasticities of transformation are defined. Additional modifications include factor substitution between purchased farm input intermediates, and between the aggregate intermediates and farm-owned inputs.

In general, the problem with the CET approach is that the "transformation" of land from one use to another destroys the ability to track the allocation of hectares across agricultural activities. Instead of constraining the sum of hectares across uses to equal the total availability of hectares in a given country, the CET function constrains the land rental share weighted sum of hectares to equal the total endowment of land. In this framework, differential land rents reflect differences in the effective productivity of a given hectare of land across uses and it is these effective hectares that are constrained in the aggregate (Hertel et al. 2009a, b). This is not a big problem only when reporting land-use shifts as percentage changes is sufficient. However, in most of the analyses focused on land use this is not sufficient. Also, given the lack of an explicit link to yields and the underlying heterogeneity of land, this model is difficult to validate against the observed data.

In addition, a well-known property of CET and CES functions is that they are share preserving. This feature assures that radical changes in land use does not occur, making short term projections more "realistic." However, for longer term analysis where demand for some uses could expand substantially the CET approach may unrealistically limits land use change. The CET approach also does not explicitly account for conversion costs (Gurgel et al. 2007).

In short, while it is an extremely versatile approach to limiting factor mobility across uses, the CET function suffers from several major limitations. Baltzer and Kløverpris (2008) partially solve this problem by requiring that average productivity for all types of land remain the same. This resolves the acreage inconsistency, but it may create another discrepancy: between different concepts used in the allocation of land and in the production function. A more explicit approach to handling land heterogeneity in deeper theoretical foundation would be desirable.

Gurgel et al. 2007 follow a similar direction to consistently introduce land as an economic factor input and in physical terms into a computable general equilibrium EPPA model. The authors argue that modifying CET function of land transformation is not a sufficient improvement when a study addresses a long term analysis as in case of climate change assessment. The share preserving feature of CET assures that radical changes in land use do not occur. However, for longer term analysis where demand for some uses could expand substantially the CET approach may unrealistically limit land use change. Therefore, the authors explicitly model land conversion from natural areas to agricultural use in two different ways: in one approach they introduce land supply elasticity based on observed land supply responses and in the other approach they consider only the direct cost of conversion. The version with the land supply elasticity allowed much less conversion of land from natural areas, forcing intensification of production, especially on pasture and grazing land, whereas the pure conversion cost model led to significant deforestation.

4 Modeling agro-ecological zones (AEZs)

The approach illustrated above focuses on land types, without considering regional or climatic differences. However, the capacity of a given acre of land to produce a particular farm product varies with soil type, location in the watershed, and climatic conditions.

The Future Agricultural Resources Model (FARM) was developed in the mid-1990s to evaluate impacts of global climate change on the world's agricultural system (Darwin et al. 1995; Darwin et al. 1996). The authors disaggregate land classes into six types, characterized by the length of the growing season, and identify water as an input in the production function of each crop. These land classes are employed differentially across farming and forestry sectors, according to observed patterns of production.

The model has been used to assess the impact of alternative climate-change scenarios on patterns of agricultural production, trade, consumption and welfare. While FARM was originally a static model, a dynamic version, denoted D-FARM, is now available. The latter is a recursive dynamic model based on estimates of annual growth rates of regional GDP, gross domestic investment, population, and skilled and unskilled labor (Ianchovichina et al. 2001; Wong and Alavalapati 2003).

GTAP-AEZ (Lee et al. 2009) continues along these lines, but with much superior data and more structured production functions. This model considers different land inputs which are imperfectly substitutable in the production function within, but not across, climatic zones.

In the first version of GTAP-AEZ (Lee 2004), it is assumed that each of the land-using sectors in a specific Agro-Ecological Zone (AEZ) has its unique production function. For example, the wheat sector located in AEZ 1 has a different production function from the wheat sector located in AEZ 6. This allows identifying differences in the productivity of land in different climatic conditions. Yet all six wheat sectors in various AEZs produce the same homogeneous output. For this approach, information is needed on cost shares and respective input shares in the AEZs, which are not yet provided in the GTAP-AEZ database.

In the extended version of GTAP-AEZ (Lee et al. 2009) it is assumed, instead, that a single national production function exists for each (agricultural) commodity. Various AEZs are inputs in the national production functions, where they can be combined through a quite high elasticity of substitution.

Golub et al. (2006) move one step further and expand the GTAP-Dyn (Ianchovichina and McDougall 2001) dynamic CGE model of the global economy to investigate long-run land-use changes on the global scale. They modify both the supply and the demand of land. Consumer demand is translated into derived demands for land through a set of sectoral production functions, differentiating the demand for land by AEZ. On the supply side, land mobility across uses is addressed via a sequence of increasingly sophisticated models of land supply, beginning with one in which land is perfectly mobile and undifferentiated, and ending with one in which land mobility across uses is governed by a nested CET function which also accounts for the heterogeneity of land within AEZs. In this final formulation, land owners solve a sequential revenue maximization exercise, in which land is first allocated between forestry and agriculture, then between grazing and crops, and finally, among competing crops. Although this ultimate version offers the most sensible representation of land supply, the resulting baseline land-rental changes in forestry and grazing seem (to the authors) unrealistically high.

To resolve this problem, Golub et al. (2009) iterate between GTAP-Dyn and the Global Timber Model of Sohngen and Mendelsohn (2006), to determine forestry input-augmenting productivity growth of forestry processing sectors in GTAP-Dyn. Using the rate of unmanaged forest access predicted by the Global Timber Model, Golub et al. introduce the possibility of conversion of unmanaged forest-land to land used in production, when demand for cropland and pasture is high and land rents are high enough to cover costs of access to unmanaged land.

To summarize, the AEZ methodology is analogous to the CET approach, but it is based on anexplicit yield heterogeneity. The main limitations of AEZ are data requirements and corresponding modeling difficulties connected to operating a large-scale model.

5 Top-down bottom-up coupling method

Instead of modeling the economics of land use as a part of a CGE model, as in the models presented in the two previous sections, a detailed bottom-up land allocation model is linked to a top-down CGE model. On the basis of relative prices estimated by a CGE, a land-use model can predict how land is allocated among competing uses. A certain land allocation could therefore be taken as exogenous in the CGE model. Figure 2 presents the output interchange between the two models. Generally the process is iterated until a reasonable convergence can be found.

In the EURURALIS project the IMAGE model is coupled to GTAPEM (Hsin et al. 2004; Klijn et al. 2005). Crop yields and a feed conversion factor, determined by IMAGE, are exchanged with production of food and animal products and a management factor (describing the management induced yield changes) as calculated by GTAPEM (van Meijl et al. 2006). The advantage of coupling the two comprehensive models lies in detailed and exhaustive process representation. Moreover, this is one of the few approaches where a feedback between economy and vegetation is at least partly realized. However, the land allocation tool of the coupled framework is still based on empirically estimated rules according to land potential, largely disregarding economic motivations of allocation decisions.

Bosello and Zhang (2005) offer another coupling exercise to evaluate climate change impact on agriculture. They couple a global circulation model GCM containing a crop-growth model with a global CGE model based on GTAP-E. The climatic scenario is endogenously produced by the economic model, which is benchmarked to reproduce a hypothetical world economic system in 2010, 2030 and 2050. Their results confirm both the limited impact of climate change on agricultural sectors, largely determined by the smoothing effect of economic adaptation, but also the relatively higher penalization of the developing world. The authors admit that this exercise suffers from some major limitations, such as simplifications and generalizations of both climatic conditions and crop responses, and the small number of observations.

KLUM@GTAP (Ronneberger et al. 2009) is another coupling exercise in which a static global GTAP-based CGE model is linked to the land use model KLUM. The latter is a land allocation PE model, in which, for each hectare of land a representative farmer maximizes her expected profits. Risk-aversion ensures that she prefers multi-product land uses over monoculture. The biophysical aspects of land are included indirectly, as area-specific yields

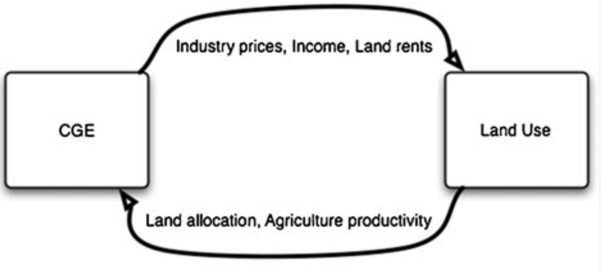

Fig. 2 A flow diagram of CGE/Land Use model coupling

differ for each unit of land. In the coupling experiment, yield changes due to climate change in 2050 (as reported by Tan et al. 2003) are applied to KLUM, which calculates the corresponding changes in land uses. These in turn are fed into the GTAP-based model to obtain management-induced yield and price changes (through changes in input combinations), which then are fed back into KLUM.

Although the experiment shows that the results of the coupled and uncoupled simulations can vary substantially, it also shows that linking the models encounters serious difficulties. One is that GTAP has its land data in value terms, with prices normalized to unity, while the KLUM database uses a quantity format. This makes the models' land data incomparable. To overcome this limitation, a key parameter in GTAP (the elasticity of substitution among land, capital and labor) had to be tripled, to make the model less sensitive to the input that comes from the KLUM model. Without this intervention, the results of the two models would not converge.

In sum, the ideal case of a joint solution of a CGE and PE is no different from the solution of a single extended CGE. Assuming that the original CGE is given in reduced form and the PE as a constrained optimization problem, the extended coupling method is constructed by merging the original CGE equations with the Kuhn-Tucker conditions of the PE. Some of the previously exogenous items (the parameters) of the CGE and the PE become endogenous in the new equation system, and new functions are added that map CGE variables to PE parameters, and vice versa (Banse and Grethe 2008).

In practice, perfect integration of the models may be difficult to obtain for technical as well as to theoretical reasons, and special solution methods may be required to reach equilibrium. Furthermore, the PE and CGE models are often implemented in different software, and the system must be solved iteratively, without any guarantee of convergence.

Another challenge in linking models is to obtain a joint baseline. The models may rely on different data sources, may use different units of measurement and may be based on different assumptions. The task of the joint baseline calibration is essentially to choose parameters of the mapping and aggregation functions so that if no exogenous shock is introduced, the stand-alone models give precisely the same result as the linked system.

6 Major achievements, deficits and potentials

Two major approaches to more accurate representation of agriculture in CGE models can be found in the reviewed literature. Introducing heterogeneity of available land, as outlined in Sections 3 and 4, enhances the applicability of CGE models in analyses which involve changes in agricultural production. Linking a CGE to a PE land use model, as presented in Section 5, improves realism even further, but it may come at a cost due to technical problems of establishing the link between different models and obtaining convergence in the iteration process.

The surveyed (representative) studies are still not sufficient to provide an all-inclusive analytical framework for the various aspects of modeling agriculture for climate-change analysis such as global coverage; a dynamic and long-term horizon; multiple GHG emissions; land heterogeneity; water issues; tradeoff between different land uses. However, some models, like GTAP-Dyn/AEZ and D-FARM, do address many of these issues. Both models have a detailed and heterogeneous representation of land, based on length of growth periods. An important advantage of the current version of GTAP-Dyn/AEZ is its multi-gas and dynamic approach, while the advantages of D-FARM are the inclusion of water and a broader regional coverage. On the other hand, both models have only a single forest type, do not consider a bio-fuels sector, and have limited regional disaggregation. GTAP-Dyn/AEZ currently only has three world regions, while D-FARM contains no more than 12 regions.

A fundamental problem in modeling agriculture and forestry production at the sub-national level involves estimation of input usage and production by spatial unit. The GTAP-AEZ model circumvents this problem, by having a single, national production function in which land types from different AEZs substitute one another. Hertel et al. (2009a, b) show that this is a legitimate approximation to an approach in which production on each AEZ is modeled separately, provided that (a) the sub-sectors (i.e., different AEZs) produce identical products, (b) non-land input–output ratios are the same across AEZs, (c) common non-land input prices prevail across AEZs, and (d) the elasticity of substitution between AEZs in a given land use is set very high. These assumptions, combined with cost minimization and zero pure profits, mean that land rents must vary in direct proportion to yields. It would be useful to test the requisite hypotheses for key countries, using disaggregated data on inputs and prices. Of particular interest is the extent to which non-land input–output ratios vary systematically with AEZs, either due to differences in choice of technique across different land qualities or due to differing input prices. If this proves to be the case, then the simple rule of proportionality between yields and land rents, as well as the capacity of an aggregate production function to capture the impact on the derived demand for land, are both doubtful.

An additional disadvantage common to CGE models is due to non-linear treatment of land in the production functions, whereby land cannot be measured in physical units of area but instead is quantified through monetary units in the value added. This complicates the interpretation of the resulting changes in land allocation. Another weakness of the most developed CGEs for agricultural and climate change analysis (like GTAPEM and GTAP-Dyn/AEZ) is the absence of empirical evidence of the land transformation structure and related elasticities, which may have a crucial effect on the models' performance.

Integrated land-use modeling approaches show that some of the intrinsic limitations of PE and CGE models can be overcome to a certain extent. The coupling of IMAGE and GTAP-LEI (EURURALIS), as well as linking of KLUM and GTAP, aim to overcome the weakness of the economic demand module in IMAGE and KLUM respectively, and to better the representation of land supply in the corresponding GTAP version.

On the other hand, despite certain achievements, the full potential of integrating CGE and PE models seems not yet fully explored, as the advantages stand against the risk of inconsistencies and redundancies. EURURALIS, for example, lacks endogenous methods to determine whether food demand will be satisfied by expansion of agricultural area rather than by intensification. Beyond a more detailed representation of agricultural management, including the feedback with soil and water is also needed. Irreversibly degraded soil and the exhaustion of freshwater resources are major constraints on future land use. These have not yet been sufficiently tackled by any land-use or CGE model.

7 Conclusions and directions for the future work

In this paper we surveyed of the various approaches taken to describe, model and measure the complex relationships of climate change, agriculture and land use. Two major strategies were outlined: internal model extension and soft-link coupling of CGE and PE land-use models. The main message that can be grasped from the relevant literature is that climatic, agricultural and economic information needs to be consistently collated to provide a reliable and sound impact assessment analysis in this field. This is attested by the constant effort to expand the comprehensiveness of the investigation. But despite the achievements and individual strengths of the selected modeling approaches, core problems of global land-use modeling are not yet resolved.

To date, the main advantage of the coupling approach is the ability to benefit from the strength of partial equilibrium, which represents in detail agriculture and land use aspects, in the economy-wide comprehensive framework of the CGE model. Yet coupling top-down with bottom up models encounters major difficulties in the sense of data incomparability, computational limitations and sophisticated programming. In addition, establishing the link may demand theoretically or empirically inconsistent compromises. By contrast, internal extension of a CGE model, through the introduction of new structural relations and corresponding parameters, seems a more feasible and reliable method. However, despite recent developments it still does not compare with the coupling method for accuracy and realism.

Overall, the modeling of global land-based climate-change mitigation is relatively immature, with significant opportunities for improving baseline and land-use scenarios and better characterizing the emissions and mitigation potential of land. Essential to future land modeling are improvements in the dynamic modeling of regional land-use competition, since the cost of any land-based mitigation strategy should consider the opportunity costs of land.

The agricultural soil carbon stock and flux modeling is notably absent from current approaches, even though agricultural soils are thought to offer substantial carbon sequestration potential (IPCC 2007). Moreover, technological change will alter the emission rates of agricultural production activities. Explicit consideration of this interaction is important to avoid arbitrary emission growth and to explore emission uncertainties associated with technological uncertainty.

The analysis of bio-fuels within global CGE models meets two main obstacles. The first is data availability. Many of the potentially important bio-fuel technologies (e.g., ethanol from cellulose) are not currently commercially viable, so they do not appear in databases recording current market transactions, like SAMs. Introducing them into the model requires the formulation of an appropriate profile of costs, sales, and even trade shares, to foresee when they will come into production. A related question is profitability: how high energy prices have to rise before these technologies enter into commercial production.

A range of problems also relate to adequately representing forestry in economic models. It takes decades for a new forest to grow, and growth in the forest stock, as well as sequestration potential, depends critically on the type of forest and its vintage.

Finally, for comprehensive analyses of climate-change impacts it is important to include water demand and supply, and to distinguish farmland in terms of water access. Berrittella et al. (2007) include water in a global CGE model, but their framework offers only a rudimentary representation of land. Future research will need to integrate such analyses of land and water into a single, global general equilibrium framework.

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