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Modeling linkages between climate policy and land use: An Overview*

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Abstract: 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 include land use, land-use change, and forestry (LULUCF) explicitly in economy-climate models. This paper gives an overview and assessment of existing approaches to include land use, land-use change, and forestry into partial and general equilibrium economy-climate models. For each class of models, we describe different examples, their treatment of land, and their potential for and applicability to policy analysis, as well as their shortcomings. We identify data requirements and conceptual problems, and provide suggestions for future research.

Keywords: climate change, climate policy, modeling, land use, forestry

JEL codes: Q15, Q24, Q54

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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 (CO_2) 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 (CH_4) and nitrous oxides (N_2O): in the year 2000, agricultural byproducts accounted for 40% of methane emissions and 62% of N_2O 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 CO_2 and non-CO_2 GHG emissions. At the same time the use of biomass for producing electricity, heat or biofuels might, under certain conditions, result in reduced CO_2 emissions if the bioenergy replaces fossil energy.

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 CO_2 from the atmosphere, and increased CO_2 emissions to the extent that the wood has been burned. Nevertheless, sustainably managed forests and agricultural lands create a natural sink for CO_2.

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. As including non-CO_2 and CO_2 land-use and forestry mitigation options provides greater flexibility and cost-effectiveness, compared to “fossil-fuel only” strategies, it was decided in 2001 that the parties to the Kyoto Protocol may (partly) offset their emissions by increasing the amount of greenhouse gases removed from the atmosphere by so-called carbon “sinks” through afforestation, reforestation, forest management, cropland management, grazing land management and revegetation.

As agriculture and forestry are important sources and important sinks of GHGs, it is necessary to include land-use changes as well as non-CO_2 GHGs into economy-climate models to better analyze 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 rewarding 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 economy-climate models, including projects that link economy-climate models to land-use models.[1] We will describe different modeling approaches, their treatment of land, their potential for 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.

Following Van Tongeren et al. (2001), we distinguish two categories of models: partial equilibrium models and general equilibrium models. The partial equilibrium models, discussed in section 2, are 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 local climate policies on the agricultural or forest sector and on land use and land cover. However, these models generally lack links to non-agricultural sectors and other regions or countries than the one(s) under scrutiny. These links become more important as the geographic and time scale of the policy becomes larger.

The second category of models, discussed in section 3, consists of general equilibrium models. These are, generally, top-down, computable general equilibrium (CGE) models, which are the standard tool to analyze 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 multi-sector multi-country models goes at the expense of the modeling of details in agricultural production, including the biophysical aspects of land. In section 4, we discuss the (dis)advantages of the modeling approaches to study particular types of climate policy. 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 agricultural input-output simulation models. In section 2.2, we look at econometric simulation models, which are models based upon past observed behavior of landowners. Section 2.3

[1] Note that our aim is not to provide a comprehensive overview of models and papers, rather we want to give an

discusses models that treat forestry in a dynamic way. We conclude this section with a discussion on the strengths and weaknesses of each type of model.

2.1 Agricultural input-output models

In agricultural input-output models, production technologies are described through Leontief production possibilities, each of which specifies fixed quantities of inputs and outputs. Examples are the ASMGHG model (Schneider, 2000, McCarl and Schneider, 2001, Schneider and McCarl, 2006) and the model of De Cara et al. (2005) that both use mixed integer programming models to study the supply of agricultural products. In the former model, the competitive market equilibrium is computed by maximizing the sum of consumers' surplus in all output markets plus the sum of producers' surplus in all input markets. In the model of De Cara et al. (2005), each 'farm type' maximizes its annual profits. For these purposes, it has to be decided how much of each crop, dairy, or animal type or product has to be produced, and how much of each input type has to be used. Choices are for example over amounts of land, soil types, fertilization alternatives, and feeding strategies. In ASMGHG, choices are made between different sets of fixed input-output coefficients, instead of optimizing the level of each production input individually.

Both models have been used to estimate carbon supply curves for GHG emission reductions. First, a baseline model is simulated, with a zero tax in GHG emissions. Next, a tax on emissions, where different GHGs are translated into CO_2-equivalents, is introduced and increased in steps of, say, \$5, and the resulting emission reduction stemming from agricultural and forestry activities is calculated.

Input-output models might use auxiliary models to provide some of the model's inputs, or calculate part of the outputs (for example, ASMGHG uses FASOM (discussed below) to provide estimates of tree carbon sequestration). They are mostly static, although the model of De Cara et al. (2005) includes a cattle demography module.

An advantage of input-output models is the high level of detail in technologies (input-output combinations) and/or regions. For example, ASMGHG depicts production in 63 US agricultural sub-regions, with more than 30 commodities, and multiple tillage intensities and feeding and nitrogen fertilization alternatives. The partial equilibrium characteristics of this

overview of approaches to the modeling of climate policy and land use.

type of models show in the lack of detail in the modeling of the demand side (if at all), and the absence of non-agricultural markets.

2.2 The revealed-preference approach

2.2.1 Econometric simulation models

A second class of partial equilibrium models uses a method by which the costs of carbon sequestration can be estimated based on evidence from landowners' observed behavior when confronted with the opportunity costs of alternative land uses: the models are therefore based upon revealed preferences of landowners. Examples are Stavins (1999), Plantinga et al. (1999) and Lubowski et al. (2006).

Lubowski et al. (2006) estimate a model of land use decisions using detailed panel data for US counties and parcels. In their model, a risk-neutral landowner seeks to maximize the present discounted value of the stream of expected future returns. They estimate probabilities of transitions among land uses as functions of the anticipated economic returns to alternative uses, taking into account the quality of the parcel. Then the authors use the estimated model to simulate a subsidy on land conversion towards forestry, and a tax on conversion away from forestry, for a range of tax/subsidy values as a means to generate a forest acreage supply function. The prices of major commodities are endogenized during the simulations using (own-) price elasticities from econometric studies via an iteration process. A carbon sink model then accounts for changes in carbon stocks in the relevant biomass, soil, and product categories for each of the land uses.

The advantage of the revealed-preference approach is that simulations build directly upon patterns of how landowners have actually responded to economic incentives in the past: the probabilities in Lubowski et al. (2006) are estimated using data on parcel-level land-use data and county-level average returns only. No further behavioral assumptions need to be made. In this way, these models (partly) take into account that non-pecuniary as well as non-observable costs and returns play a role in the decision-making process. Furthermore, it explicitly takes into account land quality at a very detailed geographic level. A drawback of this approach is that it is assumed that estimated parameters remain valid with variable values for the carbon price in the counterfactual simulations.

2.2.2 *Linked econometric simulation models*

The econometric simulation models just described subsequently induced a new literature where a land-use simulation model is linked to a crop ecosystem model. This powerful integrated assessment approach to study LULUCF at a very detailed level is described in Antle and Capalbo (2001) and in Pfaff et al. (2000). It has been applied in Antle et al. (2001) and Antle et al. (2003) for the Great Plains region in the US, and in Kerr et al. (2003) for Costa Rica. In both models, 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 decision-making process of the farmer. Although both models have a time horizon of 20 years, the agents are not forward-looking, and hence not intertemporally optimizing. Rather, a sequence of static decisions – using previous years' results as inputs in the decision-making process – is simulated. 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 simulation model and a crop ecosystem model, and both modeling groups mentioned above use the Century ecosystem model (Parton et al., 1987) for this. Century is a generalized-biochemical ecosystem model that simulates carbon, nitrogen, and other nutrient dynamics. For each period, the ecological and economic models are coupled through the land manager's choice of land use. This choice depends on economic returns from a range of land uses, given ecological conditions, and the interaction between land-use choices and 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 simulation model and the ecosystem model are constructed using data at a highly disaggregated level, the linked models are capable of simulating carbon sequestration policies for a relatively small geographical area, with a high level of detail and hence realism.

The coupled models allow for the simulation of several types of climate policy ranging from very general policies like a GHG emissions tax to very locally applied policies. For example, Antle et al. (2001) simulate two land use policies 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 in and emitted by agricultural soil. Kerr et al. (2003) estimate a baseline for the amount of carbon sequestered through forestry in Costa Rica, with which the results of policy simulations can be compared, and then estimate a carbon sequestration supply function by simulating the model for a range of carbon prices.

2.3 Dynamic models

2.3.1 A forward market for forest products

Before we move to dynamic optimization models in the next subsections, we briefly discuss a model that is interesting because of its way of coping with dynamics. The Agriculture and Land Use (AgLU) model (Sands and Leimbach, 2003) was developed to simulate global land-use change and the resulting carbon emissions in response to a carbon policy. Landowners select the land use with the greatest economic return. The model is static outside forestry. As described in Sands and Kim (2009) the modelers found that in order to include forestry in a land-use model, it was necessary to take into account the intertemporal nature of forest decisions. The problem was solved by including a forward market for forest products. Discounted profits of forestry are then equalized, but agents are not intertemporally optimizing. AgLU models a fixed 45-year (3 model steps) time lag between planting and harvest of forests. In this way of modeling, AgLU stands in between the static models described in section 2.1 and the dynamic optimization models of the next subsection.[2]

2.3.2 Stand-alone optimization models

Dynamic optimization models are forward-looking intertemporal optimization models. This type of model is used in particular to model the forestry sector, where due to long rotation times static models are less meaningful. Two well-known models in this class are the FASOM model (Forest and Agricultural Sector Optimization Model; Adams et al. 1996) and the dynamic global timber model developed in Sohngen et al. (1999). Contrary to the dynamic econometric models mentioned in section 2.2, models of the current class of simulation models are not estimated using data at a very detailed level, but rather based upon data for a particular year for a broader range of activities and a broader geographic scope. Indeed, FASOM is partly based upon the ASM model described in section 2.1 and covers US forestry

[2] It should be noted that a second distinguishing feature of AgLU is the modeling of agricultural yields using a joint probability distribution of yield over each alternative land use within a region.

and agriculture, whereas Sohngen et al. (1999) develop a global timber market model. The optimization models are then solved for intertemporally optimal activity choices using the maximum principle. Both FASOM and the model of Sohngen et al. are forward-looking and maximize the net present value of the sum of consumers' and producers' surpluses.

FASOM has a 100-year time horizon and solves in 10-year steps. In each period, owners of agricultural land can decide (a) whether to keep each acre of land in agricultural production or plant trees; (b) what crop-commodity mix to plant and harvest, if the land stays in agricultural land use; and (c) what type of timber management to select, if the land is to be planted in trees. Correspondingly, owners of timberland can decide in each period (a) whether to harvest a stand or keep it for another decade; (b) whether to replant a harvested stand in trees or convert to agricultural crops; (c) what type of timber management to select if the land is planted in trees; and (d) what crop-commodity mix to plant and harvest, if the land is converted to agricultural use.

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. 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.[3]

Alig et al. (1997) use the FASOM model to simulate policies aimed at carbon sequestration through forestry. Lee et al. (2005) extend FASOM 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 has been reached. They simulate the model for prices between \$0 and \$50 per ton of CO_2–equivalent.

The dynamic timber model in Sohngen et al. (1999) has been developed to study the economic incentives in global industrial timber markets. A social planner maximizes global discounted consumer surplus, net of production costs. Ecological characteristics vary by region, and costs of harvesting and transportation vary by timber type and region. Investment decisions and management intensities are endogenous in all regions. The global scope of the model goes at the expense of multi-sectoral interactions: the model only describes global

[3] Recently a European counterpart, EUFASOM, has been developed (Schneider et al., 2008), which includes novelties like a biomass crop plantations for bioenergy and wetland ecosystem reserves.

timber markets and the development of regional forests, which are built up of several tree types. Hence, the opportunity costs of land, stemming from alternative land uses, are not taken into account.

2.3.3 Linked dynamic optimization models

As with the econometric models, there can be gains from coupling the original model with models of other disciplines or narrower/broader scope, when studying linkages between climate policy and land use. The dynamic global timber model of Sohngen et al. has been used to scrutinize the effects of climate policies on forest sequestration. Sohngen and Mendelsohn (2003), Van ‘t Veld and Plantinga (2005), and Tavoni et al. (2007) all linked the model to an integrated assessment model (IAM) of macro-economic activity and global warming, where we ordered the papers by increasing complexity of the IAM (DICE, RICE01, and WITCH, respectively). Through a soft link between the forestry optimization model and the IAM, the interactions between GHG emissions abatement related to energy production and abatement via carbon sequestration in forests can be studied.

A second example of links between models with different scopes, with as the core a model for intertemporal optimal use of agricultural and forestlands, is the Dynamic Integrated Model of Forestry and Alternative Land Use (DIMA) model presented in Rokityanskiy et al. (2007). It builds on Benítez et al. (2004) and on Benítez and Obersteiner (2006), and like the model of Sohngen et al. (1999), it takes a global perspective. 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 land use, 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 is obtained indirectly, and the agent compares this value with the net present value of afforestation and deforestation. Rokityanskiy et al. (2007) link DIMA 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 IPCC SRES scenarios.

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 their level of economic and biophysical detail. Their suitability to answer particular questions depends especially on the regional and temporal scope of the policy considered.

Linked econometric simulation models can study local polices in depth and can provide many details regarding ecological variables and interactions. Indeed, the strength of the linked econometric simulation models is that they allow for interaction between biophysical processes and economic decisions. Furthermore they have an advantage over the other models in this section and the models of section 3 in that by estimating past observed behavior they (partly) capture variables that are not directly observed and that are hard to model in the behavioral models of the other subsections. However, as they are based upon observed behavior, they cannot include activities and technologies that are not yet economically feasible, but might be so after the introduction of a particular policy. Furthermore, it would be interesting to make them forward-looking.

When climate policies directly or indirectly affect the forestry sector, a dynamic and forward-looking model that includes detailed modeling of agricultural non-forestry sectors becomes indispensible (which is an advantage of FASOM over the static input-output models). As noted above, to study the carbon uptake of forests a model covering several decades, like the dynamic optimization models of section 2.3, is needed. However, as these models have a broader regional scope, they lack the geographic detail of the econometric process models and hence the site-specific biophysical details, although (EU)FASOM and DIMA do use vegetation models to simulate some of the biophysical processes and how these in turn affect yields and economic choices.

As FASOM and EUFASOM focus on a particular region of the world (while still allowing for basic trade linkages), they can model the agricultural sector with quite some detail as well. DIMA and the model of Sohngen et al. (1999) on the other hand are global timber models with only rudimentary linkages to other agricultural sectors.

In sum, the partial-equilibrium models are used to assess the effects of certain climate policies on the agricultural or forest sector, and on land use and land cover. The main strength of the linked econometric process 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 strength of the forest models is that they are forward-looking: agents make an intertemporal trade-off, which is crucial given that a single forest rotation make take several decades. In general, for all model classes described in this paper, there is a trade off between geographic scope on the one hand, and economic, geographic and biophysical detail on the other hand.

All models described above miss linkages to non-LULUCF sectors, although DIMA's 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. The consumption side is often modeled only in a very basic form as well, thereby neglecting income effects. The models also often miss linkages to other countries or regions than the ones under scrutiny. They are thus not able to capture macro-economic and international feedbacks or even income effects. If the question to be answered considers only a limited regional scale, this is perfectly legitimate. Sub-national or small-country policies will probably not affect world prices, and will probably not have significant income effects that affect the relative and absolute demands for agricultural and forestry products.

However, the models described in this section are not able to show the role of LULUCF in an optimal national (especially when a larger country or region like the US or the EU is considered) and international policy mix, or the feedbacks of economy-wide climate policy measures resulting from LULUCF, and can thus only play a limited role in the assessment of national and international climate policy options. Indeed, climate policies related to LULUCF are only part of a broader spectrum of possible policies that includes policies aimed at non-agricultural sectors. Ideally, climate policy puts a price on all GHG emissions, for all agricultural and non-agricultural sectors, inducing an intra- and international and intra- and intersectoral search for low-cost options. Partial equilibrium models are able to provide a first assessment of the costs and potentials of emission reductions from LULUCF that can be compared with costs and potentials of other climate mitigation options. They can thus be used to derive a first picture of how an optimal policy mix can look like. As the scale of the policy and the region under study becomes larger, links between LULUCF policies and other policies as well as links to other sectors and regions become more important and might significantly change the results of the partial equilibrium models.

The general conclusion from this section is therefore that partial equilibrium models are a good tool to study local or short-run policy questions that do not affect international prices. 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.

3 General equilibrium models

In general equilibrium models, the agricultural sectors are part of a larger model. Links between these sectors and other sectors – both because one good is an input in the production process of another and because consumers with a given budget have preferences over different goods – are explicitly modeled. In most models relevant for the current paper, perfect competition on input and output markets assures that all markets, including the land and agricultural markets, clear. Furthermore, all of the models discussed here cover multiple countries with explicit trade linkages for all goods.

In the past 10 years, there have been different attempts to extend computable general equilibrium models to include questions regarding LULUCF. There are two broad approaches. The first approach 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 (Hertel et al., 2009b) models. These models are discussed in section 3.2. The second approach, discussed in section 3.3, is to couple an economic general equilibrium model with a partial equilibrium model or with detailed biophysical models. We draw some conclusions on the general equilibrium models in section 3.4.

3.1 ‘Standard’ CGE models

As the starting point of our discussion of CGE models, we take the GTAP model (Hertel, 1997). The standard GTAP (Global Trade Analysis Project) model is a static multi-region, multi-sector, computable general equilibrium model, with perfect competition and constant returns to scale. International trade is handled via the Armington assumption: imports of a particular good from different countries are modeled as imperfect substitutes, and the composite of the imported good in turn is an imperfect substitute to the relevant domestically produced good.

In the standard GTAP model, land is modeled as 'weakly heterogeneous': it is supplied via a Constant Elasticity of Transformation (CET) function such that for landowners, different uses of their lands are imperfect substitutes. However, there is no distinction between soil types, altitudes, temperature, etc. Consequently, any activity that uses land (the production of a particular crop or animal type, or forestry) can use any amount of land. Furthermore, land is not modeled as being available as a given amount, and then to be allocated over different activities (like for example labor). Although the CET approach prevents that a policy shock would lead to a 'bang-bang' solution where due to the increase in returns of land in a particular use, all available land would go into this activity, its drawback is that strictly speaking there is no restriction on the amount of land available. The CET function only constrains the land rental share weighted sum of hectares to equal the total endowment of land (Hertel et al., 2009a). As a result, it could be that landowners in a particular country rent out more land than is actually available.

The standard GTAP model is static, where the model's output represents the economy after all markets are in equilibrium again after a (policy) shock, and is supposed to represent the 'mid-term' (some 20 years according to Hertel et al., 2009b, and Hertel et al., forthcoming).

3.2 Modeling agro-ecological zones (AEZs)

The GTAP AEZ project (see Hertel et al., 2009b) has tried to solve the problem of lack of land heterogeneity. It has developed an integrated land-use database including data on land use and land cover, forest carbon stock, and non-CO_2 emissions that can be used together with the GTAP database.[4]

Based on data from Monfreda et al. (2008), Ramankutty et al. (2008) developed a new global data set of croplands and pastures by combining agricultural inventory data and satellite-derived land cover data. Monfreda et al. (2009) use these data to construct a data set in which 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. Consequently, land is treated as a heterogeneous input.

[4] 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 113 regions and 57 sectors.

Concerning forestry, two types of timberland data are obtained from the dynamic global timber market model discussed in section 2.4 (Sohngen et al., 1999, Sohngen and Mendelsohn, 2003): 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. For each country, the data in this dataset are provided for different forest types (hardwoods, softwoods, and mixed forest types) within agroecological zones.[5]

Hertel et al. (2009b) and Hertel et al. (forthcoming) use the database to develop the GTAP-AEZ model that integrates land-use and land-based emissions into the CGE framework. 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. Thus, land is mobile between crop, livestock and forestry sectors within, but not across AEZs, and hence land is a heterogeneous input. It is assumed that there is a single, national production function for each (agricultural) commodity, and the different AEZs are inputs to the national production function for this crop. A sufficiently high elasticity of substitution assures 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, which still has the drawback that more land can be rented out than is physically available. Another improvement over the standard GTAP model is that it now has a nested CET structure, such that land is no longer equally easy substitutable between its uses (forestry, grazing, and different crop types).

The GTAP-AEZ model has been used to analyze competition for heterogeneous land types across and within sectors and input substitution between land and other factors of production, following a carbon tax on agricultural GHG emissions. The focus is on land allocation decisions and general equilibrium effects. Generally, the model facilitates the study of the role of non-CO_2 GHG reductions and LULUCF in national and international climate policy and assesses the implications of different climate policy strategies on land-use decisions. The

[5] Note that GTAP is a static model. Its model solutions are supposed to represent the 'near-term' response to a policy shock, which is generally noted to be 20 years. The model of Sohngen et al. (1999) is a dynamic model; to match this model's results with the GTAP model, the response to a policy shock after 20 years is taken from this model.

model and database are still to be integrated with the model and database for energy-based CO_2-emissions, so that it becomes possible to compare single-gas and multi-gas strategies, and strategies with and without agriculture and/or forest sequestration. Furthermore, it is still static, and lacks data on soil carbon sequestration.

A second model that has been developed to have a detailed representation of land use in a CGE model is the Future Agricultural Resources Model (FARM). It 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), which links climate variables with land and water resources on a 0.5 by 0.5 degrees grid scale, and an aggregation and extension of the standard GTAP CGE model. In different versions, the model is aggregated to eight (Darwin et al., 1996) or 12 (Ianchovischina et al., 2001; Wong and Alavalapati, 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. 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.

Whereas 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 (that is, agents are not intertemporally optimizing) 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 2020 (Wong and Alavalapati, 2003).

3.3 Linked CGE models

In this section, we describe two examples where CGE models derive information on land availability from an external land-use model. IMAGE (Integrated Model to Assess the Global Environment; Bouwman et al., 2006) is a biophysical-based integrated assessment model that contains several sub-models. It includes a terrestrial vegetation model that simulates the potential distribution of natural vegetation and crops based on climate conditions and soil characteristics, on a spatial resolution of 0.5 degree latitude by 0.5 degree longitude (AEZ approach). Furthermore, it estimates potential crop productivity, which is used by another sub-model to determine the allocation of the cropland to different crops. Another sub-model is the recursively dynamic economic model WorldScan (Lejour et al., 2006), which provides macroeconomic developments to the other models that are part of LEITAP-IMAGE. Since WorldScan contains only a very rudimentary representation of the agricultural sector, IMAGE is linked with to the static economic model LEITAP, which is an adapted version of the standard GTAP model. The most interesting extension, for the current discussion, is the inclusion of land supply curves. In the standard GTAP model described in section 3.1, land was in fixed supply. LEITAP includes land supply curves for each of the 24 regions (this aggregation is needed for the coupling with WorldScan), where the amount of land supplied depends on the inverse of its yield (Van Meijl et al., 2006). In this way, the model is able to distinguish between regions where land is abundant and regions where land is scarce. Furthermore, LEITAP has a nested (rather than a single) CET structure for land supply, albeit a different one than the GTAP-AEZ model discussed above. The coupled model is able to capture links between countries via the economic model as well as geographical explicit information on crop growth within each world region.

KLUM@GTAP (Ronneberger et al., 2009) is a coupling experiment in which an extended version of the static global CGE model GTAP is linked to the land-use model KLUM (Ronneberger et al., 2005). 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 biophysical 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 can come 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 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, 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 general equilibrium models have developed to take these features better into account. Introducing heterogeneity in available land, as was done in section 3.2, increases the credibility of the CGE models regarding changes in agricultural production and allows for calculating emissions from land-use changes. 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. Generally, the increase in model complexity due to inter-sectoral and international links, as compared to the models of section 2, goes at the expense of detail in modeling of the agricultural and forestry sectors, and of biophysical processes and geographical scale. Whereas some of the models of section 2 were able to study processes at the parcel level, the uncoupled CGE models do not go into more geographical detail than a 0.5 latitude by 0.5 longitude grid scale. Of course, this is already a great improvement over the 'standard' CGE models.

Even though CGE models naturally have less detail then partial equilibrium models, 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 in a much better way than a 'standard' CGE model with a simple CET representation of (otherwise homogenous) land supply. The models presented in this section can be used to assess a wide range of LULUCF related policy questions where intersectoral and international feedback effects are relevant, for example the effects of biofuel targets as they are currently implemented and discussed in many countries around the world. Increased production of biofuels can have a significant effect on land use, food production and international agricultural prices (Banse et al., 2008; see Kretschmer and Peterson, 2008, for an overview of modeling biofuels with CGE models). Other topics include the analysis of multi-greenhouse gas mitigation options including emissions from LULUCF and the optimal mitigation mix as well as the implications of different climate policy strategies on land-use decisions, food production and food security.

As noted by Sohngen et al. (2009), the modeling of forestry in CGE models is a major challenge. The forest capital stock can only be adjusted over a period of decades, which requires the tracking of its age profile after a policy shock. However, also management choices are crucial for amounts of carbon stored in forests. As carbon sequestration and timber production tend to be complements in the long-run (expanding forest area, increasing forest carbon through management, and increasing rotation all increase production), but can be substitutes in the short-run, a model can lead to wrong conclusions if it fails to represent the aspects in which the modeler is interested (e.g. short-run vs. long-run outcomes). Sohngen et al. (2009) therefore conclude that modelers will need to make compromises when modeling forestry in a static or recursively dynamic model.

Ideally, forestry should be included in a dynamic forward-looking model (intertemporally optimizing agents), but such CGE models are rare. It is promising that the latest version of MIT's EPPA model is forward-looking (Babiker et al., 2008). The previous version of EPPA is part of MIT's integrated assessment model IGSM (which, like IMAGE, is a set of coupled human activity and earth system models; Sokolov et al., 2005). However, the new EPPA model focuses on fossil fuel emissions from energy production, and includes agriculture as an aggregate sector only with land as in input that is imperfectly substitutable with the energy-materials composite. Hence, it is still a challenge to include the forestry sector, and to disaggregate the agricultural sector further, with sufficient detail.

4 An assessment of modeling approaches

There are three important characteristics of the model approaches described in this paper, which mostly hold for uncoupled models only. First, the two approaches largely differ in their geographical scope and biophysical detail. Whereas the CGE models are all global, the forestry model of Sohngen and co-authors is the only partial equilibrium model that covers the whole world. At the same time, it is clear that as the region that is covered becomes larger, sacrifices have to be made in the detail of soil characteristics, climate characteristics, biophysical processes, etc. A similar story holds for inter- versus-intra sectoral detail: as the level of detail of a particular sector increases, the less are linkages with other sectors being modeled. Indeed, the more agricultural sub-sectors are identified within a model, the less likely it is that linkages with non-agricultural sectors are being modeled. Third, as noted above, detailed modeling of the forestry sector requires a model with intertemporally optimizing agents. Thus far, this has only been successfully implemented in some partial equilibrium models.

This paper has shown that, over time, there has been considerable progress in both the classes of partial and general equilibrium models. Satellite technology allows for GIS-based models, which has improved both model types by allowing for a more detailed modeling of land quality. Indeed, the importance of spatial issues in agricultural economics is more and more recognized, see for example the special issues of *Agricultural Economics* (November 2002) and of *Journal of Agricultural Economics* (September 2007). In addition, more (general equilibrium) models start to include non-CO_2 greenhouse gases.

The adequate type of model to use for studying a particular climate policy depends upon the policy under scrutiny. Indeed, 'climate policy' covers a broad variety of policies, ranging from local specific agricultural policies such as a sequestration subsidy for a particular region, to a generic price for GHG emissions, covering all gases and all sources (both industrial and agricultural) in a large group of countries. The choice for the type of model to use depends on whether it is expected that the policy will affect other sectors or regions than the one directly affected. The policy studied in Antle et al. (2001) is a sequestration policy for the US Northern Plains – a limited region with a limited number of land classes and crop types. As it is unlikely that the policy will affect international (or even US-level) prices, a partial equilibrium model can be sufficient, with the advantage that – given the trade off between level of detail and scope – biophysical processes can be studied in more detail, leading to more realistic outcomes in terms of land use changes and amounts of carbon sequestered. However, regional policies can easily lead to international spillovers. Although biofuel policies are often aimed at decreasing local fossil-fuel dependency and environmental benefits, it can affect international agricultural prices. Using a general equilibrium model, Banse et al. (2008) show that European biofuel policies have a strong impact on agriculture at both the global and the European levels. This in turn affects world food prices and consumer welfare in a way that would be neglected in a partial equilibrium model.

Concerning model dynamics, policies aimed at non-forestry agricultural sectors, especially when aimed at a sub-national geographic scale and when not expected to affect prices in other sectors, can be studied using a static model. Although there is competition for land with forestry, forest dynamics will probably not affect land (opportunity) costs when the price of forest products is not directly affected by the policy. However, when the policy does directly affect forestry, a dynamic, forward-looking model (i.e. intertemporally optimizing agents) becomes indispensible. A 'forestry only' policy can then perhaps be studied using a partial equilibrium model of the forestry sector, but when the policy includes the entire agricultural sector, then general equilibrium effects will surely play a role as the relative price of the forestry and agriculture aggregate will be affected. Depending on the size of the region affected, one might need a local general equilibrium model, or a global model (when the region under scrutiny is large enough to affect world prices, for example the USA or the EU). Although forward-looking partial equilibrium models of the forestry sector have successfully been developed, general equilibrium models still need to take this additional step.

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 – each of which has its own advantages and disadvantages. While the first group of models has an advantage in the level of detail and in modeling the effects of regional, short-run policies, the second group is able to capture inter-sectoral and international feedback effects.

A recent development is multidisciplinary cooperation, especially when models of different kinds are linked. 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) behavior of farmers. The general equilibrium models include more biophysical realism through the modeling of agro-ecological zones, or are being linked to (groups of) models with geographical and biophysical detail. Further work in this direction, together with increasing availability of GIS-based data, is a very promising avenue of research.

An optimal policy would put a price on all GHG emissions, irrespective of the source, and would hence have a multi-gas (CO_2, CH_4, etc.) approach. In this way, agricultural and energy markets become linked via the carbon market. Partial equilibrium models are able to provide a first assessment of the costs and potentials of emission reductions from LULUCF that can be compared with costs and potentials of other climate mitigation options. A true integrated analysis requires a dynamic, forward-looking CGE model, in which forest dynamics as well as biophysical processes are properly modeled, such that changes in GHG emissions and storage can adequately be accounted for.

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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