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**Modeling Linkages Between
Climate Policy and Land Use:
An Overview**

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Modeling Linkages Between Climate Policy and Land Use: An Overview

Summary

Agriculture and forestry play an important role in emitting and storing greenhouse gases. For an efficient and cost-effective climate policy it is therefore important to explicitly include land use, land use change, and forestry (LULUCF) in economy-climate models. This paper gives an overview and assessment of existing approaches to include land use, land-use change, and forestry into climate-economy models or to link economy-climate models to land-use models.

Keywords: Climate Change, Climate Policy, Modeling, Land Use

JEL Classification: Q23, Q24, Q25, Q42

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1. Introduction

Agricultural sectors can contribute significantly to the portfolio of policy measures to combat global warming. Houghton (2003) has estimated that about one-third of total carbon dioxide (CO₂) emissions since 1850 come from changes in land use, and two-thirds come from fossil fuels. In addition, land use and changes in land use cause emissions of other greenhouse gases (GHGs), most notably methane (CH₄) and nitrous oxides (N₂O): in the year 2000, agricultural byproducts accounted for 40% of methane emissions and 62% of N₂O emissions, while land use and biomass burning were responsible for 6.6% of methane and 26% of nitrous oxide emissions (MNP, 2005). Changes in the type and intensity of land use, such as crop changes and different types of soil management for a given crop, lead to changes in soil use and hence in CO₂ and non-CO₂ GHG emissions. For example, paddy rice production leads to more methane emissions than most other crops, while improved agronomy and nutrient, tillage and residue management can reduce emissions from agriculture. At the same time the production of crops for bio-fuels might, under certain conditions, result in reduced CO₂ emissions if these fuels replace fossil fuels.

Forests play an important role in climate change as well. Over the last decennia, the world has faced a dramatic deforestation. This has reduced the global potential to take CO₂ from the atmosphere (sinks), and increased CO₂ emissions to the extent that the wood from the trees has been burned. Nevertheless, sustainably managed forests and agricultural lands create a natural sink for CO₂.

The importance of land use, land use change, and forestry (in the remainder of the paper abbreviated as LULUCF) in taking up and emitting GHGs is also recognized in international climate policy. The Conference Of the Parties (COP) 7, in Marrakesh, 2001, adopted a decision on the rules of accounting for LULUCF in meeting emission targets of the Parties to the Kyoto Protocol: *“Parties may offset their emissions by increasing the amount of greenhouse gases removed from the atmosphere by so-called carbon “sinks” in the land use,*

*land-use change and forestry (LULUCF) sector (through) **afforestation, reforestation and deforestation** (...) and **forest management, cropland management, grazing land management and revegetation...** “(UNFCCC, 2007)*

Although agriculture and forestry are important sources and important sinks of GHGs, the potential of LULUCF for an efficient reduction of GHG emissions is still poorly understood. Most economy-climate models focus on emissions of CO₂ from the burning of fossil fuels, while LULUCF might contribute significantly to GHG emission reductions at relatively low costs. Indeed, LULUCF can help to provide low- or even negative-cost near-term climate policy strategies, buying time for technological developments (Lal, 2004). It is therefore necessary to include land-use changes as well as non-CO₂ GHGs into climate-economy models to better analyse cost-effective climate policy. Furthermore, a more detailed modeling of land, and recognition of land heterogeneity, can lead to more accurate projections of shifts in crop production after the introduction of some form of climate policy (like subsidizing bio-fuels fuels or the awarding of carbon sequestration activities), and contribute to discussions surrounding the trade-off between biofuel production and food production.

The aim of this paper is to give an overview and assessment of state-of-the-art approaches to integrate issues of LULUCF into climate-economy models, including projects that link economy-climate models to land-use models. We will describe different models, their treatment of land, their potential for an applicability to policy analysis, as well as their shortcomings. We will identify data requirements and conceptual problems in order to outline directions for future research.

We distinguish two categories of models. The first category, discussed in section 2, consists of partial equilibrium models. In general, these are bottom-up models with a detailed representation of agricultural and/or forestry production, possibly including a module describing the biophysical aspects of the geographical region (usually a country or a part of a country) under scrutiny. These models are mostly used to assess the effects of certain agricultural, trade or climate policies on the agricultural or forest sector and on land use and

land cover, through an exogenous change in the prices of agricultural products. However, these models lack a general equilibrium approach where policy affects relative prices of inputs and goods, and hence land-use decisions. The second category of models therefore consists of general equilibrium models, which are discussed in section 3. These are top-down, computable general equilibrium (CGE) models, which are the standard tool to analyse the economic effects of international climate policy at the macro-level. CGE models are able to capture macro-economic and international feedback effects through changes in relative prices of inputs and outputs. However, the level of aggregation of these models goes at the expense of the modeling of details in agricultural production, including the biophysical aspects of land. In section 4 we discuss – based on the experience with the existing models – how an “ideal” LULUCF model should be designed to be able to analyse different relevant policy questions. Section 5 concludes and outlines some directions for future research.

2. Partial equilibrium models

Although partial equilibrium models have a detailed representation of agricultural production and/or forestry in common, they still differ along many dimensions. First we will discuss two models that focus on a relatively small geographic region, but contain a high level of detail as refers to the biophysical aspects of land. In section 2.2 we look at two models that have a focus on the forestry sector: one that focuses on the U.S. market for forestry products and its interactions with agriculture, and one that takes a global perspective. In section 2.3 we discuss two models that neither include detailed biophysical characteristics of land, nor include forestry dynamics, but are still partial equilibrium in nature and do focus on land use changes. The first one looks at agricultural production in Germany, while the second one looks at production in Europe and links production to world markets for agricultural products.

We conclude this section with a discussion on the strengths and weaknesses of each type of model.

2.1. Linking an econometric process model to a crop ecosystem model

A powerful tool to study LULUCF at a very detailed level is to combine an econometric process model with a crop ecosystem model, using field-specific data. Antle et al. (2001) use cross-sectional data from a sample of 425 farms and over 1200 fields to estimate a simulation model for the grain-producing regions of Montana, USA. Kerr et al. (2003) use data for Costa Rica to estimate a land-use simulation model for that country. In both cases, data consist of both ecological data on site characteristics and of socioeconomic data, including crop prices. The economic production model which is then estimated is subsequently used in a simulation model that represents the dynamic decision-making process of the farmer (both models have a time horizon of 20 years).

The econometric process model simulates the farmer's crop choice and input choices, and the related output and production costs at the field scale, by maximizing the expected returns for each sample field. Since the data are site-specific, the simulation can represent spatial and temporal differences in land use and management, such as crop rotations, which leads to different economic outcomes across space and time.

The detailed representation of the production system allows the coupling between the econometric process model and a crop ecosystem model, called Century (Parton et al., 1987), to estimate the impacts of production system choice on soil carbon (Antle et al., 2001) or carbon sequestration through forestry (Kerr et al., 2003). Century is a generalized-biochemical ecosystem model which simulates carbon, nitrogen, and other nutrient dynamics.

The ecological and economic models are coupled through the land manager's choice of land use. This choice depends on (expected) economic returns from a range of land uses. These returns are contingent on both current and expected future ecological and economic

conditions. Given the land-use choices and management practices, Century calculates the levels of soil carbon sequestered and the resulting sequestration costs.

Since both the econometric process model and the ecosystem model are constructed using data at a very disaggregated level, the linked models are capable of simulating carbon sequestration policies for a relatively small geographical area. Antle et al. (2001) simulate a policy for conversion of cropland to permanent grass that gives producers a fixed annual per hectare payment, and a policy that pays producers on a per hectare basis for fields switched to continuous cropping, for the Northern Great Plains of Montana. The model then reports the amounts of land shifted to permanent grass or continuous cropping, and the resulting amounts of GHG sequestered and emitted. Kerr et al. (2003), on the other hand, do not simulate policy scenarios but estimate a baseline for the amount of carbon sequestered through forestry in Costa Rica, with which the results of policy simulations can be compared.

2.2. Models with a focus on forestry

The FASOM model (Forest and Agricultural Sector Optimization Model; Adams et al. 1996) is an intertemporal model for the U.S. agricultural and forestry sectors. It builds on the Agricultural Sector Model (ASM) of McCarl et al. (1993). The endogenous land use and forest management investment decisions allow the user to study the effect of intersectoral market forces on carbon storage and fluxes, and on costs. The model is an optimization model as the objective function maximizes the discounted welfare of producers and consumers in the agriculture and forest sectors. The model has a detailed representation of the log market part of the forest sector, and has 36 primary and 39 secondary agricultural products and has a 100-year time horizon. The dynamic structure of the model and the detailed modeling of the log market facilitate the study of forest and hence carbon sequestration dynamics, while the inclusion of the agricultural sector allows land to move between sectors.

Alig et al. (1997) use the FASOM model to simulate policies aimed at carbon sequestration through forestry. Lee et al. (2005a) extend the model with GHG emissions from, and possible mitigation strategies of, agricultural sectors. They consider the level and potential alteration of nitrous oxides, methane, and carbon dioxide emissions from agricultural crop and livestock, plus forest management and forest establishment activities. In addition they take into account saturation in agricultural soil sequestration and in forest sequestration, as carbon only accumulates until a new equilibrium is reached. They simulate the model for prices between \$0 and \$50 per ton of CO₂-equivalent. Alig et al. (1997) and Lee et al. (2005a) both show that changes in land use and sequestration activities need not be permanent. The former paper shows that large areas of land shifted from agriculture to forestry in early years and were subsequently allocated back to agriculture later, while the latter paper shows that carbon sequestration is the primary mitigation strategy in the early decades but then saturates and even turns into a source after 40-60 years.

Where FASOM is aimed at the U.S. forestry sector, the DIMA model presented in Rokityanskiy et al. (2006) takes a global perspective. It builds on Benítez and Obersteiner (2003) and Benítez et al. (2004) and combines a land-use component with an energy systems model (the optimization model MESSAGE, see Messner and Strubegger, 1995) and a global vegetation model (TsuBiMo, see Alexandrov et al. 2002). The latter estimates forest growth, while MESSAGE provides carbon-bioenergy price trajectories, based on the ICCP SRES scenarios. DIMA is a global, grid-based (0.5 degree latitude by 0.5 degree longitude) model, in which for each grid a risk-neutral agent maximizes expected profits under given biophysical and socioeconomic constraints. The agent chooses, for each 10-year time interval, which of the land-use processes (afforestation, reforestation, deforestation, or conservation and management options) should be applied. The land-use component takes prices, cost of forest production and harvesting, site productivity, population density, and estimates of economic growth as given, and gives as output 100-year forecasts of LUC, carbon sequestration, impacts of carbon incentives (i.e. avoided deforestation), biomass for bioenergy, and climate policy impacts. The modeling of the agricultural sector is not as

detailed as in FASOM. In DIMA, the net present value of profits from agriculture are obtained indirectly, and the agent compares this value with the net present value of afforestation and deforestation. The model is suitable to study the effects of all kinds of climate policies on forestry.

2.3. Agricultural input-output models for Germany and Europe

The Regional Agricultural and Environmental Information System (RAUMIS; Heinrichsmeyer et al. 1996) is a policy information system for the 431 German "Kreise" (regional units). Its main objective is the description and analysis of the relations between agriculture and the environment and medium-term simulations of agricultural and environmental policy options.

The methodological concept of the modelling system RAUMIS is an activity based non-linear programming approach. The most relevant information being processed in RAUMIS are activity specific data on production and yields from the official agricultural statistics, technical input-output coefficients, cost estimates, and data from a network of representative farms (Gömann et al., 2004). The partial equilibrium supply model covers the entire agricultural sector of Germany. The activities are differentiated into 77 crop activities (including set-aside programmes and less intensive production systems) and 16 activities for animal production. From a regional point of view, the model covers 431 model regions at the county-level, covering the whole of Germany. In each region a representative farmer maximises income from agricultural activities. A set of environmental indicators (e.g. nutrient balances, greenhouse gases) is implemented to assess the impact of agricultural production on natural resources. The data base can be divided into the sectoral economic account for the agricultural sector, regionalised statistics (activity levels, yields) and computed data (especially activity based input calculations). To perform comparative static policy analyses, a reference scenario for the year 2010 is constructed against which the results from the policy scenarios are compared.

Where RAUMIS focuses on Germany, the Common Agricultural Policy Regional Impact analysis tool (CAPRI) takes a European perspective. CAPRI is a static, global agricultural sector model focussing on the EU-27 and Norway (for a description, see Britz, 2005). As the name suggests, the model initially focussed on the European Common Agricultural Policy and its interaction with world agricultural markets. For this, the model consists of two modules. The supply module is a set of nonlinear programming models (one for each region), where the coefficients are estimated using farm-level data. It calculates the agricultural supply in the EU-27 and Norway, covering about 250 regions and up to six farm types for each region (in total CAPRI comprises 1000 farm-regional models). In each model, a representative farmer maximizes income subject to restrictions.

The supply module is coupled to a market or international trade model which is a spatial, global, multi-commodity model for 40 agricultural products from 40 countries in 18 trade blocks. Agricultural products from different countries are considered to be imperfect substitutes (Armington assumption). In the overall modelling system, the global trade model is responsible for simulating market clearing prices, so that prices are endogenous. However, during solution of the regional supply models, prices are fixed and given, and the farmers react as price takers. An iterative link between the supply and market models ensures convergence between the prices used in the supply models and the ones generated by the market models.¹

Regarding environmental variables, the model also provides nutrient balances and greenhouse gas emissions, with global warming potential based on the production system. Typically, CAPRI is used to simulate and compare ex-ante, for a medium term horizon, impacts of different set of agricultural policies.

2.4 Partial equilibrium models and their implications for policy analysis

The models discussed in this section differ in their focus, their regional covering, and level of detail. In section 2.1 we saw two models with a high degree of disaggregation, the disadvantage of which are the data requirements: the demand for data grows beyond control when the model is expanded to a larger region. On the other hand, the detailed modeling of the biophysical characteristics makes the modeling of local land-use changes very realistic. These models are therefore well-suited to study the short-term and local effects of climate policies on land use. The same holds for the FASOM model discussed in section 2.2. It is well-suited to study specific U.S. policies aimed at the forestry and agricultural sectors, but the exclusion of links to international markets for forestry and agricultural products, and the absence of markets for other goods (and hence substitution possibilities at a more aggregate level) makes FASOM less suited to study the long-run effects of a more general, national policy or a global climate policy.

Although RAUMIS is, like the models in Antle et al. (2001) and Kerr et al. (2003), a regional model (focusing on Germany in the case of RAUMIS), it does not have the detailed modeling of the biophysical aspects of land. However, it does contain a broad portfolio of choices for the land-owners as it has data on the production of many crops and livestock products.

The DIMA and CAPRI models are somehow 'less partial' than the other models discussed in this section. The DIMA model has a less detailed modeling of the agricultural sector than FASOM has, but covers the global forestry sector. Its capability of being linked to the global energy systems model MESSAGE allows it to take the effects of global climate policy on other sources of GHG emissions (indirectly) into account. CAPRI on the other hand contains optimization models for agricultural products in regions within Europe, that are linked to a global market for agricultural products. A global perspective and linkages to other sources of GHG emissions and uptakes are very important aspects if one wants to study global, long-run questions.

¹ The model developed by De Cara et al. (2005) takes a position between RAUMIS and CAPRI. It is a linear programming model, covering 101 regions in the EU-15, 24 crop-activities and 27 animal activities. Contrary to

In sum, the partial-equilibrium bottom-up models are used to assess the effects of certain agricultural, trade or climate policies on the agricultural or forest sector, and on land use and land cover. The main strength of the partial equilibrium models lies in their capability to operate on a very disaggregated scale. They are thus able to include detailed biophysical land use characteristics, to simulate very detailed policy proposals (for example concerning differentiated agricultural policies) and to capture local or at least regional environmental and economic effects. The bottom-up models lack a general equilibrium approach where policy affects relative prices and hence land-use decisions. They are thus not able to capture relevant macro-economic and international feedbacks and are thus suitable only for a partial equilibrium analysis of the effects of climate policy on the agricultural and forestry sector, or to assess the potential of emission reductions from LULUFC. In particular, these models are not able to show the role of LULUFC in an optimal national and international policy mix, or the feedbacks of economy-wide climate policy measures resulting from LULUFC, and can thus only play a limited role in the assessment of national and international climate policy options.

The general conclusion from this section is therefore that partial equilibrium models are a good tool to study local or short-run policy questions. In these cases, there is no need to look at international effects or general equilibrium effects. The higher level of detail that comes along with a lower level of regional aggregation then comes as an advantage. However, if the problem under scrutiny has a long-run or international dimension, one might want to take into account general equilibrium effects. Models that focus on these effects will be studied in the next section.

CAPRI, it is not linked to an international trade model.

3 General equilibrium models

In the past 10 years, different attempts have been made to extend top-down computable general equilibrium models to include questions regarding LULUFC. There are two broad approaches. The first approach is to improve the treatment of land within the CGE framework. A first step in this respect is to better model the transition of land between different uses – in particular crop production, livestock and forestry. In section 3.1 we present a few papers that take this direction. An additional step is to differentiate between different land classes, such that they have different characteristics and productivities and are only suitable for some uses. Two models that take this approach, which requires a high level of detail and hence has a considerable demand for data, are the FARM (Wong and Alavalapati, 2003) and GTAP-AEZ (Lee, 2004, and Hertel et al., 2006) models. These models are discussed in section 3.2. The second approach to extend CGE models to be better capable to answer questions related to LULUCF is to couple or link an economic model with a detailed sectoral model of land use. An example of this is the KLUM@GTAP project (Ronneberger et al., 2006), which is discussed in section 3.3. We draw some conclusions on the top-down models in section 3.4.

3.1 'Simple' extensions

A first rather ad-hoc approach to include at least a better representation of shifts of land between different purposes in a CGE model, is the GTAPE-L model. Burniaux and Lee (2003) extend the standard static GTAP model to track inter-sectoral land transitions and to estimate sectoral net emissions of methane, CO₂ and N₂O, due to land-use changes.² On the supply side of the land market, land owners rent out land (which is a homogenous input) to

uses that give the highest return, under a land transformation restriction: a Constant Elasticity of Transformation Function (CET) determines the degree of land mobility between different crops, livestock and forestry. Perfect competition on input and output markets assures that all markets, including the land market, clear.

The value added of the paper is that it tracks GHG emissions from changes in land use. To obtain land transition emission rates, a land transition matrix is derived for 1995 from the IMAGE 2.2. model (IMAGE team 2001), and so are the 1995 net carbon emissions (tons of carbon equivalents). After applying a policy shock to the model, a new land transition matrix occurs. When multiplying the land transition emission rates with the land use changes that occur after the policy shock, one can calculate the corresponding change in GHG emissions due to changes in land use.

A second extension of an existing CGE model, to better model changes in land use, is by Abdula (2005) and Ignaciuk (2006, chapter 5). The main modeling improvement in these papers is that land is explicitly treated as a heterogeneous input as particular land types are treated to be not suitable for certain crops. Abdula (2005) uses a static CGE model for the Philippines and extends it with a bio-fuels sector, to study the conflict between food production and bio-fuel production. Since both activities use scarce land, subsidizing bio-fuels may induce farmers to move away from food production towards the production of inputs for the bio-fuel industry. Land is treated as a heterogeneous input as Abdula distinguishes three land types (cropland, pasture and forest, all in fixed supply), some of which are only suitable for particular uses. That is, some land types are not suitable for producing certain agricultural products. Ignaciuk (2006, chapter 5) introduces land that has been 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 biofuels production, hence it is excluded from food production. Consequently both papers

² The standard GTAP model is a multi-region, multi-sector, computable general equilibrium model, with perfect competition and constant returns to scale. Bilateral trade is handled via the Armington assumption. For details see Hertel (1997).

treat land as a heterogenous input, which brings the models a step closer to reality compared to those models that treat land as a homogenous input.

3.2 Modeling agro-ecological zones (AEZs)

Section 3.1 described two first approaches in integrating land use changes directly into a CGE model. We saw that Abdula (2005) and Ignaciuk (2006, chapter 5) introduced heterogenous land by restricting the possible uses of some land types. The GTAP AEZ project (see e.g. Lee et al. 2005b) takes an important step further in this direction through the development of an integrated land-use data base including data on land use and land cover, forest carbon stock, and CO₂- and non-CO₂ emissions that can be used together with the GTAP data-base.³

Based on the widely recognized SAGE land-use data (Ramankutty et al. 2005), and (unpublished) additional data from the FAO, land quality is differentiated into 18 agro-ecological zones (AEZs; 6 length of growing periods combined with 3 climate zones; FAO 2000), and geographically divided into 0.5 degree (latitude by longitude) grid cells. Lands located in a particular AEZ have similar (though heterogeneous) soil, landform and climatic characteristics. As a consequence land is treated as a heterogenous input.

Concerning forestry, two types of timberland data are obtained from the Dynamic Global Timber market Model (Sohngen and Tennity, 2004): forestland inventories for different timber types in 9 regions of the world, and economic parameters associated with each of these timber types. The latter include fundamental economic values associated with forestry activity and carbon sequestration for the particular timber types, e.g. land rents, management costs, timber prices, forest area and area change, yields, production, growth parameters, and carbon accounting values. The information drawn from this work include the following items, disaggregated across 124 countries/regions: (1) basic economic and biophysical data on

³ The GTAP database is a global data base describing bilateral trade patterns, production, consumption and intermediate use of commodities and services. The current disaggregation includes 87 regions and 57 sectors.

timber types within the region; (2) inventory data on the hectares of land in each timber type class, 10-year age class (if available), and AEZ; (3) information on carbon in each timber type, age class, and AEZ. To facilitate modeling of different global timber markets, each timber type in each country was mapped into one of three timber species categories – coniferous, broadleaf, or mixed. Finally, the data base provides CO₂ as well as methane (CH₄) and nitrous dioxide (NO_x) emissions disaggregated by GTAP regions and sectors.

Lee (2004) and Hertel et al. (2006) use the data base to develop the GTAP-AEZ model that integrates land-use and land-based emissions into the CGE framework.⁴ GTAP-AEZ is again based on the static GTAP model, and has so far only been used for illustrative purposes using three world regions only (USA, China and the rest of the world). It is assumed that land located in a specific AEZ can be moved only between sectors if it is appropriate for their use (see our discussion of Abdula (2005) above). Thus, land is mobile between crop, livestock and forestry sectors within, but not across AEZs.

In a first version of GTAP-AEZ (Lee, 2004) it is assumed that each of the land-using sectors in a specific AEZ has its unique production function. For example, the paddy rice sector located in AEZ 1 has a different production function from the paddy rice sector located in AEZ 6, which allows to identify differences in the productivity of land of different climatic characteristics. All six paddy rice sectors in the different AEZs though produce the same homogenous output. For this approach it is necessary to have information on cost shares, respectively input shares, in the different AEZs, which are not yet provided in the GTAP-AEZ data-base.

In an extended version of GTAP-AEZ (Hertel et al., 2006) it is assumed instead, that there is a single, national production function for each (agricultural) commodity: instead of having for some crop a different production function for each AEZ, the different AEZs are now inputs to the national production function for this crop. With a sufficiently high elasticity of substitution

⁴ Although the GTAP-AEZ database is more or less finished, the model is still under development (Lee, 2007). As a consequence the model documentation is rather thin, so that is not always clear how the authors model several aspects of the model, while the results of the papers cited should be treated with care.

(20), it is assured that the return on land across AEZs, but within a given use, will move closely together. Land supply within an AEZ is constrained via the Constant Elasticity of Transformation (CET) frontier. Although the authors estimate the elasticities of transformation amongst crops, they have to make (reasonable) assumptions about the elasticities of land transformation between crops and livestock and between forestry and agriculture.

Concerning policy analysis, the GTAP-AEZ model has been used to simulate the effects of different taxes on GHG emissions to derive abatement supply schedules under different assumptions. In addition it is possible to compare single-gas and multi-gas strategies, and strategies with and without forest sequestration. The focus is on land allocation decisions and general equilibrium effects. Generally, the model facilitates the study of the role of non-CO₂ GHG reductions and LULUCF in national and international climate policy and assess the implications of different climate policy strategies on land-use decisions.

The GTAP AEZ model and corresponding database are not the only attempt to have a detailed representation of land use in a CGE model. 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., 1996). It is composed of a geographic information system (GIS) and an aggregation and extension of the GTAP CGE model. In different versions, the model is aggregated to eight (Darwin et al., 1996) or 12 (Ianchovischina et al., 2001; Wong et al., 2003) world regions. The GIS links climate variables with land and water resources in FARM's environmental framework, based on information from several global databases relating to the associated area's climate, natural vegetation, and current land-use. In each region, land is divided into six classes, based mainly on the length of the growing season (as with the AEZs of the GTAP AEZ project). As in GTAP-AEZ, land classes differ in productivity. Land from each class is supplied to all sectors separately. Land supplies for each class of land are derived from a CET function which allows land to shift between economic sectors in response to changing conditions

while simultaneously simulating productivity differences within land classes. A distinguishing feature of FARM is that the GIS provides data on regional water supply. The GTAP model is extended to include land as a primary input in all producing sectors, and water as a primary input in the crops, livestock and service sectors.

While FARM was originally a static model, there is now also a dynamic version denoted D-FARM. It enriches the original model with asset ownership and investment theory to create a recursive dynamic model based on estimates of annual growth rates of regional GDP, gross domestic investment, population, skilled and unskilled labor. D-FARM has a time horizon that goes until the year 2007 (Ianchovichina et al., 2001) or even 2020 (Wong et al., 2003).

In summary, FARM's treatment of land embodies both ecological (length of the growing season) and economic (CET function) concepts regarding land productivity. The model is designed to track changes in land use and cover not only with the production of goods and services but also with the ecological resources of a region.

3.3 Coupling a CGE model with a land use model

KLUM@GTAP (Ronneberger et al., 2006) is a coupling experiment in which the static global CGE model GTAP is linked to the land use model KLUM (Ronneberger et al., 2005). That is, instead of modeling the economics of land use as an integrated part of the top-down model, as was done by the models in the previous sections, a detailed bottom-up land allocation model is linked to a standard top-down CGE model. KLUM is a land allocation 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 bio-physical aspects of land are included indirectly, as area specific yields differ for each unit of land.

In the coupling experiment, yield changes due to climate change in 2050 (as reported by Tan and Shibasaki, 2003) are applied to KLUM, which gives changes in land uses. These in turn are fed into GTAP (which has been scaled up to represent the economy in 2050) to obtain

management induced yield and price changes (through changes in input combinations), which in turn are fed back into KLUM.

Although the experiment shows that the results of the coupled and uncoupled simulations can differ by several hundred percent, it also shows that linking models comes with serious difficulties. In this case, one problem was that GTAP has its land data in value terms with its price normalized to unity, while KLUM has quantities. This makes land quantity data incomparable between the models. To solve this, a key parameter in GTAP (the elasticity of substitution between land and capital and labour) 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, and hence coupling of the two models would not give meaningful results.

3.4 General equilibrium models and their implications for policy analysis

In the introduction of this paper, we noted the importance of taking into account land use, land-use changes, and forestry, when studying questions related to climate change and climate policy. In this section we have seen how top-down models have been further developed to better take into account these features. Introducing heterogeneity in available land, as was done in sections 3.1 and 3.2, increases the credibility of the CGE models regarding changes in agricultural production. A second approach is to link them to a land use model, although we saw in section 3.3 that this can come at a cost, due to technical problems with establishing the link. In addition, we saw that several of these models have a multi-GHG approach, allow for carbon sinks through afforestation, and/or include biofuels.

The introduction of heterogeneity in available land allows the study of the effects of climate change and climate policy on land use decisions, and the role of LULUCF in an optimal climate policy mix. Of course, the more elaborate the model, the better it is suited to study these questions. The inclusion of non-CO₂ GHGs and of a bio-fuels sector not only allows the

models to study a wider array of questions, it gives more flexibility to the models (or more precisely: to the agents in the models) as well. A multi-gas model gives agents the possibility to reduce the emissions of the GHG such that the emission target can be reached at the lowest cost. The extension of a model with a biofuels sector not only facilitates the study of questions related to biofuel subsidies, it also allows the substitution of non-fossil fuels for fossil fuels in energy generation.

Clearly, none of the models described in this section currently includes all relevant aspects mentioned above, although the GTAP-AEZ and FARM models do contain many. 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-AEZ is its multi-gas approach, while the advantages of FARM are the inclusion of water, the fact that it is a dynamic model, and a more detailed regional disaggregation.⁵ However, both models (thus far) only have a single forest type, while the issue of carbon sequestration through forestry is best studied with a dynamic model, using data on several forest types, with each forest type divided into several age classes. In addition, neither GTAP-AEZ nor FARM contains a biofuels sector. Here, both models face some scope for improvement. Finally, both models currently only have a limited regional disaggregation. GTAP-AEZ currently only has three regions, while FARM contains not more than 12 regions

4 Designing the ideal LULUCF model

In the previous two sections we saw that models on LULUCF and climate policy have several characteristics, some of which are particular to the type of model (partial equilibrium vs. general equilibrium), and some of which can be found in both types of models. In the next

⁵ As noted before, the development of the GTAP-AEZ model is still work in progress, and this model will be extended to cover more countries.

subsection we discuss these characteristics, as an introduction to our discussion of the 'ideal' LULUCF model in section 4.2.

4.1 Model characteristics

A first characteristic that can be found in some partial equilibrium models and in some general equilibrium models is a multi-gas approach. However, the purpose of this characteristic seems to differ over the model types. In the first group of models, non-CO₂ GHGs seem to be more of an interesting by-product of a policy simulation. It allows the modeler to study the effect of some climate policy on, say, methane uptake and release. In the general equilibrium models, however, including non-CO₂ GHGs serves as an additional degree of freedom for a constrained economy to cope with climate policy in a cost-effective way. Incorporating methane in a CGE model, for example, allows the economy to reduce methane emissions instead of CO₂ emissions if the marginal abatement costs for the former are lower than the marginal abatement costs for CO₂.

A second characteristic that can be found in both some of the partial equilibrium models and some of the general equilibrium models is dynamics. Given that carbon sequestration (either through forestry or through soil sequestration) is a dynamic process, this is an important characteristic if one is interested in amounts of carbon stored and emitted. Hence it is an important advantage of the combined econometric process/crop ecosystem models, the forestry models, and the FARM general equilibrium model. However, if one is more interested in the regional short-run effects of some policy on sectoral (agricultural) production, and hence on shifts in land use, a static input-output based model like RAUMIS or CAPRI might be sufficient.

Thirdly, both the partial equilibrium model DIMA and the CGE models of Ignaciuk (2006) and Abdula (2005) contain biofuel or biomass production. This characteristic is not typical for one of the two modeling approaches, and mainly hinges on the question in which the researcher

is interested and on data availability. Again, in the partial equilibrium model DIMA biomass production seems to be more of a result of the model, while in the CGE models it gives the economy an additional degree of freedom to cope with climate policy: with biomass or biofuel production, an economy facing a ceiling on the level of emissions of CO₂ can decide to produce less energy, or to keep the level of energy production constant after the policy shock while substituting from fossil fuels to biofuels.

Clearly, some model characteristics are typical for one of the two modeling approaches. The combined econometric process/crop ecosystem models can provide a much higher level of detail in the modeling of land characteristics than the CGE models. This higher level of detail allows the partial equilibrium models to study soil carbon sequestration. Since CGE models usually cover a much larger geographical region, the data requirements (and computing power) prohibit a too detailed modeling of the biophysical features of land. At the same time the general equilibrium feature of the CGE models allow this group of models to study sectoral and regional interactions through changes in relative prices, and to study the role of LULUCF in an optimal national or international policy mix. The sectoral and macroeconomic feedbacks that are necessary to study these questions are lacking in partial equilibrium models.

Another feature that differs over the two modeling classes is the time horizon employed. Although both some of the partial equilibrium models and some of the general equilibrium models are dynamic in nature, only the latter group is capable of coping with questions regarding the long-run. The longer the period under scrutiny, the larger the number of parameters that actually become variables. For example, for a short-run question one might want to abstract from the effects of foreign trade, while these are indispensable for problems of a long-run nature, even for domestic policies, because of terms of trade effects.

4.2 The 'ideal' LUCF model

On first sight the 'ideal LUCF' model includes all possible information on all scales, and combines and extends what is already in the models described in this paper. In practice though, such a model is impossible to build and to handle. The discussion so far clearly shows that the best model to answer a certain question depends on the exact scope of the problem.

Important determinants for the model to use are geographical scope, time horizon, and scope of the policy. Partial equilibrium models can provide a high degree of detail for a certain geographic area and can hence provide good insights in the short-run effects of a local policy on local behavior. However, when the time horizon is longer than a few years, or when the policy comprises a nation-wide or multi-sectoral policy, the use of a general equilibrium model becomes indispensable. In these cases, intersectoral and international feedbacks, which are best studied using a CGE model, will play an important role. Nonetheless a CGE model is an insufficient tool to study, say, a forest sequestration policy in a certain (relatively) small geographical area, as it lacks the degree of detail that is necessary to study such a specifically targeted policy. As noted above, the data and computational requirements to study such a policy using a CGE model are prohibitive to extend these models to the same degree of detail as, say, a combined econometric process/crop ecosystem model. However, CGE models are the preferred tool to study cost-effective climate policy. Indeed, forestry and land use are not the only tools to mitigate GHG emissions, and only a CGE model is capable to show the optimal reductions in, say, emissions of CO₂ from energy generation and emissions from the agricultural sector through changes in land use.

5 Concluding remarks

This paper has given an overview of existing approaches to include issues of land use, land-use change and forestry (LULUCF) into climate-economy models. We saw that the literature broadly contains two important classes of models – partial equilibrium models and general equilibrium models – that each have their advantages and disadvantages. While the first group of models has an advantage in the level of detail (and hence in modeling the effects of regional, short-run policies), the second group is able to capture inter-sectoral and international feedback effects. Which of these advantages is more important, and hence which model type is the appropriate tool, depends on the policy question at hand.

The paper showed that, over time, there has been considerable progress in both classes of models. Satellite technology allows for GIS-based models, which has improved both the partial equilibrium and the general equilibrium models by allowing for a more detailed modeling of land quality. In addition, more models start to include non-CO₂ greenhouse gases. Nevertheless, there is still scope for improvement. As noted before, the GTAP-AEZ model is still work in progress: for example, the model has to be adjusted to have the same level of regional and sectoral disaggregation (for example the forestry sector) as the standard GTAP model. For a full use of the available forestry data, however, it would be best if a dynamic version of GTAP-AEZ would come available. In that case it would be possible to follow the age structure of trees in different regions, which facilitates a better modeling of carbon sequestration through forestry. For FARM, on the other hand, a more detailed regional disaggregation and including non-CO₂ greenhouse gases would be beneficial for a better modeling of LULUCF.

A second line of future research and model extensions would be to couple models of different scale and focus. Recently, Tavoni et al. (2007) have coupled a global timber market model to a global dynamic CGE model that includes GHG abatement through energy-related policy options. In section 3.3 we described a first attempt to do so, the KLUM@GTAP project (Ronneberger et al., 2006). Even though the latter project showed the technical problems of

coupling models of different scale and focus, we believe that this approach is a promising one. Using the output (land allocations) of a highly detailed, though partial equilibrium, model as input in (part of a) CGE model, or using the output of a CGE model (prices of goods and factors) as input in a partial equilibrium model, the modeling of the impact of climate change or climate policy on a particular region might be improved.

A final development that can be seen in both the partial equilibrium models and the general equilibrium models is multidisciplinary cooperation. In some of the partial equilibrium models we see that a crop ecosystem model describing biophysical processes is linked to an econometric process model, describing (profit maximizing) behaviour of farmers. The general equilibrium models include more biophysical realism through the modeling of agro-ecological zones. Further work in this direction, together with increasing technological and computational possibilities, can push the two classes of models closer to each other, at the benefit of the modeling results.

It should be noted, however, that with every extension of a model, the demand for data (and computing power) increases. For all models and approaches described in this paper, the data collection process was at least as important as the construction and development of the model. Still, in every model some heroic assumptions had to be made for those model parts where appropriate data are unavailable. In this sense, linking existing models of different scopes or scales comes with an advantage, as this might give value added and additional insights compared to the individual models, without demanding additional data.

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