



## **Land Use in Computable General Equilibrium Models: An Overview\***

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# LAND USE IN COMPUTABLE GENERAL EQUILIBRIUM MODELS: AN OVERVIEW

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## **1. Introduction**

Human intervention over the last several centuries has markedly changed land surface characteristics, primarily through large scale land conversion for cultivation (Vitousek *et al.*, 1997). The future will not be different. Populations and economies continue to grow, and climate change and climate policy will affect land use at a massive scale. However, land has long been neglected in global economics. That is now changing. For the first time, modeling teams have explicitly introduced global land use into computable general equilibrium (CGE) models, the work horses of economic policy analysis. In this book, we present a collection of pioneering papers in the applied economics of land use in CGE models. This book describes and critically assesses the underlying data, the methodologies used, and the first CGE applications. The applications are all with respect to climate change and climate policy, but the methods and data can also be used for other applications, such as land use change, energy security, and nature conservation.

The policymaking community is trying to determine the potential role for agriculture and forestry in climate change mitigation, and define implementation protocols, like the Clean Development Mechanism (CDM). Land-using activities appear to offer considerable potential for GHG mitigation, with recent studies suggesting that land-based mitigation could be cost-effective and assume a sizable share of overall mitigation responsibility in economically optimal abatement and climate stabilization policies. The non-climate implications are also important—social welfare (e.g., food security, clean water access), environmental services (e.g., water quality, soil retention), and economic welfare (e.g., output prices and production). Agriculture and forestry are also considered to be particularly susceptible to climate change, as the relative productivity of lands change with changes in plant productivity, weather variability, and disturbances (IPCC, 2007). To date, modeling has not been able to fully account for the opportunity costs of alternative land-uses and land-based mitigation strategies, which are determined by heterogeneous and dynamic environmental and economic conditions of land and economy-wide feedbacks that reallocate inputs, international production, and consumers' budgets.

CGE economic models are well suited to evaluate these kinds of tradeoffs. However, existing CGE frameworks, regional and global, are not structured to model land use alternatives and the associated emissions sources and mitigation opportunities. This work

has been hindered by the lack of data; specifically, consistent global land resource and non-CO<sub>2</sub> GHG emissions databases linked to underlying economic activity and GHG emissions and sequestration drivers. Recent development of global land-use and emissions data, as well as new mitigation cost data, have provided a solid foundation for advancing global economic land modeling.

The papers in this volume are a compendium of methodological insights and advances for CGE modeling of land-use. They identify challenges likely to confront most land-use modelers, and then describe strategies for addressing the challenges. While the papers do not emphasize new theoretical developments, they are mindful of recent such developments – for example in economic geography. The chapters presented here are breakthroughs in model development and application: applying consolidated, well-established methods, to novel datasets. Only now do we have access to globally consistent databases of land use, coupled with data on the physical characteristics of the land and the environment, and integrated with global economic activity. The new data have facilitated model development and, in so doing, they have unearthed implementation issues. The chapters describe and address the issues. Despite differences in focus, many of the chapters are forced to overcome similar obstacles, though sometimes via alternative approaches.

The book outlines key empirical and analytical advances and issues associated with modeling land use and land use change in the context of global climate change policy. It places special emphasis on economy-wide domestic and international competition for land and other resources; and, the explicit modeling of land management options, versus land use change. By offering a synthesis and evaluation of a variety of different approaches to this challenging field of research, this book hopes to serve as a reference for future work in the economic analysis of regional and global land use, and climate change policy.

This chapter begins by reviewing the previous literature, including methodological issues, the role of land in climate change, and opportunities for land-use in climate policy. It then provides an overview and synthesis of the important contributions of each chapter and the challenges they address, as well as identifying directions for future modeling of global land use within the context of the climate change debate.

## **2. Previous literature**

### *2.1. Methodological issues*

#### *2.1.1. Land-use modeling and climate change*

Sound economic modeling of land-use is fundamental to improving climate change policy analysis. Land use is important to climate change in three ways. First, land use patterns influence emissions of greenhouse gases, the water cycle, and the surface albedo (see Section 2.2). These matters are increasingly important in climate models, and the demand for realistic land use scenarios is rising. Spatially explicit land use will be one of

the main issues in the eventual coupling of economic models and biophysical earth system models.

Land use is also important in assessing the impacts of climate change. Changes in temperature, precipitation, extreme weather, and atmospheric concentrations affect the productivity of land, overall production opportunities, and carbon stocks (and the carbon cycle) on managed and unmanaged lands (see Section 2.2). Explicit modeling of land use is essential for characterizing net damages from climate change that include adaptation responses and costs such as changes in irrigation, fire management, pest control, and cropping systems.

Finally, land use is important in greenhouse gas emissions reduction, particularly because of emissions from farming activities, such as livestock and paddy rice production, carbon sequestration in forests, and bio-energy crops (see Section 2.3). All compete for land and water, with implications for food crops, nature conservation, energy use, and wood product supplies. Modeling competition for land requires a characterization of land qualities, which needs spatial inputs. For most practical purposes, however, this characterization changes rather slowly so that land heterogeneity can be reduced to a finite number of uniform classes (as in Chapter 6)<sup>1</sup> or a probability distribution (as in Chapter 7)<sup>2</sup>.

#### 2.1.2. *Land use in economics*

Economics is Greek for the laws of the household – particularly the traditional farm, for which subsistence and barter were more important than trade. The first systematic economists, the Physiocrats, argued that agriculture is the primary sector. We still use that moniker, but only in a numeric sense. The Physiocrats thought that land was the only true source of value. The Classical economists similarly placed substantial emphasis on agriculture and land. David Ricardo's (1817) notion that land rents reflect land quality is hotly debated today (Mendelsohn *et al.*, 1994; Darwin, 1999; Schlenker *et al.*, 2005, Timmins, 2006). Economic textbooks still explain decreasing returns to scale with the example of additional farmhands on a field – Turgot's (1793) intensive margin. Steuart's (1767) extensive margin, another source of decreasing returns to scale, partly explains land use patterns. Similarly, externalities are often introduced with the example of the beekeeper and the farmer. However, as agriculture is a minor economic sector in the industrialized countries nowadays, it is the vertically integrated, manufacturing sector that serves as the canvas upon which much of the modern economic theory is painted. (See Hubacek and van der Bergh (2006) for more historical perspective.)

Land use has attracted even less attention. In the Classical literature, there is Von Thunen's (1826) model of farm specialization as a function of the distance to town, and Zipf's Law on the relative size of cities (e.g., Duranton, 2006).<sup>3</sup> In economic geography, there are the location analysis of Weber (1909) and the central-place theory of Christaller (1933) and Loesch (1940). But land use plays a minimal role in current economic theory.

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<sup>1</sup> GTAP Working Paper No. 44

<sup>2</sup> GTAP Working Paper No. 45

<sup>3</sup> Zipf (1935) specified the functional form, but only applied it to the relative frequency of words.

Partly, this may be because land is – for many purposes – a minor problem. The built-up environment, and hence more than 95% of the world economy, occupies less than 1% of the land surface (Gruebler, 1994). Distance matters, of course, but can be parameterized (e.g., as an iceberg; Samuelson, 1954) without an explicit two-dimensional model of the land surface. Krugman (1998a) offers another explanation: City formation can only be explained by a combination of congestion and agglomeration externalities. As agglomeration implies increasing returns to scale, city formation resisted rigorous analysis before the monopolistic competition revolution (Dixit and Stiglitz, 1977).

This has now changed (Krugman, 1991; Fujita *et al.*, 1999; Brakman *et al.*, 2001). New economic geography offers micro-founded, general equilibrium models of activity location (Krugman, 1998b). See Martin (1999) for a defense of the “old” economic geography of Isard (1954) and Henderson (1974), which is less rigorous but more empirical. New international economics has its roots in the monopolistic competition revolution too. Rossi-Hansberg (2005) shows that, in a spatial model, tariffs and transport costs are different – tariffs are step changes, whereas transport costs are continuous. Bioeconomics is also gradually going spatial (Sanchirico and Wilen, 1999), particularly in the investigation of marine protected areas (Smith and Wilen, 2003). General equilibrium models of ecosystems are now emerging (Tschorhart, 2000, Finnoff and Tschorhart, 2003) and have recently been extended to include land – as a factor of production not for humans, but for plants (Eichner and Pethig, 2006). As promising and exciting as these developments may be, this is theory only (Neary, 2001) – with but a few empirical tests (Brakman *et al.*, 2006). Although this work is increasingly applied (e.g., Stelder, 2005), practical applications cannot be expected in the near future – at least, not in the sense of a well-calibrated, global model that can be used for numerical questions about land allocation, either in climate policy or other contexts. Empirical analysis and operational models particularly suffer from the lack of data. Nordhaus (2006) is a first step towards spatially explicit economic data. In the meantime, spatial down-scaling techniques are also being developed to generate gridded socio-economic data from regional aggregates (e.g., Asadoorian, 2005; Gruebler *et al.*, 2007). Validating these methods against actual spatial data will be necessary for assessing performance and reducing uncertainties across alternative methods.

### 2.1.3. *Geographic models of land use*

Geographers obviously have a keen interest in land use, but mathematical analysis and numerical models are not core tools for much of this work. Most geographic models are small-scale, often limited to a small part of a country, and cannot be generalized; indeed, many geographers resist generalization and large-scale research. Nonetheless, there are a few large-scale models of land use. Heistermann *et al.* (2006) distinguish between statistical models and rule-based models.

CLUE is a prominent example of a statistical model (Veldkamp and Fresco, 1996). Most of the equations in the model are estimated by multiple regression, but the model is completed by rule-based competition and transition. The largest scale applications of

CLUE are for China (Verburg *et al.*, 1999) and for tropical South America (Wassenaar *et al.*, 2007). The latter model works at the impressive spatial resolution of 3x3 km.

SALU and IMAGE are examples of rule-based models. For instance, demand-driven expansion of agricultural production is met on the basis of a suitability ranking, based on soil, climate, distance, and so on. The trade-off between infra- and extra-marginal expansion is modeled in a similar way. The SALU model (Stephenne and Lambin, 2001, 2004) is restricted to the Sahel, but the IMAGE model (Alcamo *et al.*, 1998) is global with a spatial resolution of 0.5°x0.5°.

In ACCELERATES (Rounsevell *et al.*, 2003) and KLUM (Ronneberger *et al.*, Chapter 12)<sup>4</sup>, the rules are derived from profit maximization. In both cases, a risk-averse farmer maximizes profits given fixed prices of inputs and outputs to the land-using sectors, and a probability distribution of yields.

#### 2.1.4. Economic models of land use

Partial equilibrium models are based on the same optimization principles as KLUM, but include both the response of production and consumption to prices, as well as the adjustment of these prices to attain a global equilibrium between supply and demand for selected commodities. Examples are IMPACT (Rosegrant *et al.*, 2002) and WATSIM (Kuhn, 2003) for agriculture; GTM (Sohngen *et al.*, 1999) for forestry; and AgLU (Sands and Leimbach, 2003; Sands and Edmonds, 2005) and FASOM (Adams *et al.*, 1996; USEPA, 2005) for both agriculture and forestry. The distinct advantage of a partial equilibrium model is that it captures price dynamics in the land-using sectors and is able to model substantial spatial and land management detail. The disadvantage of partial equilibrium models is that the rest of the economy is ignored. General equilibrium models do not have this problem.

The first global Computable General Equilibrium (CGE) model with land use disaggregated by physical characteristics was the FARM model by Darwin *et al.* (1995). Land, typically treated as a non-tradable endowment in CGE models, was split into a number of different land categories, distinguished by length of growing period. Land endowment by category was an aggregate taken from a spatially explicit bioclimatic model. The model was used to estimate the impacts of climate change (Darwin *et al.*, 1995), of sea level rise (Darwin and Tol, 2001), and of nature conservation (Darwin *et al.*, 1996) – each of which changes the relative land endowments in various regions of the world. Changes in demand for land were met, in the spatially-explicit biophysical model, on the basis of rules, but not on the basis of optimal behaviour. That is, Darwin *et al.* (1995) brought biophysical realism into their economic model, but they did not bring economic realism into their biophysical model.

GTAP-L (Burniaux, 2002) extends, the work of Darwin *et al.* (1995) with explicit tracking of the transformation of land (from one crop to another); thus, competition between alternative land uses was introduced. However, the input data were rudimentary.

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<sup>4</sup> GTAP Working Paper No. 50

The GTAP-AEZ model (Chapter 6)<sup>5</sup> extends the earlier work with a more extensive land use data base, and a more sophisticated representation of land-based emissions and forest carbon sequestration.

## 2.2. *Land use and climate change*

Atmospheric composition and climate are affected by land cover and land use changes via biogeophysical and biogeochemical mechanisms. Biogeophysical mechanisms, such as the effects of changes in surface roughness, transpiration, and albedo, are thought to have had a global cooling effect over the past millennium (Brovkin *et al.*, 1999), while biogeochemical effects from direct emissions of GHGs into the atmosphere have a global warming effect. Cumulative emissions from historical land cover conversion for the entire industrial period 1850–2000 accounted for roughly a third of total anthropogenic carbon emissions over this period (Houghton, 2003). In addition, land management activities were estimated to be responsible for over half of global anthropogenic methane (CH<sub>4</sub>) and over three quarters of nitrous oxide (N<sub>2</sub>O) emissions in 2000 (USEPA, 2006a). Land management activities include, among other things, cropland fertilization and water management, manure management and changes to forest rotation lengths.

However, until recently, projected changes in land use were not explicitly represented in carbon cycle modeling (Cramer *et al.*, 2004; House *et al.*, 2002; Levy *et al.*, 2004). Recent studies have shown that land use (e.g., Brovkin *et al.*, 2006; Matthews *et al.*, 2003; Gitz and Ciais, 2004) and feedbacks in the society-biosphere-atmosphere system (e.g., Strengers *et al.*, 2004) must be considered for realistic estimates of the future development of the carbon cycle. Long-run integrated assessment models have begun to explicitly model land use. One example is offered by Tubiello and Fischer (2007) who utilize the AEZ model of IIASA and FAO to analyze the impact of climate change on agricultural productivity. This framework uses detailed agronomic-based knowledge to simulate potential yields and the availability and use of land as a function of climate. They develop estimates of changes in productivity at the level of 2.2 million grid cells and then aggregate these to serve as productivity shocks to the Basic Linked System (BLS) economic model of world trade. However, there is no interaction between the economic model and the land use model. In general, economic frameworks for capturing dynamic and heterogeneous global land use decisions are still rather immature. Much of the work reflected in the chapters of this book was motivated by the need for theoretically sound and consistent global frameworks for modeling land use.

Land use is driven by the demand for land based products and services (e.g., food, timber, bio-energy crops, and ecosystem services) and land use production possibilities and opportunity costs (e.g., yield improving technologies, temperature and precipitation changes, and CO<sub>2</sub> fertilization). Non-market values will also shape land use outcomes, both use and non-use values, such as environmental services and species existence values respectively. Total world food consumption is expected to increase by more than 50% by 2030 (Bruinsma, 2003) with significant structural change in consumption patterns, including increases in global per capita meat consumption, on the order of 25% by 2030,

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<sup>5</sup> GTAP Working Paper No. 44

with faster growth in developing and transitional countries of more than 40 and 30%, respectively (Bruinsma, 2003; Cassman *et al.*, 2003). Additional cropland is expected to be required to support these projected increases in overall food and livestock feed demands.

Technological change is a critical driver of land use, and a critical assumption in projections. For example, Sands and Leimbach (2003) suggest that globally 800 million hectares of cropland expansion could be avoided with a 1.0% annual growth in crop yields. The Millennium Ecosystem Assessment (MEA, 2005) scenarios project positive but declining crop productivity growth over time due primarily to diminishing marginal technical productivity gains and environmental degradation.

Ludena *et al.* (2007) examine patterns of agricultural productivity growth over the past 40 years, decomposing it into that portion due to outward movement in the technological frontier, and that due to “catching up” to the global frontier. Typically the latter is more important for developing countries. This historical analysis of productivity growth in global agriculture forms the basis for projections to 2040. They anticipate continued differential growth rates between developed and developing countries, as well as across sub-sectors. Developing countries are expected to show the fastest productivity growth in non-ruminant livestock, while industrialized countries are expected to continue with faster productivity growth in crops. This difference is fueled in part by the massive private sector R&D investments being made in the rich countries, which now dwarf public sector investments. Ruminant livestock productivity growth shows a strong tendency towards divergence, with high growth in developed and some developing countries and negative productivity growth anticipated in others. Since increasing (decreasing) net productivity per hectare results in reduced (increased) cropland demand, this work suggests that the derived demand for land is likely to grow at very different rates in different parts of the world. To the extent that rapid productivity growth relieves the pressure for deforestation, this could have very significant impacts on CO<sub>2</sub> emissions. This “footrace” between long run supply and demand for land use is the subject of Chapter 10<sup>6</sup> in this volume.

While land use shapes climate change, climate changes will also shape future land use. Rising temperatures and CO<sub>2</sub> fertilization could improve regional crop yields in the near term, thereby reducing pressure for additional cropland and deforestation. However, modeling the productivity impacts of climate change is not straightforward with, among other things, the distributions of precipitation, weather extremes, and disturbances difficult to model, as well as interactions with other environmental variables, e.g., air quality, soil erosion (IPCC, 2007). Current land use modeling generally considers, if anything, only CO<sub>2</sub> fertilization and changes in annual average global temperature (e.g., Clarke *et al.*, 2007; van Vuuren *et al.*, 2007).

Figure 1 presents recent baseline land-use projections for global cropland, forest land, and grazing land (IPCC, 2007). Most global scenarios—from integrated assessment, computable general equilibrium, and sectoral modelling—project significant changes in agricultural land use caused primarily by regional changes in food demand and production technology. Scenarios with larger amounts of agricultural land result from

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<sup>6</sup> GTAP Working Paper No. 48

assumptions about higher population growth rates, higher food demands, and lower rates of technological improvement. Drawing on the studies represented in Figure 1, projected cropland changes vary from -18 to +69% by 2050 relative to 2000 (-123 to +1158 million hectares) and forest land changes range from -18 to +3% (-680 to +94 million hectares) by 2050. However, most of the long-term scenarios assume that forest trends are driven almost exclusively by cropland expansion or contraction, and only deal superficially with driving forces such as global production, consumption and trade in agricultural and forest products and conservation demands. In these scenarios, biomass crops are not projected to play a large role in global business-as-usual land cover. Higher long-run energy price expectations (due to the pricing of carbon, greater economic scarcity, energy security initiatives, or other forces) would, *ceteris paribus*, create pressure to expand biomass crop areas.

Increasing GHG emissions are projected in the near future for CO<sub>2</sub> (Figure 2) and over the long-term for non-CO<sub>2</sub> GHGs (IPCC, 2007). Net deforestation pressure is projected to decrease over time as population growth slows and crop and livestock productivity increase; and, despite projected losses of forest area in some scenarios, carbon uptake from afforestation and reforestation results in net sequestration. Recent non-CO<sub>2</sub> GHG emissions baseline scenarios agree that agricultural CH<sub>4</sub> and N<sub>2</sub>O emissions increasing until the end of this century, potentially doubling in some baselines. However, the modeling of forest and agricultural emission sources and carbon sinks varies across scenarios with limited consideration of explicit emissions drivers and the actual production trade-offs that affect land use, emissions, and production costs. Accordingly, this issue will be taken up in considerable detail in Chapter 6<sup>7</sup> of this volume.

### 2.3. Land use and climate policy

Land-use practices can be modified to mitigate GHG emissions, such that they reduce emissions of CO<sub>2</sub>, CH<sub>4</sub> and N<sub>2</sub>O, increase sequestration of atmospheric CO<sub>2</sub> into plant biomass and soils, and/or produce biomass fuel substitutes for fossil fuels. Forests alone have substantial potential to sequester carbon (Watson *et al.*, 1995; Watson *et al.*, 2000; IPCC, 2001). In addition, current technologies are capable of substantially reducing CH<sub>4</sub> and N<sub>2</sub>O emissions from agriculture (USEPA, 2006b, Section V), while a number of global biomass energy potential assessments have been conducted (see Berndes *et al.* (2003) for an overview).

Recent climate stabilization studies have found that land use mitigation options could provide cost-effective abatement flexibility in achieving climate stabilization targets (Rose *et al.*, 2007), accounting for 15 to 40 percent of cumulative required abatement over the century. Four particular studies found that including land-based mitigation (both non-CO<sub>2</sub> and CO<sub>2</sub>) reduced the costs for stabilizing radiative forcing (Kurosawa, 2006; van Vuuren *et al.*, 2006; Rao and Riahi, 2006; and Jakeman and Fisher, 2006).

Rose *et al.* (2007) showed that annual forestry, agriculture, and biomass abatement levels are projected to grow over time in stabilization scenarios with relatively stable annual

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<sup>7</sup> GTAP Working Paper No. 44

increases in agricultural mitigation and gradual deployment of biomass mitigation that accelerates dramatically in the last half of the century to become the dominant land mitigation strategy. In some scenarios, increased commercial biomass energy (solid and liquid fuel) provides 5 to 30% of cumulative abatement, and 1 to 15% of total primary energy (500 to 9,500 EJ of additional bio-energy above the baseline over the century).

However, there are substantial uncertainties. There is little agreement about the magnitudes of abatement (Figure 4). The scenarios disagree about the role of agricultural strategies targeting CH<sub>4</sub> versus N<sub>2</sub>O as well as the timing and annual growth of forestry abatement, some scenarios suggesting substantial early deployment of forest abatement, while others suggesting gradual annual growth or increasing annual growth. Furthermore, while there is some indication that agricultural mitigation is projected to be a larger share of the developing countries' total mitigation portfolio; and, developing countries are likely to provide the vast majority of global agricultural mitigation, it is currently not possible to assess the regional land-use abatement potential in stabilization scenarios given the scarcity of published regional results (IPCC, 2007).

Overall, the modeling of global land based climate change mitigation is relatively immature with significant opportunities for improving baseline and mitigation land use scenarios and better characterizing the emissions and mitigation potential of land. Essential to future land modeling are improvements in the dynamic modeling of regional land use and land-use competition. The cost of any land based mitigation strategy should include the opportunity costs of land, which are dynamic and regionally unique functions of changing regional bio-physical and economic circumstances. Subsequent development efforts should address competition between mitigation options, as well as modeling of the implications of climate change for land-use and land mitigation opportunities, including the potential climate driven changes in forest disturbance frequency and intensity. These challenges provide the motivation for this book, and we now turn to the contributions made by this volume.

### **3. Contributions of this Volume and Challenges for Future Work**

This book provides a unique reference on recent key methodological advances in the analysis of global land use as it relates to climate change policy. It also provides a guide for implementation by others. In this section, we discuss some of the most challenging issues facing authors in this volume, as well as potential future directions for research in this field.

#### **3.1 *The Spatial Dimension***

As noted previously in this chapter, the spatial dimension is at the very heart of land use modeling. With global land use data now available at the 0.5 degree grid cell level (see Chapter 2<sup>8</sup> of this volume) there is ample scope for dramatically increasing the dimensions of any global model. If such a model also endeavors to cover *all* economic

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<sup>8</sup> GTAP Working Paper No. 40

activity, not just agriculture or just forestry, then the data and modeling requirements become truly overwhelming at this level of resolution. As a consequence, the chapters in this book have focused exclusively on land use in the agriculture and forestry sectors. Furthermore, most of the chapters have adopted a somewhat aggregate level of resolution, which is more in line with the spatial resolution of economic statistics. For example, in the MIT, LEITAP and KLUM models (chapters 8<sup>9</sup>, 9<sup>10</sup> and 12<sup>11</sup>, respectively), global results of land allocation across crops are produced at the country level. In the GTAP-AEZ model (chapters 6<sup>12</sup> and 10<sup>13</sup>), land use is aggregated to the level of Agro-Ecological Zones within countries. Even the Sands-Kim study, which focuses solely on the US (Chapter 7<sup>14</sup>), aggregates to the level of major watersheds.<sup>15</sup> A fundamental problem in modeling agriculture and forestry production at the sub-national level involves estimation of input usage and production by spatial unit. The GTAP-AEZ model circumvents this problem, by having a single, national production function in which land types from different AEZs substitute for one another. This begs the question: Is this an appropriate approach to modeling land use? In their chapter, Hertel *et al.* (Chapter 6<sup>16</sup>) show that this is a legitimate approximation to a model in which production on each AEZ is modeled separately, provided that: (a) the sub-sectors (i.e., different AEZs) produce identical products, (b) non-land input-output ratios are the same across AEZs, (c) common non-land input prices prevail across AEZs, and (d) the elasticity of substitution between AEZs in a given land use is set very high. These assumptions, in combination with cost minimization and zero pure profits, mean that land rents must vary in direct proportion to yields. This is the same assumption that Eickhout *et al.* make in constructing their land supply schedule (Chapter 9<sup>17</sup>). In light of the central role of the national production function assumption in many of the chapters in this volume, it would be useful to test the requisite maintained hypotheses for key countries, using disaggregated data on inputs and prices. Of particular interest is the extent to which non-land input-output ratios vary systematically with AEZs, either due to differences in choice of technique across different land qualities or due to differing input prices. If this proves to be the case, then the simple rule of proportionality between yields and land rents, as well as the capacity of an aggregate production function to capture the impact on the derived demand for land, are both brought into doubt.

### 3.2 *Mobility of Land Across Uses and Diversification of Production*

Closely related to the spatial dimension is the issue of the homogeneity of land and its potential mobility across uses. If the unit of observation is small enough so that for all practical purposes the land is perfectly homogeneous, then we would expect rental rates

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<sup>9</sup> GTAP Working Paper No. 46

<sup>10</sup> GTAP Working Paper No. 47

<sup>11</sup> GTAP Working Paper No. 50

<sup>12</sup> GTAP Working Paper No. 44

<sup>13</sup> GTAP Working Paper No. 48

<sup>14</sup> GTAP Working Paper No. 45

<sup>15</sup> In other work, the KLUM model has been calibrated to crop production data at the grid-cell in Europe.

<sup>16</sup> GTAP Working Paper No. 44

<sup>17</sup> GTAP Working Paper No. 47

on all land within that unit to be equalized. In the absence of risk and uncertainty, and in the absence of technological interdependence amongst the crops (e.g., benefits from crop rotation or the sharing of common inputs), we would expect farms to specialize in the crop with the highest return, net of non-land input costs. However, farms are often diversified, and certainly most of the larger units of observation (e.g., grid cells or AEZs) exhibit diversification of production. Explaining this diversification therefore presents the modeler with a special challenge. The authors in this volume take two different approaches to reconciling this puzzle. The first approach is to appeal to risk considerations. This is the approach taken in KLUM (Chapter 12<sup>18</sup>), where risk averse producers maximize expected utility and returns to different crops are uncertain. This combination of factors leads farmers to diversify production. The authors use half the data in their time series from the FAO to calibrate the risk aversion and cost parameters for their model. They reserve the second half of the data series for model validation and find that the model performs reasonably well in this out-of-sample test. Such model validation is extremely valuable, and should be more widely undertaken by authors in this field.

Of course, risk aversion is a producer-level issue, not a market-level issue. So when we move to the level of regions, or indeed countries, the appeal of a risk-based approach to model calibration is somewhat lessened. For such large areas, it would seem that diversification likely reflects heterogeneity of the underlying land and climatic endowments, as well as the heterogeneity of local markets. For example, it may be attractive to (e.g.) grow certain crops in the valley and others on the hillside. So physical heterogeneity is a reason why we might observe diversification in crops within a given AEZ.

This brings us to a group of diverse approaches to reconciling observed patterns of production with the economic structure of global land use models. There are two approaches used in the book for dealing with land heterogeneity. The first is to employ a simple Constant Elasticity of Transformation (CET) function by which an aggregate endowment of land is transformed across alternative uses, subject to some transformation parameter that governs the responsiveness of land supply to changes in relative yields. This approach was first introduced by Hertel and Tsigas (1988) in their agriculture-focused CGE model of the US economy and it has subsequently been used in the standard GTAP model (Hertel, 1997) to handle the allocation of land across sectors in the economy. This approach is also embedded in several of the chapters in this book (Hertel *et al.*, Chapter 6<sup>19</sup>; Golub *et al.*, Chapter 10<sup>20</sup>; Eickhout *et al.*, Chapter 9<sup>21</sup>). The problem with the CET approach is that the “transformation” of land from one use to another destroys the ability to track the allocation of hectares across agricultural activities. Instead of constraining the sum of hectares across uses to equal the total availability of hectares in a given AEZ or country, the CET function constrains the land rental share-weighted sum of hectares to equal the total endowment of land. In this framework, differential land rents reflect differences in the *effective* productivity of a given hectare of

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<sup>18</sup> GTAP Working Paper No. 50

<sup>19</sup> GTAP Working Paper No. 44

<sup>20</sup> GTAP Working Paper No. 48

<sup>21</sup> GTAP Working Paper No. 47

land across uses and it is these *effective* hectares that are constrained in the aggregate. Also, given the lack of an explicit link to yields and the underlying heterogeneity of land, this model is difficult to validate against the observed data. In short, while it is an extremely versatile approach to limiting factor mobility across uses, the CET function “covers a multitude of sins”. A more explicit approach to handling land heterogeneity would be desirable.

The AgLU model, featured in Chapter 7<sup>22</sup> by Sands and Kim, also reflects land heterogeneity in its attempt to reproduce a diversified mix of output in a given AEZ (or in their case, a given watershed). This methodology, developed by Sands and Leimbach (2003) and inspired by the work of Clarke and Edmonds (1993) on heterogeneous energy technologies, is isomorphic to the CET approach in its representation of maximum profits and supply response. However, unlike the CET function, their framework is based on an explicit model of yield heterogeneity. Indeed, in this model, the variance parameter (possibly adjusted for the correlation of yields across crops), determines the extent of the supply response (see the appendix in Sands and Leimbach, 2003). And it can be shown that there is a direct mapping from these parameters to the transformation parameter in the CET function. Of course, as with any practical approach to modeling complex phenomena, this one involves some restrictive assumptions, in particular, the form of the underlying yield distribution (log-Gumbel). The supply function also implies that, at the margin, land rents (profits in their terminology) are equated across uses. This is a testable hypothesis that warrants econometric investigation.

In Chapter 7, Sands and Kim calibrate AgLU to watershed data by permitting prices and intrinsic yields to vary in order to satisfy the model’s equations when evaluated at observed yields and land cover shares. So a natural way to validate the model would be to work in the opposite direction, for a region where such data were available. Another validation approach would be to estimate the log-Gumbel distribution directly and compare the supply elasticity implied by these distribution parameters to those obtained directly from estimation of land supply functions. In short, the appeal of the AgLU approach is that it has strong, and observable implications, which may be tested against the data.

In the case of any of the models based on land heterogeneity, authors typically “nest” the supply functions such that producers first determine the allocation of land amongst crops, then, based on the average return to crop land, an allocation is made between crops and livestock or crops and forestland (e.g., Sands and Kim, Chapter 10<sup>23</sup>). In the case of Eickhout *et al.*, in Chapter 9<sup>24</sup>, certain crops are singled out for special treatment in the land supply nesting structure. As documented in Chapter 10 by Golub *et al.*, this pattern of nesting can have important implications for the long run supply of land to different uses, as well as the path of land rents over time. Yet there are as many different patterns of nesting as there are models, and little evidence in favor of one pattern over another. This type of nesting, or separability, is amenable to econometric testing (e.g., Berndt and Christensen, 1974). It amounts to a restriction on the cross-elasticities of supply between land rents in one nest and land supply in another nest. Rigorous testing of these

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<sup>22</sup> GTAP Working Paper No. 45

<sup>23</sup> GTAP Working Paper No. 48

<sup>24</sup> GTAP Working Paper No. 47

separability hypotheses would greatly assist future authors in narrowing the range of acceptable land supply nests.

### 3.3 *Incorporation of the Forestry Sector in Global Models of Land Use*

One of the most difficult challenges faced by authors in this volume is that of incorporating forestry into their analysis of climate change mitigation. In their chapter on this topic (Chapter 11<sup>25</sup>), Sohngen *et al.* outline the problems and challenges of adequately representing forestry in economic models of land use and land use change. Unlike most other production processes in the economy, which can be adjusted within a matter of a few years, it takes decades to grow a new forest. Furthermore, growth in the forest stock, as well as sequestration potential, depends critically on the type of forest and its vintage. There are very few global forestry models that handle all these aspects well in partial equilibrium. So expecting proper treatment within general equilibrium in the near future is probably asking too much. However, the authors in this volume have explored a number of different approaches to tackling important (and different) pieces of the problem. And we turn now to a discussion of these diverse approaches.

Perhaps the most obvious approach is to establish a soft link between an intertemporal, partial equilibrium model of forestry and the CGE model. This is what is done in Golub *et al.* (Chapter 10<sup>26</sup>). First the recursive, dynamic CGE model is run for 100 years to establish the baseline path for the economy, and, in particular, the growth rate in aggregate demand for forest products.<sup>27</sup> Based on this path of global forest products demand over the next century, Sohngen runs his Global Timber Model and produces a price path for forest products. This price path embodies all of the forward-looking behavior in the intertemporal, partial equilibrium forestry model and serves to inform the CGE model about the change in value of forest products over time. The recursive dynamic CGE model is then calibrated to follow this same price path over time. (The calibration variable is the – as yet unobserved – rate of technological change in the forest products using sector.) This approach is attractive due to its relative simplicity in transmitting information about the intertemporal adjustment in the forestry sector over time. However, the CGE results clearly depend on the method of calibration and more work is required to explore alternative approaches and their implications.

A similar, but somewhat more ambitious approach to linking the partial and general equilibrium models with respect to forestry behavior is offered by Hertel *et al.* in Chapter 6<sup>28</sup>. Those authors focus on deviations from baseline (in this case the baseline is simply the current state of the economy, since the analysis is comparative static). In particular, they consider the impact of alternative carbon prices on climate change mitigation. In the case of forestry, this involves three major mechanisms for responding to the carbon price: (a) averted deforestation, (b) afforestation, and (c) optimal changes in forest management practices, including aging of the forest stock and use of more non-land inputs in more

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<sup>25</sup> GTAP Working Paper No. 49

<sup>26</sup> GTAP Working Paper No. 48

<sup>27</sup> Since the macro-economic baseline is largely independent of what is assumed about forestry, this is a one-way flow on information (i.e. the authors do not iterate between the two models on this point).

<sup>28</sup> GTAP Working Paper No. 44

intensive management practices. The authors begin by running the partial equilibrium model many times in order to trace out the sequestration supply schedules for the forestry sectors in each region of the global model. The sequestration is decomposed into the response at the extensive margin (more land in forests), which has a direct impact on the other land-using sectors, and the response at the intensive margin (more carbon in the existing forest lands), which reflects optimal adjustments on existing forest land. The CGE model is then calibrated so that it mimics both the intensive and extensive carbon sequestration schedules. The authors find this to be a reasonably effective means of incorporating the sequestration potential of forestry into a more comprehensive analysis of climate change mitigation. Compared to other CGE treatments in this book, the most important forestry element of the Hertel *et al.* approach seems to be the distinction between the intensive and extensive margins. These have very different implications for land use, and ignoring the intensive margin, as many integrated assessment models do, tends to over-emphasize the competition for land in the wake of sequestration subsidies. The biggest problem in the Hertel *et al.* analysis relates to the fact that the forest carbon sequestration supply schedules shift over time. In Chapter 6<sup>29</sup>, they focus on the 20 year abatement schedules. However, if they had worked with 50 year schedules, the answer would have been different (more sequestration at lower costs) due to the greater opportunities for intertemporal adjustment.

In Chapter 7<sup>30</sup>, Sands and Kim seek to incorporate key features of the forestry problem directly into a recursive dynamic framework. These authors derive a steady-state condition for the determination of optimal forest rotation and embed this in their CGE model of the US economy. This has the virtue of capturing the impact of carbon sequestration subsidies on the optimal timber rotation, thereby capturing an important part of the intensive margin response to carbon prices. However, in so-doing, these authors ignore the issues of vintages and adjustment paths. Clearly some combination of these two approaches will be required on the path forward for improving upon the current state of this literature.

### 3.4 Accessing New Lands

A critical issue in modeling the long run supply of land to different activities in agriculture and forestry is the availability of new lands that might be brought into production. The simplest way to handle this problem is to construct a land supply schedule in which rising land rents causes additional land to be brought under cultivation. This is the approach adopted by Eickhout *et al.* in their specification of the LEITAP model (Chapter 9<sup>31</sup>). The appeal of their approach lies in the way they build up this supply schedule. In particular, they capitalize on the detailed productivity information available in the IMAGE data base. For each region, they first remove all the lands which are: (a) non-productive, or (b) unavailable for conversion to agriculture (i.e., protected or built-up). The remaining lands are thrown into a pool and subsequently arranged in order of diminishing productivity. The authors then invoke the assumption that land rents are

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<sup>29</sup> GTAP Working Paper No. 44

<sup>30</sup> GTAP Working Paper No. 45

<sup>31</sup> GTAP Working Paper No. 47

inversely related to yields, which gives them a land supply schedule where the total amount of land in production is an increasing function of land rents. As equilibrium land rents rise, the model brings in additional lands up to the point where the benefit of the last hectare of land, as measured by its marginal value product, equals the “marginal cost” of this land, i.e. the land rent that must be paid in the market place. This approach brings detailed biophysical information in the integrated assessment model to bear on the issue of land supply, with special areas, such as forest reserves and national parks omitted from the commercial supply schedule. The problem is that there is no spatial component to the supply decision – as might be the case if there were AEZs distinguished in the model. Furthermore, the authors only consider the supply of land to agriculture and ignore the use of land in forestry in their CGE model.

Indeed, much of the new land that might be brought into commercial production – either agricultural or forestry – under future scenarios is currently covered with forest. Sohngen and Mendelsohn (2007) term these “inaccessible forests”, i.e. forests that are not economically accessible given current market conditions. Their modeling introduces a supply function for these inaccessible lands and calibrates their model to bring in roughly the same amount of these forest lands as has deforested over the past decade in key regions of the world. This represents an important part of their baseline, and forestalling this deforestation also becomes an important feature of the response to carbon prices in their framework.

In Chapter 10<sup>32</sup> on the long run supply and demand for land, Golub *et al.*, explore the issue of inaccessible forests in considerable detail. They draw on the work of Gouel and Hertel (2006), which formulates the access problem as an investment decision in which the discounted stream of benefits of accessing an additional hectare is equated to the marginal cost of access. By modeling the access costs explicitly (in this case as a function of labor and capital), Golub *et al.* are able to close their general equilibrium model with respect to these new lands. That is, they don’t just come in “out of the blue”. Rather, the access of new lands requires real resources. These authors find that adding the inaccessible lands makes a sizable difference in the long run scarcity of land in some regions of the world.

### 3.5 Biofuels and Land Use

In the literature review offered above, we emphasized the important role of biofuels in long run climate change stabilization scenarios. Accordingly, this topic also receives attention in the present volume. Chapter 8<sup>33</sup> by Reilly and Paltsev focuses specifically on biofuels, but their analysis does not really delve into the implications for land use of current biofuels programs. They focus primarily on bioenergy from cellulosic conversion – something that remains a long way from commercial viability in current market conditions. In Chapter 7<sup>34</sup>, Sands and Kim, on the other hand, focus largely on biomass for energy produced from crops. As such, they tie biofuels production explicitly to land

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<sup>32</sup> GTAP Working Paper No. 48

<sup>33</sup> GTAP Working Paper No. 46

<sup>34</sup> GTAP Working Paper No. 45

use. They project a major role for biofuels for high carbon price scenarios (above \$100/TCE), but their analysis is focused only on the United States. In Chapter 9<sup>35</sup>, Eickhout *et al.* include biofuels in their global analysis, but the expansion of the biofuels production is largely exogenous.

There appear to be two main obstacles to the incorporation of biofuels into global CGE models. The first is simply the issue of data. In the case of biofuels, many of the potentially important technologies (e.g., ethanol from cellulose) are not currently commercially viable – so they don’t appear in our data bases at all! Introducing them into the model requires coming up with an appropriate profile of costs, sales, and even trade shares, to invoke when they would come into production. This is not a small task. Secondly, there is the question of profitability – how high do competing energy prices have to rise before these technologies enter commercial production? In their chapter<sup>36</sup>, Reilly and Paltsev do a very nice job laying out the key assumptions in the case of “bio-oil” and “bio-electric” technologies. However, they do so in a stylized example (e.g., the feedstock in both cases is a “resource”). Taking this to a level of detail that bears directly on land use will be more challenging; and, it is in the competition for land that the global impact of biofuels production may be most significant. This fact is highlighted by the work of van Vuuren *et al.* (2007), who project a massive increase in land devoted to biofuels and hence continued rapid rates of deforestation in developing countries. Sorting out how biofuels will compete with forestry and crops, particularly in the face of GHG subsidies/taxes is a high priority for future work.

### 3.6 *Agricultural greenhouse gas emissions and mitigation*

Agriculture is responsible for the vast majority of global methane and nitrous oxide emissions and is considered to be important for managing the costs of climate change mitigation policies. However, modeling of the detailed drivers of non-CO<sub>2</sub> emissions within agricultural production and internalization of the costs of non-CO<sub>2</sub> emissions mitigation is lacking in current analyses of climate change policy. This, in turn, frustrates accurate evaluation of the mitigation potential of agricultural non-CO<sub>2</sub> strategies. In Chapter 5<sup>37</sup>, Rose and Lee introduce an emissions data base linked to the GTAP global economic data base that can support this kind of detailed analysis of non-CO<sub>2</sub> emissions. And the chapter by Hertel *et al.* (Chapter 6<sup>38</sup>) utilizes these data to provide a more realistic and comprehensive picture of non-CO<sub>2</sub> emissions—with economic sectors generating multiple emissions fluxes from various points of production and mitigation possible through explicit substitution between more and less emissions intensive input mixes (vs. output reduction).

There are three key challenges to modeling agricultural emissions and mitigation. First, agricultural soil carbon stock and flux modeling is noticeably absent from current approaches; and, agricultural soils are thought to offer substantial carbon sequestration

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<sup>35</sup> GTAP Working Paper No. 47

<sup>36</sup> GTAP Working Paper No. 46

<sup>37</sup> GTAP Working Paper No. 43

<sup>38</sup> GTAP Working Paper No. 44

potential (IPCC, 2007). This absence is, among other things, due to a lack of global spatial soil carbon stock data and the difficulty of modeling changes in soil carbon, which calls for an additional modeling tool as complex as a crop process model or as simple as a spreadsheet carbon pool accounting tool. Second, tracking net greenhouse gas effects from land conversion (e.g., forestry to agriculture) requires knowledge of previous and future land use, and, for soil carbon stocks, historic land use. Tracking the evolution of every parcel of global land is challenging given current technical capacities. However, land transitions should not be ignored and simplifying strategies are needed to provide a reasonable approximation of the net greenhouse gas implications of land conversion. A notable example of such an approach is the LEITAP link to the IMAGE model (Eickhout *et al.*, Chapter 9<sup>39</sup>), where regional agricultural land decisions are downscaled to grid cells, with above and below ground soil carbon stocks adjusted and emissions based on forest land conversion and agricultural land abandonment (see Leemans *et al.*, 2002, for details on this particular element of their modeling). Finally, technological change will alter the emissions rates of agricultural production activities. Explicit consideration of this interaction is important to avoid arbitrary emissions growth and explore emissions uncertainties associated with technological uncertainty.

### 3.7 *The Role of Non-primary Demands for Land*

As noted previously, the chapters in this book studiously avoid dealing with demands for land by the non-primary sectors, i.e., commercial, residential, recreational uses.<sup>40</sup> Yet in some parts of the world, these represent the main area of future growth in land use. Furthermore, in some parts of the world, non-agriculture and non-forestry uses dictate land values, and hence the opportunity cost of expanding these primary sectors. In the U.S., nonagricultural uses have been shown to play a role in determining the value of farmland in selected metropolitan areas (Lopez *et al.*, 1988), but this has not proven to be an important determinant of aggregate agricultural land values. However, in Japan, the case is quite different. There, the proximity of farmland to major population centers is much greater and arable/buildable land is extremely scarce. Thus the demand for residential, recreational, and commercial land may be expected to exert considerable pressure on land values in agriculture and forestry.

Of course, the degree to which land can move between primary sectors and other uses depends on land use legislation. In Japan, landowners have historically been required to obtain the permission of the prefecture or of the Ministry of Agriculture, Forestry, and Fisheries in order to transfer farmland into other uses (ABARE, 1988, p. 75). Extremely favorable property and inheritance taxation of farmland, coupled with high rates of capital gains taxation, serve to further discourage movement of land into nonfarm uses. As a result, the percentage of land devoted to agricultural uses in the three major metropolitan areas in Japan (16 percent) exceeds the share of this land devoted to residential, commercial, and industrial plant uses (11.5 percent). It also exceeds the share of farmland in Japan's total land area (15 percent) (ABARE, 1988, p. 316). Despite these

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<sup>39</sup> GTAP Working Paper No. 47

<sup>40</sup> The one small exception to this statement is the chapter by Eickhout *et al.*, who net out such uses before building their land supply curve.

distortions in the land market, there is evidence that nonfarm demands support agricultural land values. For example, between 1979 and 1985 the price of rice relative to the price of rice paddy land fell by about 20 percent (ABARE, 1988, p. 321), indicating that those holding the land are likely focused on non-agricultural uses.

The first step in incorporating non-primary demands for land in CGE models involves identifying its importance in the other sectors' production functions. A natural place to start would be the residential and commercial sectors, which are typically broken out in CGE models and which are clearly land-intensive. In the long run the demand for land in parks for recreation and the preservation of ecological diversity is likely to be very important. But these sectors have not yet been well-developed in global CGE models. Improving their specification, as well as estimating how the demand for their services is likely to grow with higher incomes, will necessarily precede the incorporation of these land demands into CGE models.

#### **4. Conclusion**

The role of global land use in climate change policy is extremely important. Yet, in comparison to other areas, such as fossil fuel use, it has received relatively little attention by climate economists – hence the need for this book. The chapters in this volume as a group offer all the elements needed for a sound analysis of the role of agriculture and forestry in greenhouse gas emissions and emissions reductions, as well as a structured economic foundation for evaluating the net impact of climate change on these sectors. The necessary data are now available in Part II of the book, and, Part III provides applications that have been extended to study all parts of this issue. While none of the individual frameworks presented here considers all aspects, in combination they do achieve this goal. As such, they lay a solid foundation for a new generation of research in this area.

Given the variety of different approaches to modeling global land use, there is need for model testing and validation: Which of these approaches best fits the data? Which approaches are based on maintained hypotheses that can be rejected, and therefore should be abandoned? In this chapter we have discussed some approaches to model validation, as well as key hypotheses to be tested. It is only through such systematic research that we will be able to eliminate the least promising approaches and focus on those that are worthy of further attention.

Throughout the book, we have largely ignored two “elephants in the global land use room”. The first is that of spatially explicit analysis. Computable general equilibrium models will not run any day soon on a spatial scale that satisfies natural scientists modeling global change. The simplest approach involves proportional downscaling (every unit within the aggregate inherits the same growth rate). But this ignores a great deal of useful information and can result in absurd projections, e.g., where a developing country ends up with GDP/capita twice as high as developed countries. Thus the current compromise is to use a combination of optimization and statistical techniques to downscale results of economic models to the grid. One of the most recent examples of this work is the effort at IIASA which downscales global results in two steps (Grübler *et*

*al.*, 2007). The first involves moving from aggregated regions to the country level based on population projections and projected GDP growth rates. The economic growth rates are based on the estimated “inverted U-shaped” relationship between GDP growth rates and GDP per capita. The authors then solve a constrained optimization problem which permits them to respect the regional constraints. At the second level, this approach to down-scaling incorporates statistical relationships pertaining to rates of urbanization and assumptions about the fundamentals under-pinning rural-urban income differentials, in order to put some structure on the sub-national down-scaling of economic activity. These authors are in the process of testing their down-scaling methodology against data-based approaches, such as G-ECON developed by William Nordhaus (2006). Such comparisons should help improve future downscaling methodologies and guide researchers to a common standard, which may be used to downscale not only total economic activity, but sectoral activity as well.

This book has also largely ignored water. Land is useless without water. Bio-energy and food not only compete for land, but also for water. The models used in this book do not omit water, but they treat it as a property of the land rather than as a scarce resource, that can be traded and the value of which can be enhanced by investment. Rosegrant *et al.* (2005) have developed a partial equilibrium model for analysis of global trade and water issues based on 69 river basins. Berrittella *et al.* (2007) include water in a global computable general equilibrium model – but their framework offers only a rudimentary representation of land. Future research will need to integrate such analyses of land and water into a single, global general equilibrium framework.

Omission of these two “elephants” notwithstanding, we think that this book represents a useful step forward. It lays the practical foundations for economic policy analysis of land-based greenhouse gas mitigation, and is therefore an important stepping stone to further research in the economics of land use and climate change policy.

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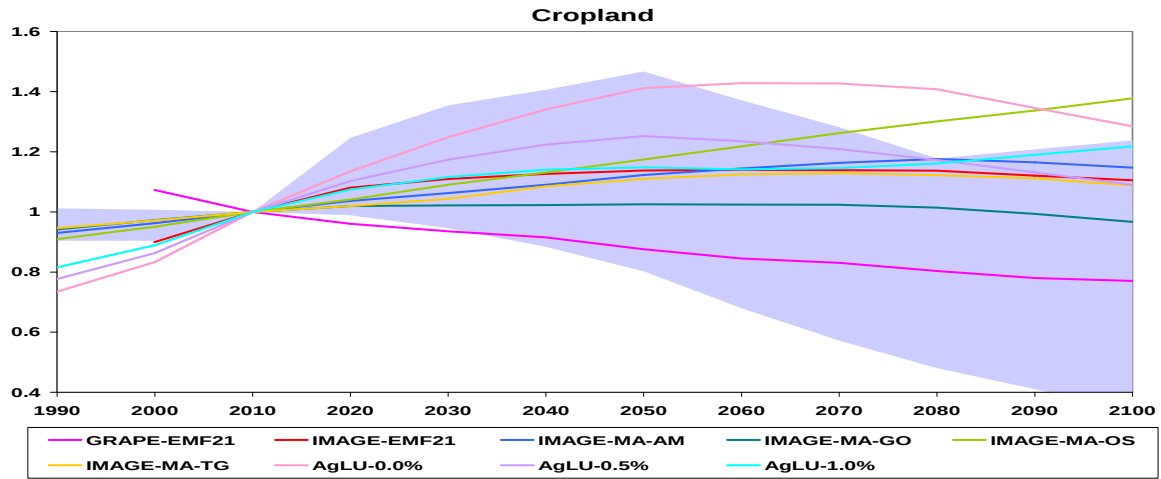
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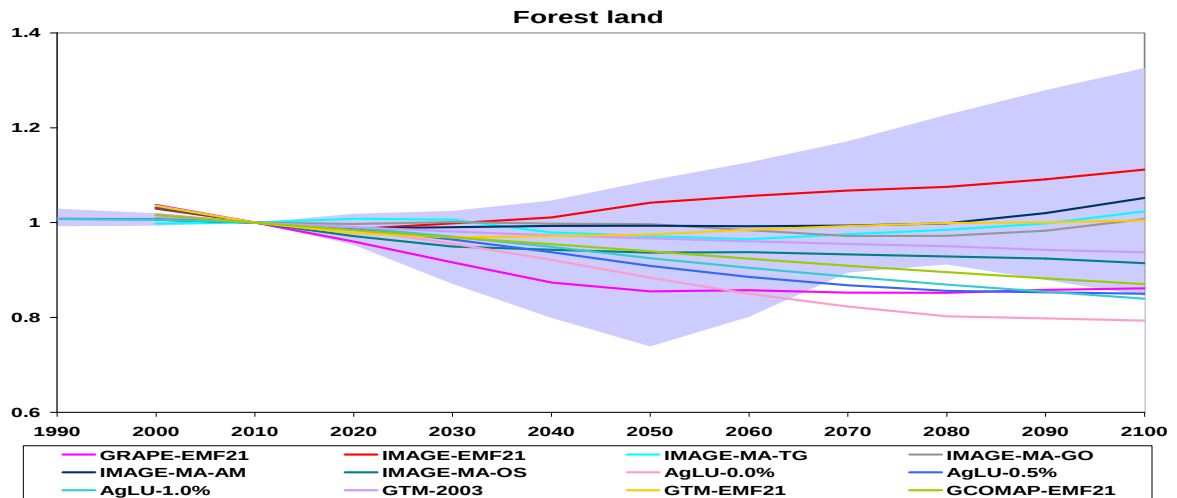
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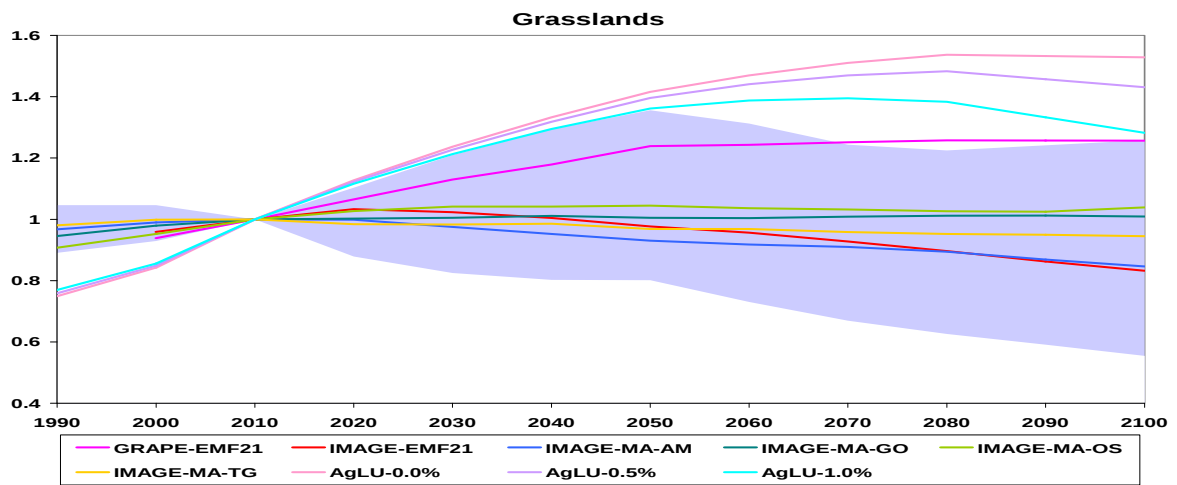
(A)



(B)



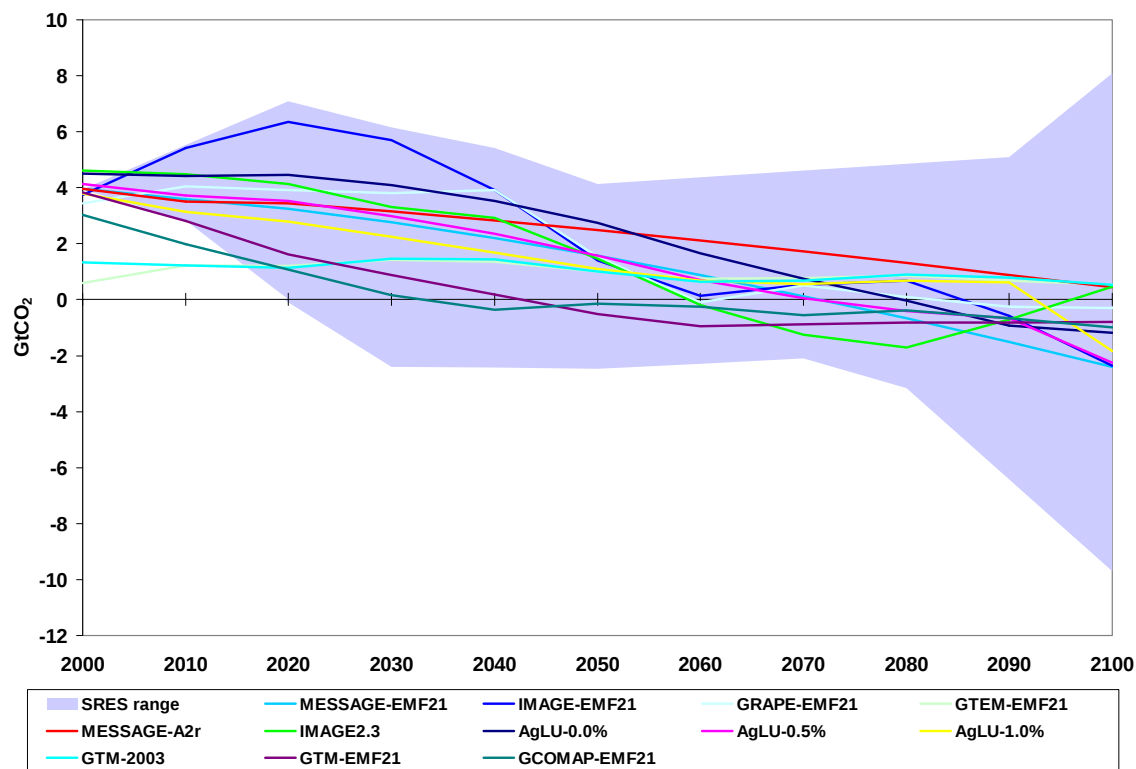
(C)



Notes: IMAGE-EMF21 = van Vuuren *et al.* (2006a) scenario from EMF-21 Study; IMAGE-MA-xx = Millennium Ecosystem Assessment (2005) scenarios from the IMAGE model for four storylines (GO = Global Orchestration, OS = Order from Strength, AM = Adaptive Mosaic, TG = TechnoGarden); AgLU-x.x% = Sands and Leimbach (2003) scenarios with x.x% annual growth in crop yield; GTM-2003 = Sohngen and Mendelsohn (2003) global forest scenario; GTM-EMF21 = Sohngen

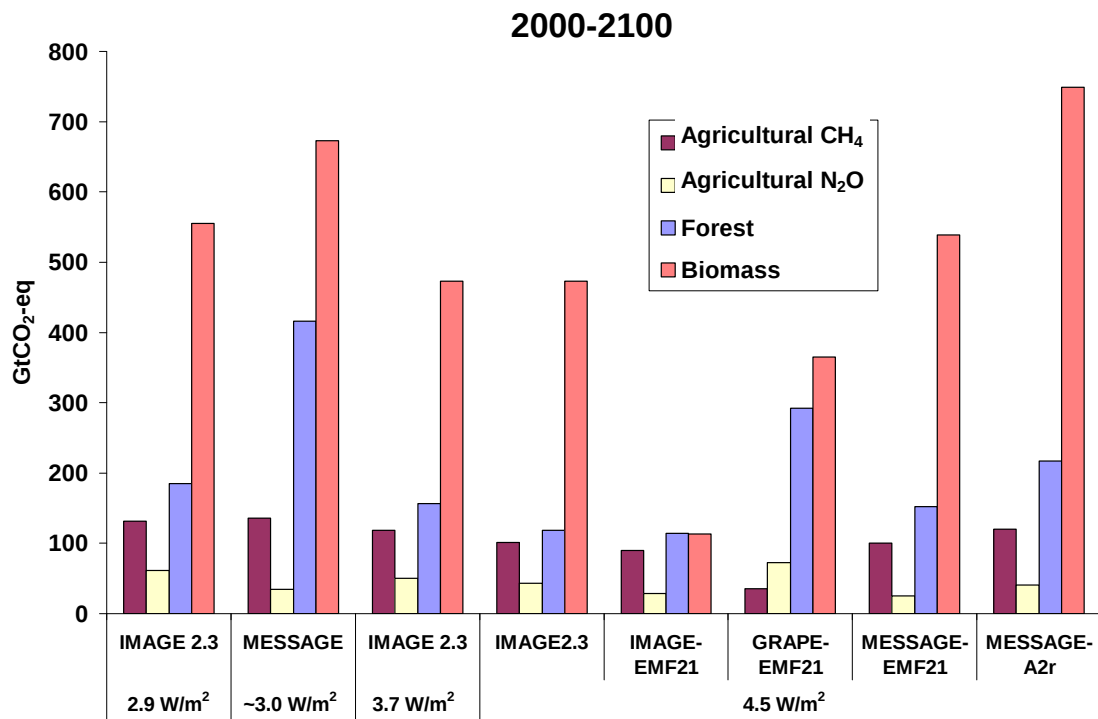
and Sedjo (2006) global forest scenario from EMF-21 Study; GCOMAP-EMF21 = Sathaye *et al.* (2006) global forest scenario from EMF-21 Study; GRAPE-EMF21 = Kurosawa (2006) scenario from EMF-21 Study

Figure 1. Global cropland (a), forest land (b) and grassland (c) projections (2010 = 1; shaded areas indicate SRES scenario ranges, post-SRES scenarios denoted with solid lines)



Notes: MESSAGE-EMF21 = Rao and Riahi (2006) scenario from EMF-21 Study; GTEM-EMF21 = Jakeman and Fisher (2006) scenario from EMF-21 Study; MESSAGE-A2r = Riahi *et al.* (2007) scenario with revised SRES-A2 baseline; IMAGE 2.3 = van Vuuren *et al.* (2007) scenario. The IMAGE 2.3 LUCF baseline scenario also emits non-CO<sub>2</sub> emissions (CH<sub>4</sub> and N<sub>2</sub>O) of 0.26, 0.30, 0.16 GtCO<sub>2</sub>eq in 2030, 2050, and 2100 respectively.

Figure 2. Baseline land-use change and forestry carbon net emissions.



Source: Rose *et al.* (2007)

Figure 3. Cumulative cost-effective agricultural, forestry, and biomass abatement 2000-2100 from various 2100 stabilisation scenarios.