



## **Modeling Land-use Related Greenhouse Gas Sources and Sinks and their Mitigation Potential\***

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# MODELING LAND-USE RELATED GREENHOUSE GAS SOURCES AND SINKS AND THEIR MITIGATION POTENTIAL

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## **1. Introduction**

To date, global economic and integrated assessment modeling of land 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 budgets (e.g., Rosegrant et al., 2001; Sohngen and Sedjo, 2006; Smith et al., 2007; Reilly et al., 2006; van Vuuren et al., 2006; Riahi et al., 2007).

Computable general equilibrium (CGE) economic models are well suited to evaluate these kinds of tradeoffs. However, existing CGE frameworks, regional and global, are not currently structured to model land use alternatives and the associated emissions sources and mitigation opportunities (e.g., Fawcett and Sands, 2006; Reilly et al., 2006). Partial and general equilibrium and integrated assessment frameworks are developing to more carefully study climate change policy and the role of land use change in mitigating GHG-induced climate change. 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. New global land-use and emissions data developments (Lee et al., 2005; Rose et al., 2007b), as well as new engineering mitigation costs estimates (USEPA, 2006b), have provided a solid foundation for advancing global land modeling.

In this paper we develop a framework for assessing the mitigation potential of land-based emissions. This framework could be readily combined with existing GHG mitigation studies of fossil fuel-based CO<sub>2</sub> emissions. Using the newly available data, we construct a novel modeling framework to understand how land-use opportunities for GHG abatement interact with one another and the rest of the economy on both a regional and global scale in light of global market clearing conditions for product markets. This paper extends the initial conceptual work of Lee (2004), and develops a fuller and more realistic global-scale model. Lee (2004) illustrates the potential importance of land mobility in GHG mitigation, finding that failure to account for land mobility within agriculture and between agriculture and forestry is likely to result in a large overstatement of the marginal cost of GHG mitigation.

The CGE framework developed in this paper introduces intra- and inter-regional land and land-based GHG emissions heterogeneity and analyzes land allocation decisions and general equilibrium market feedbacks under emissions taxation policies. We work with a

more disaggregated model and GHG emissions and mitigation structure designed to more explicitly capture key GHG emissions and sequestration activities. The model has 24 sectors and 3 regions (USA, China, and ROW). In line with the goals of this paper, special attention is paid to the land-using activities, including forestry, paddy rice, other cereals, other crops and livestock grazing. Specifically, we modify the standard GTAP CGE production structure (Hertel, 1997) in three ways. First, we introduce heterogeneous land endowments. Land heterogeneity has productivity and greenhouse gas flux implications that can effect land-use and GHG mitigation opportunities (e.g., Li et al., 2006; Sohngen and Tenny, 2005).

Second, we introduce land competition directly into land supply via a three-tiered structure, where crops compete with each other for land within a given Agro-Ecological Zone (AEZ), crops as a whole compete with grazing, and agriculture as a whole (crops and livestock) competes with forestry for land within a given AEZ. In addition, different types of land (i.e., different AEZs) can be substituted in the production for any single agricultural or forest product.

Finally, we distinguish three types of GHG emissions and mitigation (cost) responses in our analysis: those associated with sector outputs (e.g., methane emissions from agricultural residue burning), those associated with intermediate input usage (e.g., nitrous oxide emissions from fertilizer use in crops), and those associated with primary factors (e.g., emissions from livestock capital, or alternatively sequestration associated with forest land cover). Because forestry and agricultural markets compete for the same land, we explicitly model intensification (e.g., timber management) efforts differently from extensification (e.g., land-use change) efforts in the forestry sector. Each individual type of response in the agricultural sector is calibrated to engineering information from the USEPA (2006b), assuming a partial equilibrium (PE) closure of fixed input prices and fixed output, by adjustment of the relevant elasticities of substitution in production. Individual responses in the forestry sector are calibrated by utilizing data generated from an intertemporal optimizing partial equilibrium model of forestry and land use.

In developing the model structure, we incorporated four new datasets:

1. The GTAP land use database, which enhanced the standard GTAP global economic database by disaggregating land endowments and land use (cropland, grazing land, forest land) into 18 Agro-ecological Zones (AEZs). See chapters 2 – 4<sup>1</sup>.
2. The GTAP forest carbon stock database, which has detailed regional forest inventory and forest carbon stock data by forest age and species management cohorts. See Chapter 3<sup>2</sup>.
3. The GTAP non-CO<sub>2</sub> emissions database, which has mapped in a highly disaggregated emissions dataset from the US Environmental Protection Agency (USEPA) specifically designed for economic models directly to GTAP regions,

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<sup>1</sup> GTAP Working Papers No. 40, No. 41 and No. 42

<sup>2</sup> GTAP Working Paper No. 41

- sectors, and emissions drivers; See Chapter 5<sup>3</sup>.
4. Non-CO<sub>2</sub> GHG mitigation cost data from the USEPA that estimates economic mitigation potential for individual technologies for each emissions source category (USEPA, 2006b).

The focal point of our analysis will be regional and global land-use CGE GHG abatement responses.

Given our interest, and that of the book, we focus on modeling the unique GHG abatement responses in sectors and regions for the major non-CO<sub>2</sub> GHG emissions and carbon sequestration categories associated with land-using activities, such as methane emissions from livestock production and rice cultivation, N<sub>2</sub>O emissions from nitrogen fertilizer applications, and CO<sub>2</sub> sequestration in forestry. With our new model, we observe substantial interaction between sectors in response to a carbon price shock—primarily via competition for land—and between regions in the global economy—in this case via competition in the product markets. More specifically, we see land-use change within and across sectors, and across regions. We see the re-allocation of intermediate and factor inputs within land-using sectors and across the economy. We also see a reallocation of global production as relative prices change to reflect the disproportional effects of the carbon price.

Section 2 describes our CGE model framework (GTAP-AEZ), including the land use and non-CO<sub>2</sub> GHG data bases, as well as the specification and calibration of mitigation costs. Sections 3 and 4 present the model simulation design and results respectively. Finally, Section 5 provides summary remarks and discusses future opportunities.

## **2. GTAP-AEZ model**

### **2.1 Land use data**

The GTAP-AEZ model is a modified version of the standard GTAP model that incorporates different types of land. We do this by bringing climatic and agronomic information to bear on the problem – introducing different types of productive land via Agro-Ecological Zones (AEZs) (FAO/IIASA, 2000). Lee et al. (2005) developed a land-use and land cover database to facilitate global economic and integrated assessment modeling of land. The database offers a consistent global characterization of land in crops, livestock and forestry, taking into account biophysical growing conditions. Specifically, the database defines 18 global AEZs, and identifies 2001 crop and forest extent and production for each region by AEZ for specific crop and forest types.<sup>4</sup> Details

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<sup>3</sup> GTAP Working Paper No. 43

<sup>4</sup> The AEZs represent six different lengths of growing period (6 x 60 day intervals) spread over three different climatic zones (tropical, temperate and boreal). Following the work of the FAO and IIASA (2000), the length of growing period depends on temperature, precipitation, soil characteristics and topography. The suitability of each AEZ for production of alternative crops and livestock is based on

are offered in chapters 2<sup>5</sup> and 4<sup>6</sup> of this book, although readers should note that our chapter is based on an earlier version of the GTAP land data base, the database detailed in Lee et al. (2005).

Table 2 reports the aggregated land rents for crops, livestock and forestry (at market prices) for the three regions and six aggregated AEZs.<sup>7</sup> From Table 2 we can see the relative economic importance (land rental share) of each AEZ in each region of our model. From this aggregation it is clear that AEZ6 dominates the economic value of land in China, while AEZ4 dominates in the USA. Not surprisingly, given that it is not far from the global aggregate, ROW land rents are more evenly spread across AEZs, with AEZs 3 – 6 all generating significant economic activity.

## 2.2 Economic Behavior

The basic (non-forestry) production function in the GTAP-AEZ framework is given in Figure 1. The model specification of forestry production and the treatment of output-related emissions are discussed later. From Figure 1, it can be seen that conventional output (i.e. output as measured in the standard GTAP data base) is a function of all intermediate inputs and a value-added composite. These factors of production substitute amongst one another with the ease of substitution governed by the parameter  $\sigma_T$ . As with the standard GTAP model, value-added is a composite of skilled and unskilled labor, capital, land, and natural resources (in the case of the extraction sectors). The land input is an aggregation of the diverse AEZs, which merits further discussion.

The most natural approach to bringing the AEZ dimension into the GTAP model would be to have a different production activity for each AEZ/product combination, with the resulting outputs (e.g., wheat) competing in the product markets. However, with as many as 18 AEZs potentially available in the current data base, and even more likely to emerge in future versions of the data base, this results in a great proliferation of sub-sectors and hence dimensions and data needs in the model (with each sector sourcing domestic and imported inputs from all other sectors.) Such a proliferation of sectors would substantially complicate solving the model, particularly in the context of dynamic modeling, without offering additional insight into how land markets adjust in response to climate policy. In an effort to simplify the model structure, while preserving its economic content, we propose a single, national production function, with multiple AEZ inputs, as shown in Figure 1.

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currently observed practices, so that the competition for land within a given AEZ across uses is constrained to include activities that have been observed to take place in that AEZ.

<sup>5</sup> GTAP Working Paper No. 40

<sup>6</sup> GTAP Working Paper No. 42

<sup>7</sup> To simplify our presentation, we aggregated the land rents across climatic zones for each length of growing period (e.g., we aggregated land rents from AEZs 1, 7, and 13, which have the same 1-60 day growing period). Therefore, AEZ1 in Table 1 represents all boreal, temperate, and tropical lands with a 1-60 day growing period, while AEZ6 represents all land with growing periods of over 300-days.

What are the implications of this specification? And how should the substitutability amongst AEZs be evaluated? To answer these questions, we must think through the economic implications of a model in which there is a different production function for each product produced on each AEZ. Of course the same products produced in the same region must share a common price, since they are perfect substitutes in use. If, as we assume, production functions are similar across AEZs, and the firms face the same prices for non-land factors, then land rents in comparable activities must move together (even if they do not share the same initial level). In this case, from the point of view of land markets -- the focus of this chapter -- the returns to land on different AEZs employed in the production of the same product must move together. This suggests a very high elasticity of substitution between AEZs in the national production function specification.

This argument can be developed more formally, beginning from the zero profit condition, as dictated by the maintained hypothesis of perfect competition. We know that for zero profits to hold, the percentage change in output price for AEZ  $j$ ,  $p_j$ , must equal the cost share-weighted sum of the percentage changes in input prices  $w_{ij}$  for all inputs  $L_{ij}$  used in production of output  $q_j$  :

$$p_j = \sum_i \theta_{ij} w_{ij} \quad (1)$$

where  $\theta_{ij} = w_{ij} L_{ij} / p_j q_j$ . In the context of a global model, where there is a single factor market clearing condition for the non-land factors in each country, there must be a unique market price for non-land inputs (e.g., fertilizer, or labor), so  $w_{ij} = w_{ik}$  for input  $i$  used in AEZs  $j$  and  $k$ .<sup>8</sup> Similarly, if two sub-sectors produce an identical commodity (e.g., wheat), then product prices will be the same, so their percentage changes will also be equal:  $p_j = p_k$ . If, in addition, we make the assumption that *non-land* input-output ratios ( $L_{ij} / q_j$ : e.g., kilograms of fertilizer per bushel of maize – note that this is *not* fertilizer use per hectare) are the same across AEZs, then the non-land cost shares must also be equalized across sectors:  $\theta_{ij} = \theta_{ik}$ .<sup>9</sup> Therefore, we have the following result, where the  $L$  subscript refers to land, and subscripts  $j$  and  $k$  refer to different AEZs producing the same product:

$$\theta_{Lj} w_{Lj} = p_j - \sum_{i \neq L} \theta_{ij} w_{ij} = p_k - \sum_{i \neq L} \theta_{ik} w_{ik} = \theta_{Lk} w_{Lk} \quad (2)$$

From (2) we see that the cost-share weighted percentage change in land rents across sectors must be equalized. Furthermore, since the cost shares must sum to one, and since

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<sup>8</sup> Of course, the firms' factor prices could differ due to taxes or subsidies that varied by AEZ sub-sector, but we do not have data at this level of detail (taxes are only reported at the sector level).

<sup>9</sup> The assumption of equal non-land factor intensities could be questioned. For example, the labor intensity (hours/bushel of corn) might be higher on low productivity land, and pesticide use could vary with rainfall or frost days. However, the only data available to us is that for the entire corn sector at the national level. So we have no real choice other than to make this assumption.

the cost shares for non-land inputs across AEZs are equal as a consequence of equal input prices and equal input-output ratios, then so too must the land cost shares be equalized across AEZs. Importantly, this *does not imply* that the *level* of land rents will be equalized across AEZs. With differing crop yields, *land rents must vary in direct proportion to yield*, so that a low yield (high input-output ratio for land) will be precisely offset by a low level of land rents, thereby resulting in an equalization of land cost shares across AEZs.

Since, to a first-order approximation, the cost shares may be considered constant, equation (2) implies that the percentage change in land rents in the production of a given (homogeneous) commodity must (to a first-order approximation) be equalized across AEZs. This is accomplished in the context of the production function in Figure 1 by specifying a very high elasticity of substitution in use (we assume a value of 20 for parameter  $\sigma_{AEZ}$ ). In this way, we are assured that the return to land across AEZs, within a given use, will move closely together, as would be the case if we had modeled production of a given homogeneous commodity on each AEZ separately.

We constrain land supply across alternative uses (sectors), within a given AEZ, via a Constant Elasticity of Transformation (CET) frontier. This is the approach taken in the standard GTAP model (Hertel, 1997), and it is an effective means of restricting land mobility. In this specification, the absolute value of the CET parameter represents the upper bound (the case of an infinitesimal rental share for that use) on the elasticity of supply to a given use of land in response to a change in its rental rate. The lower bound on this supply elasticity is zero (the case of a unitary rental share – whereby all land is already devoted to that activity). Furthermore, we follow the nested CET approach of ABARE (Ahammad, 2006). In this framework (see Figure 2), land owners first decide on the optimal mix among crops. Based on the composite return to land in crop production, relative to the return in ruminant livestock production, the land owner then decides on the allocation of land between these two broad types of agricultural activities. This also determines the average return to land allocated to farming in general. This return is, in turn, compared to that in forestry in order to determine the broad allocation of land between these two land-using sectors.

Calibration of the constant elasticity of transformation land supply functions in the model is based on the available econometric evidence. The most important elasticity in this paper will be the elasticity of land supply to forestry, as forest sequestration subsidies send a strong signal to expand forest land. Recent evidence for the United States (US) from Choi (2004) indicates that this elasticity averages about 0.25. Accordingly, we set the CET parameter at the bottom of this supply tree ( $\Omega_1$ ) equal to -0.25. This places the maximum forest land supply elasticity at 0.25. In AEZs where the forest land share is dominant, the supply elasticity will be much smaller, as would be expected. At the top of the supply tree where land is supplied to individual crops, we employ the elasticity from the standard GTAP model. The GTAP model uses a CET value of -1.0, based on econometric evidence for land supplies to US crop sectors, which suggests an upper bound of one on this elasticity. Accordingly, we set  $\Omega_3 = -1.0$ . The transformation possibilities between grazing and crops uses are deemed to be somewhat smaller, yet



larger in absolute value than the elasticity of transformation between forestry and agricultural land, therefore we set this parameter between these two values:  $\Omega_2 = -0.5$ , so that the degree of land mobility doubles at each nest as one moves up the land supply “tree” described by this nested CET function.

### 2.3 Modeling GHG emissions abatement

The modeling presented here considers only non-CO<sub>2</sub> emissions from agriculture and carbon sequestration in forests. Given our interest in land-use modeling and goal of elucidating land competition and the opportunity costs of alternative land based mitigation, we focus on the evaluation of emissions and sequestration associated with land use.<sup>10</sup>

#### *Base Emissions*

Base year non- CO<sub>2</sub> emissions are summarized in Figure 3 for the three focus regions for this study: USA, China and the Rest Of World (ROW). From this figure it can be seen that non-CO<sub>2</sub> emissions from agriculture (crops and livestock: sector numbers 1 - 5) represent well over 50% of the China and ROW total non-CO<sub>2</sub> equivalent emissions and just under half of the U.S. non-CO<sub>2</sub> emissions. Table 2 summarizes the types of non-CO<sub>2</sub> carbon-equivalent emissions produced by each of the agricultural sectors in million metric tonnes of carbon equivalent (MMTCE). In the case of USA, methane emissions from enteric fermentation, as well as nitrous oxide emissions from crops are dominant. These sources are also important in China. However, to this we must add methane emissions from paddy rice cultivation. China also has sizable methane emissions from its production of pigs and other non-ruminants. In the rest of the world, the top categories of emissions are methane gas from ruminant livestock production, paddy rice cultivation and biomass burning, and nitrous oxide emissions associated with nitrogen applications to crops and pasture lands. From the “Region total” column of Table 2, we see that the US and China account for 11% and 25% of global non-CO<sub>2</sub> emissions, respectively.

The GTAP non-CO<sub>2</sub> dataset from which these figures were drawn was developed from a detailed non-CO<sub>2</sub> greenhouse gas emissions database specifically designed for use in global economic models (Rose et al., 2007c). The dataset has a disaggregated emissions structure that maps directly to countries and economic sectors and facilitates utilization of available input activity quantity data, such as energy volumes and land-use acreage. The disaggregated structure of the dataset improves modeling capacity for representing actual emitting activities and abatement strategies. See Chapter 5<sup>11</sup> for an overview of the data

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<sup>10</sup> We have intentionally omitted fossil fuel combustion CO<sub>2</sub> emissions. In addition, other CO<sub>2</sub> emissions/sequestration and mitigation options are also not considered in this analysis. Of particular relevance here are biomass burning as well as soil carbon stocks. These emissions and sequestration categories will be integrated into the GTAP GHG emissions datasets in the future. Agricultural biomass burning non-CO<sub>2</sub> emissions are currently included.

<sup>11</sup> GTAP Working Paper No. 43

and Rose et al. (2007b) for a full description of the methods used in mapping the raw non-CO<sub>2</sub> emissions data into the GTAP version 6 database's region and sector structure. In this paper we focus only on the non-CO<sub>2</sub> related to drivers in the land-using sectors. Similar methods could be used to incorporate emissions in the industrial and services sectors of the economy.

In order to model GHG emissions and the marginal cost of abatement, we have further modified the standard model in a number of ways. We model three categories of non-CO<sub>2</sub> emissions drivers: primary factor inputs (endowments), intermediate inputs, and outputs. Emissions are assumed to fluctuate in proportion to changes in the level of a given driver. For example, increased fertilizer usage in the production of maize is associated with higher levels of N<sub>2</sub>O emissions.<sup>12</sup> We first consider how the emissions taxes are introduced into the model, and then how the model's response to these taxes is calibrated to outside cost estimates.

### *Introducing a Specific Tax on GHG-emissions*

Consider the specification of a tax associated with GHG emissions stemming from the use of inputs. These are specific taxes – that is, they depend on the quantity of emissions (in tonnes of carbon equivalent) – so they must be converted to *ad valorem* equivalent form in order to interact with the remaining tax system in the model. It is instructive to see how this works:

$$\Delta t_{ijr} = \Delta t o_{ijr} + [\varphi_{ijr} / PM_{ir}] \cdot [\Delta \tau_{ijr} - (\tau_{ijr} / PM_{ir}) \cdot \Delta PM_{ir}]$$

The left hand side of this equation represents the *change* in the *ad valorem* tax rate on input *i* in production of commodity *j* in region *r* (e.g., fertilizer used in corn production). This depends on the change in the ordinary, *ad valorem*, tax,  $\Delta t o_{ijr}$ , the change in the specific tax,  $\Delta \tau_{ijr}$ , and the change in the market price of the input in question:  $\Delta PM_{ir}$ . Assume for the time being that the ordinary tax does not change and the input is in perfectly elastic supply, so the price does not change. Then the change in the *ad valorem* tax on fertilizer use in corn production depends on the change in the specific tax on the associated emissions, adjusted for the emissions intensity of fertilizer. The latter is just total emissions from fertilizer use in corn production in a given region, divided by the amount of fertilizer used. We denote this emissions intensity:  $\varphi_{ijr}$ . We must divide this by the price of fertilizer,  $PM_{ir}$ , to obtain the coefficient in brackets [.] in the equation above, which simply represents tonnes of emissions, per dollar of fertilizer inputs purchased, valued at market prices.

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<sup>12</sup> Of course in the context of constructing an emissions baseline, one might wish to also consider exogenous adjustments to emissions factors over time, especially over long time horizons, as technologies evolve. This would be handled in our model via exogenous technical change along a baseline path.

So the economic impact of an emissions tax associated with input usage will depend not only on the size of the tax, but also on the emissions intensity of the input.<sup>13</sup> The larger this intensity, the greater the impact of a given \$/tonne tax on the input in question. Table 3 reports some key emissions intensities from the model for USA and China. (These are derived by combining the non-CO<sub>2</sub> emissions data base from Chapter 5<sup>14</sup> with the version 6, 2001, GTAP data base.) The USA has the highest emissions intensity for fertilizer use in crop production, while China has much higher emissions intensities than the other regions for ruminant livestock capital and paddy rice acreage. These are the activities/regions where we expect to see relatively stronger reductions in emissions following a uniform global carbon tax.

### *Mitigation responses*

In keeping with most CGE analysis, the extended GTAP-AEZ model represents technology via a set of production functions in which the key parameters are elasticities of substitution amongst groups of inputs. These may be viewed as smooth approximations to dozens – even hundreds -- of underlying technologies, each with their own factor intensities. As the price of one input, say fertilizer, rises, firms are expected to adopt less fertilizer-intensive practices. In our framework, the scope for conservation of fertilizer is captured by the elasticity of substitution between fertilizer and other inputs. If this is large, then a small tax on fertilizer use will induce a large reduction in fertilizer use. If the elasticity is small, then it will take a large tax to induce a significant reduction in fertilizer usage at a given level of crop output. These elasticities of substitution are therefore key to determining the marginal abatement cost for emissions from various activities in our model. This section discusses how the GTAP-AEZ GHG abatement response schedules are derived and how they are calibrated to alternative abatement technologies.

#### *Case 1: Emissions tied to the level of usage of a given input*

There are many non-CO<sub>2</sub> emissions that are closely related to input use. Nitrous oxide emissions from fertilizer usage and methane emissions from livestock are two obvious examples. Tying emissions to particular inputs allows for a more refined representation of abatement responses with emissions being managed via adjustments to individual inputs and production maintained via input substitution. In these cases, we have two choices: (1) follow the approach typically used for CO<sub>2</sub> abatement associated with energy fossil fuel combustion, and use the best possible econometric evidence on substitution elasticities amongst inputs; thereby, letting the GTAP-AEZ abatement response schedules fall where they may, or (2) adjusting the elasticities of substitution to an externally estimated degree of abatement response. The advantage of the latter approach is that it permits us to draw on detailed engineering studies which are directly pertinent to the issue at hand—emissions abatement. We have chosen the latter approach.

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<sup>13</sup> The tax on emissions is rebated to the regional household in the same way any tax would be re-circulated in the GTAP model.

<sup>14</sup> GTAP Working Paper No. 43

The U.S. Environmental Protection Agency (USEPA) has estimated the engineering mitigation costs and emissions implications for alternative management strategies for significant agricultural non-CO<sub>2</sub> emissions sources—paddy rice, other croplands (wheat, maize, soybean), and livestock enteric and manure emissions (USEPA, 2006). From these data, we constructed mitigation response curves for calibration purposes that correspond to the GTAP-AEZ region and sector structure.<sup>15</sup> USEPA (2006) also guided us in choosing the drivers associated with the derived mitigation response curves for the GTAP-AEZ land-using sectors. For example, methane emissions associated with paddy rice production are tied to acreage, as the emissions tend to be proportional to the amount of paddy land. Nitrous oxide emissions from maize production are tied to fertilizer use, while methane emissions associated with ruminants are tied to the ruminant (capital) stock. In those cases where a specific input is not associated with emissions, the driver is assumed to be output.

Refer again to the overall GTAP-AEZ production structure in Figure 1. In calibrating to the abatement possibilities associated with input-related emissions, we utilize the two input-related elasticities of substitution:  $\sigma_T$ , the elasticity of substitution between intermediate inputs, and  $\sigma_{VA}$ , the elasticity of substitution between primary factors.

In calibrating the model, we matched the partial equilibrium assumptions of the engineering cost estimates by fixing output levels in the sectors, as well as input prices. We then vary the carbon equivalent price to map out a partial equilibrium abatement response for the relevant sector in each region. Depending on the emissions source, one of the two input elasticities is adjusted so that the model mimics the estimated reduction in emissions obtained from the engineering based response curve. In particular, we target the response at \$50/tCeq. Table 4 reports the resulting elasticities of substitution among inputs obtained through this exercise.

Figure 4 illustrates the results from the calibration of the USA cropland emissions mitigation response associated with fertilizer use. The piecewise linear abatement cost schedule is obtained from the USEPA (2006), depicting the potential for emissions abatement (% of total current emissions), holding output constant. The smooth curve in Figure 4 is obtained from the calibrated GTAP-AEZ model. This figure highlights a number of important calibration issues. First, the USEPA cost curves estimate what are referred to as “no regrets” options at negative carbon equivalent prices. These options are described as profitable, but currently not adopted. As with Hyman et al. (2003), we assume that unaccounted for costs and barriers prevent the implementation of such no-regrets options and their associated emissions reduction benefits are assumed to be illusory. Therefore, our calibrated MAC curve begins at the origin and rises smoothly to the point of calibration (\$50/tCeq).

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<sup>15</sup> USEPA (2006b) year 2000 mitigation cost curves were used for calibrating the agriculture sectors.

Another calibration issue stems from the fact that the USEPA estimates represent a limited set of discrete technologies. This creates two problems for this sort of calibration: some sections of the cost response curves are non-differentiable; and, eventually all currently envisioned mitigation options are exhausted. The substitution elasticity approach cannot account for either of these characteristics. Instead, the elasticities provide smooth abatement cost curve, which may imply unrealistic abatement possibilities at very high levels of taxation. Of course additional technologies may become available when prices reach a high level. However, this is purely speculative, and so we must be wary of using this current representation outside of its calibration range. Accordingly, we restrict our analysis to carbon taxes below \$100/tC at which point abatement is slightly larger than the maximum identified in the EPA study.

*Case 2: Emissions not directly related to input use*

In other cases, it may be difficult to tie emissions directly to specific input usage. Here, it is most natural to tie emissions to the aggregate output of the sector. However, if we attempt to mitigate emissions by simply taxing output, the only vehicle for emissions reduction is to reduce the total production in the sector. This seems unrealistic, as engineering analyses suggest that – for a cost – emissions per unit of output can often be reduced, i.e., the partial equilibrium, output-constant, abatement response curve is rarely vertical at the origin. In order to capture this possibility, we follow the approach developed by Hyman et al. (2003) for use in MIT’s EPPA model. This involves modifying the GTAP data base in order to treat emissions as an “input” to the production process. Furthermore, a non-zero elasticity of substitution between emissions and all other inputs,  $\sigma_{qomac}$  in Figure 1, suggests that the emissions intensity of the industry can be reduced by substituting (all) other inputs for emissions. This can be thought of as buying new machinery, hiring additional labor, employing higher quality inputs, etc.

## 2.4 Forest Carbon Sequestration

Forest carbon stocks can be increased by increasing the biomass of existing forest acreage (the intensive margin) or by converting non-forest lands to forests (the extensive margin). Using the partial equilibrium, dynamic optimization model of global timber markets and carbon stocks described in Sohngen and Mendelsohn (2007), we have generated regional forest carbon supply curves.<sup>16</sup> We refer to this model throughout as the "global timber model". (See also Chapter 11<sup>17</sup> in the current volume for an overview of the modeling issues relating to modeling forestry in general, and carbon forest sequestration in particular.) When incentives for carbon sequestration (carbon prices) are

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<sup>16</sup> The model described in Sohngen and Mendelsohn (2007) maximizes the net present value of consumers’ surplus in timber markets less costs of managing, harvesting, and holding forests. In so doing, it determines the optimal age of harvesting trees (and thus the quantity harvested) in accessible regions, the area of inaccessible timber harvested, the area of land converted to agriculture, and timber management endogenously.

<sup>17</sup> GTAP Working Paper No. 49

introduced in the global timber model, the endogenous variables (harvest age, harvest area, land use change, and timberland management) adjust in order to maximize net surplus in the timber market and the benefits from carbon sequestration. Cumulative carbon sequestration in each period is calculated as the difference between total carbon stored in the carbon price scenario and that recorded in the baseline (no carbon prices). Annual sequestration can then be estimated from the decadal changes in cumulative sequestration. Cumulative and annual sequestration is calculated for each of the 3 aggregate regions in the model, and the results are reported in Table 5. We will turn to the specific entries momentarily.

The global timber model used in this analysis is a long-run model that simulates carbon sequestration potential by decade for 100 years. In this paper, however, we are interested in the annual sequestration potential over the first two decades because our comparative static, general equilibrium analysis focuses on the potential sequestration of a single “representative” year within this 20 year period. To make the link between the two types of models (dynamic partial equilibrium and static general equilibrium models), a projection of cumulative sequestration by the end of the first and second decades is used to calculate the present value carbon equivalent over the first 20 year period. Then, this present value amount is used to calculate the *annual equivalent* amount of carbon. Because the global timber model assumes a 5% discount rate, both the present value carbon and annual equivalent amount are calculated based on this same 5% discount rate.

Carbon sequestration in each region can be decomposed into the amount derived from land use change, aging of timber, and modified management of existing forests. The land use change component is what we refer to as the “extensive” margin, and it is reported in the first column of Table 5. These entries are determined by assessing the annual change in forestland area, tracking new hectares in forests (compared to the baseline), and tracking the carbon on those hectares. For regions that undergo afforestation in response to carbon policies (predominantly temperate regions), carbon in new hectares is tracked by age class so that the accumulation of carbon on new hectares occurs only as fast as the forests grow. For regions where reductions in deforestation are a primary action in climate policy (typically tropical countries), the reductions in deforestation have an instantaneous effect on carbon (because they maintain a carbon stock that would otherwise be lost). Reductions in deforestation have a very small impact on storage of carbon in the temperate forests of the U.S. and China. Thus smaller benefits from land use change are expected in initial periods in these two countries, while larger benefits are expected in tropical regions in initial periods. Indeed, we see this in Table 5, where the carbon storage at \$5/tC due to land use change is very small in US and China, whereas it is quite large (143 MMTCE on an annualized basis) in the ROW region. Thus the extensive margin portion of the forest sequestration abatement supply curve for ROW is quite flat initially (see Figure 5).

The combined effect of management and aging represent the “intensive” margin for sequestration, as they reflect the stock of carbon per unit of forestland. The aging component is estimated by comparing the carbon that accrues in forests under the particular carbon price scenario examined versus the carbon that would have accrued in

the carbon price scenario timberland area (and management intensity) if managed with the baseline age classes.<sup>18</sup> The management component is estimated by comparing the carbon sequestered under the carbon price scenario to the carbon sequestered assuming the carbon price scenario forest area and age classes are managed with the baseline management intensities. The forestry model's predictions for annualized sequestration at the intensive margin at each carbon price in the first 20 years are reported in the second column of Table 5. Figure 6 graphs the annual total sequestration rate on this intensive margin for the USA, in response to a carbon subsidy ranging from \$1/tC to \$200/tC. Again, remember that these annual rates have been computed using a 20 year time horizon. Extending this horizon further would increase the potential for sequestration as longer term adjustments would be taken into account. Clearly the potential for increasing the forest carbon stock at the intensive margin is considerable —particularly in the range of interest in this paper, namely up to \$100/tC.

The remaining two columns in Table 5 refer to aspects of the global timber model sequestration estimates that we do not take into account. The first of these is carbon storage in wood products. With more wood products sold, the potential for carbon losses as these products are used increases. This could be accounted for in our framework, since we do follow the wood products through the marketing channel, and tracing them eventually to consumers. However, we have not yet estimated the carbon content of these flows and the associated stocks in our model. The second aspect that we ignore is the potential for setting aside forests at the accessible/inaccessible margin in temperate and boreal regions. Here, we only focus on the competition between forest and agricultural land in these regions.

In summary, we find that, at the lower end of the price range investigated (e.g., \$5 - \$50/tC), forests in the U.S. could potentially sequester 0.4 – 95.5 million tonnes of carbon per year over the first 20 years (Table 5). These estimates are consistent with a recent detailed national assessment of U.S. sequestration potential in forestry, which suggests that for \$55/tC, up to 88.8 million tonnes of carbon per year could be sequestered in U.S. forests (Murray et al., 2005). China is estimated to have more overall potential for sequestration over similar carbon price ranges, with up to 130 million tonnes of carbon per year possible at the carbon price of \$50/tC. As prices rise above \$50/tC, sequestration potential increases. Together, the U.S. and China constitute about 13% of global potential sequestration over the next 20 years. This is a surprisingly large proportion of the total carbon given that these countries contain only about 10% of the world's total forestland. However, these estimates suggest that there is substantial potential to increase carbon by forest management in the near-term.

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<sup>18</sup> The algorithm used to calculate carbon due to aging does not distinguish between old and new hectares. Thus, if hectares newly forested in the mitigation scenario are eventually harvested in an age class older than the baseline age class, the carbon associated with longer rotations are counted as aging rather than as part of the afforestation component. This type of interaction between the extensive and intensive margins can give rise to negative contributions to sequestration at very low carbon prices (see the US entry for \$5/TCE in Table 5).

To include such potential forest mitigation strategies in the GTAP-AEZ model, we modify the production structure of the forest sector as shown in Figure 7. We apply the sequestration subsidy to an augmented land input that includes both composite land (aggregated AEZs in forestry) as well as own-use of forestry products in the forestry sector. These are allowed to substitute in production with an elasticity of substitution equal to  $\sigma_{carbon}$ . While such a grouping of inputs may not appear intuitive at first glance, it works well to mimic the two margins along which forest carbon can be increased, namely the intensive margin (modified management and aging) and the extensive margin (more land in forests).

The equation for determining the change in the *ad valorem* sequestration tax (subsidy) for forestry is the following:

$$\Delta ts_{ijr} = [\alpha_{ijr} / PMC_{jr}] \cdot [\Delta \tau s_{ijr} - (\tau s_{ijr} / PMC_{jr}) \cdot \Delta PMC_{jr}]$$

The left hand side of this equation represents the change in the *ad valorem* sequestration tax rate (this will be negative for a subsidy) on carbon-augmented land. This depends on the change in the specific tax rate,  $\Delta \tau s_{ijr}$ , and the change in the price of carbon-augmented land:  $\Delta PMC_{jr}$ . Clearly, as with the tax on emission-related inputs, the market impact of a change in the sequestration subsidy will depend on the carbon intensity of the forests,  $\alpha_{ijr} / PMC_{jr}$ . These intensity levels (reported in Table 3) are calibrated to reproduce the behavior at the *extensive* margin reported in Table 5. Specifically, if we set  $\sigma_{carbon} = 0$  in Figure 7, then the effect of the sequestration subsidy will be to increase the profitability of forest activities under current management practices, thereby leading to an expansion of forest land with constant carbon intensity. Total forest carbon is increased simply by increasing the total area in forest. This is the extensive margin and it is calibrated to the \$100/tC estimates in Table 5 by adjusting the incremental annual carbon intensity of forests. The calibrated values are reported in Table 3. The calibrated carbon intensity is larger in ROW than in China and USA, therefore advantaging ROW in the matter of forest carbon sequestration, as suggested by the estimates in Table 5 and the flat ROW abatement cost curve in Figure 5.

The forest carbon sequestration curve obtained from the model via the extensive margin for the ROW region is reported in Figure 5. By design, the GTAP-AEZ mitigation cost curve intersects that of the global timber model at the calibration point of \$100/tC. The two curves are quite similar up to the \$100/tC level. However, after that point, the calibrated MAC (dark line) has considerably more curvature than that displayed by the global timber model. It is important to note that the global timber model does not have a fully developed land competition model, and consequently, may over-estimate potential sequestration at the higher carbon prices. Thus, for this analysis, we restrict our attention to carbon prices below \$100/tC.

In contrast to the extensive margin, we calibrate the intensive margin response by fixing the total land in forestry (set  $\Omega_1 = 0$  in Figure 2), and introducing  $\sigma_{carbon} > 0$  in the forestry production function (Figure 7). In this case, as forest carbon rents rise, the



subsidy will encourage an increase in the carbon intensity of forest sector output. In our model this is reflected in a substitution of forestry product for land. This has the effect of *reducing net forestry output* from the sector (net output is gross output produced in this production function, less own-use – a key input in the forest carbon bundle), and thereby increasing the carbon intensity per unit of net output. In effect, *producers are choosing to sacrifice some sales of commercial timber by adopting production practices that increase the carbon content on existing forest land*. This is the intensive sequestration margin, and it is calibrated by adjusting  $\sigma_{carbon}$  until GTAP-AEZ produces the desired level of carbon sequestration at the \$100/tC level of subsidy. The calibrated forest carbon sequestration supply curve via the intensive margin is the dark curve shown in Figure 6 for the USA. We can see that this formulation of the GTAP-AEZ model permits us to replicate abatement costs from the dynamic timber model quite well for subsidies under \$100/tC.

### 3. Results

In order to illustrate how this analytical framework operates, and some of the insights that it can deliver, we present results from simulations that only apply a carbon tax to one region. These simulations highlight the two key mechanisms at work in the model: competition in international product markets and competition for land. Competition for land occurs within and across sectors within the abating region, and spills over to influence land competition within the non-abating regions where leakage is observed to occur through product markets. Specifically, consider the impact of a \$100/tC carbon equivalent tax *in the USA alone*. The resulting percentage change in land rents across AEZs within sectors is nearly identical (Panel 1, Table 6). This follows from our assumption of very high substitutability ( $\sigma_{AEZ} = 20$ ) between AEZs in a given use, which is an implication of the assumptions of perfect competition and homogeneous products across AEZs.

Looking at the particular sectors in Panel 1, we see that the returns to land in paddy rice production fall sharply as the tax on methane emissions from rice production hits returns to land in this use very hard. Returns to land in the other land-using sectors rise. The large rise in forestry land rents is a direct consequence of the CO<sub>2</sub> sequestration subsidy which lowers the cost of land to forestry and increases the return to land owners. The size of the increase in forest land rents is driven by the relatively small share of land in total costs in this sector in the original GTAP data base. More recent estimates suggest that this share is a substantial under-estimate (see Chapter 4<sup>19</sup> in this volume). Making this adjustment would, in turn, greatly reduce the *percentage* increase in land rents following the sequestration subsidy. The rise in other grains, other crops, and ruminant land rents is

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a consequence of the combined effects of the increased demand for land by the forest sector and the carbon tax on non-land input use, e.g., fertilizer and ruminant capital. In the case of the latter effect, producers respond by substituting land (and other inputs) for the taxed input, the cost of which has risen substantially.

Changes in land rents dictate changes in land use (Panel 2, Table 6). Land in commercial forestry increases as expected, while land in paddy rice declines with the CO<sub>2</sub> tax. In other crops and ruminants, land area increases in the shorter length-of-growing period AEZ land types (2 and 3) and decreases in longer length-of-growing period AEZ land (5 and 6) where forestry is more dominant. The latter change provides GHG emissions benefits, while the former offsets lost production.

One way to consider the economic significance of these changes in land use is to scale the percentage change in land use (Panel 2, Table 6) by the share of a given AEZ's land rents generated by each activity in the base period data (Panel 3, Table 6). With this scaling, it becomes apparent (Panel 4, Table 6) that the expansion in other crop and ruminant land uses are relatively more important in the shorter length of growing period AEZ land classes relative to forestry. Thus cropland moves primarily into grazing activities in AEZs 2 and 3. On the other hand, the direction of the land movement differs in the longer length of growing period AEZs (5 and 6) where grazing is relatively less important. In these more productive AEZs, forestry becomes much more important (particularly in AEZ 6 where land rents from forestry reach about 10% of total land rents).

Abatement supply schedules can be developed with the model by imposing a range of carbon taxes on the USA only, beginning with \$5/tC and ending with \$100/tC (Figure 8). At \$5/tC, forestry and agriculture are of roughly equal importance, however, at higher carbon prices, the agriculture abatement schedule is more inelastic than the forestry sequestration schedule. By \$10/tC, forest sequestration accounts for double the abatement of agriculture, and by the time the carbon price reaches \$50/tC, it is roughly four times as large.

About half of total forest sequestration at \$50/tC results from intensification (i.e., the amount of sequestration that would occur if no additional land moved into forestry). Given the short time-frame of this modeling analysis, this large amount of sequestration is largely due to changes in rotation ages in forestry. Forest intensification has two different effects on emissions from agriculture. On the one hand, it bids land away from agriculture production, thereby reducing output and hence emissions – particularly of those GHG emissions linked to land use. On the other hand, it encourages more intensive production on the remaining land in agriculture. In a separate simulation of the forest sequestration subsidy alone, our model suggests that the former effect dominates, and overall agriculture emissions are somewhat reduced as a result of the forest sequestration alone. Of course, when these emissions are also taxed, as in Figure 8, the emissions reduction in agriculture is greater due to the abatement incentive.

In summary, our results for the U.S. indicate that about 20 million tonnes of carbon equivalent can be abated each year in the agricultural sector and about 120 million tonnes of carbon equivalent can be sequestered in the forestry sector at a carbon price of \$50/tC. It is instructive to compare these estimates to others in the literature. For similar prices, Murray et al. (2005) find that approximately 9 million t Ceq of CH<sub>4</sub> and N<sub>2</sub>O emissions can be abated in the agricultural sector annually, and about 97 million t Ceq per year can be sequestered in the forestry sector. It is difficult to know for certain what drives these differences without more explicit examination and comparison of the modeling approaches and results. However, it is worth noting that the Murray et al. (2005) study models the United States with more limited links to the rest of the world. In contrast, this study models interactions across all global regions in all markets (inputs and outputs). Thus, one would expect that our analysis of carbon taxes only in the U.S. would lead to lower marginal cost estimates. In our model, if carbon taxes are applied only in the U.S., input and output price effects in the U.S. agricultural and forestry sectors are moderated by responses in other countries. In the US model of Murray et al. (2005), where these responses are more limited, one would expect stronger price changes, and consequently higher marginal costs for abatement and sequestration.

Within the agricultural sector, the largest share of abatement occurs in the "other grain" category (mainly maize), followed by "other crops" and "ruminants", for this particular *USA-only* carbon tax scenario (Figure 9). Abatement in rice and non-ruminants is quite modest in the US, even at our calibration point of \$50/tC, in response to a US-only carbon tax.

Perhaps not surprisingly, there are relatively large leakage effects with an USA-only carbon tax policy on emissions in ROW. The changes in international trade balances simulated by the model indicate that the USA exports substantially less in the agricultural sector with a unilateral carbon tax (Table 7). The largest decrease occurs in the heavily traded other grains and crops sectors, followed closely by ruminants trade. This decline in net exports is made up by increased exports of forestry and wood products, as well as fertilizer and energy intensive manufactures, and other manufactures and services.<sup>20</sup>

In ROW and China, net agricultural exports expand to offset the reductions in USA. This is dominated by expansion in ROW, with China accounting for a very small increase in net farm exports. Note that the row totals (sum across countries) within this experiment do not equal zero due to the presence of trade and transport margins (difference between *cif* and *FOB* valuation of trade). The column totals reflect the change in trade balance for each region. These sum to zero (subject to rounding error) due to the general equilibrium requirement of global trade balance.

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<sup>20</sup> The increase in net forestry exports illustrates one difficulty associated with utilizing a static model that focuses on the short-run. Although our results indicate that the area of forests will increase in response to the carbon tax, forests in this region grow relatively slowly, so the simulated changes in output likely overstate the feasible level of short-term gains given this slow growth.

The expansion of net exports in ROW in response to the US-only carbon tax is fueled by an increase in production, as well as an intensification of production due to lower cost inputs. This, in turn, increases non-CO<sub>2</sub> emissions in ROW (Figure 10). The emissions leakage is roughly equal for other grains and for ruminant livestock products. While the increase in net exports is larger for other grains, this sector is less emissions intensive. Trade impacts are much smaller for non-ruminants, which are also much less emissions intensive, and so the ROW leakage in this sector is very small. There is also a small reduction in ROW emissions of methane from rice production (negative leakage, or abatement). This arises due to the fact that rice is less heavily traded than other grains, and so the net export impacts are much smaller. Therefore, the direct impact on production from increased net exports in ROW is quite small, and this increased production is met via increased yields instead of increased land area. (Land rents in ROW are rising in the wake of increased demand for land in agriculture – particularly in other grains production.) Indeed, the area in rice production in ROW actually declines slightly, hence the decline in paddy rice-related emissions.

Figure 11 broadens the leakage picture to include forestry, alongside aggregate agriculture leakage. Just as forestry dominates the abatement story in the US, it also dominates the leakage of emissions in ROW, in the wake of a US-only carbon tax. With higher prices for agricultural products following the carbon tax in the US, agriculture expands in ROW and this results in more rapid deforestation, and hence increased net GHG emissions in the rest of the world. At a carbon price of \$50/tC, this leakage is about 10% of the forestry abatement reported in the US. And it is about four times as large as the agriculture-related leakage. In contrast, total leakage in China following the \$50/tC carbon tax is only about one MMTceq., or just 5% of the leakage in ROW following the US only tax. Figure 11 also offers a breakout of forestry leakage by reporting the leakage which results solely from the intensification effect in ROW. In this case, the higher global price for commercial timber encourages less carbon-intensive production techniques in ROW. However, this effect reaches its maximum at the \$50/tC carbon price, after which all of the forestry leakage is through reductions in forest land area (the extensive component).

#### **4. Conclusions**

We have developed a computable general equilibrium model with unique regional land types, detailed non-CO<sub>2</sub> GHG emissions, and forest carbon stock intensification and extensification margins, in which particular emphasis is placed on managing land-based greenhouse gas emissions and forest carbon sequestration. Using this framework, we are able to evaluate the relative importance of specific non-CO<sub>2</sub> mitigation and forest carbon sequestration mitigation options in different economic sectors and regions. We found that biophysical and economic characteristics can create comparative abatement advantages for GHG mitigation, across sectors within a given country, and between the same sectors in different countries. These comparative advantages result in intra- and inter-regional reallocations of production across the global economy in response to carbon prices. We observe these general equilibrium effects in terms of emissions reductions/increased sequestration as well as production, land-use, overall input reallocation, and trade effects across all sectors. We also find that international trade influences regional mitigation

responses, as well as international GHG emissions leakage in land-based activities in response to a regional carbon policy.

We base our assessment of partial equilibrium, mitigation possibilities in agriculture on detailed engineering and agronomic studies completed by the US Environmental Protection Agency (USEPA, 2006). In the case of forestry, we draw on estimates of optimal sequestration responses to global forest carbon subsidies, estimated with the model described in Sohngen and Mendelsohn (2007). In our analysis of carbon taxation, we find that forest carbon sequestration is the dominant means for global GHG emissions reduction in the land using sectors. We consider two avenues for such carbon sequestration: intensive and extensive responses. The former effect is captured by fixing total land area in forestry and allowing the forestry sector to sacrifice commercial timber output in favor of increased carbon storage. We capture the latter effect by fixing the carbon intensity of forests and allowing total area to change..

In our simulations of a US-only carbon tax, we find evidence of significant linkages between emissions in one region and mitigation in another (i.e. leakage). For example, based on additional simulations undertaken with this model, we find that the abatement potential in US agriculture is cut in half when we move from a national tax to a global carbon tax. This is a consequence of the strong export orientation of US agriculture, which responds to reduced production in the rest of the world by increasing its own production and hence emissions.

In summary, we find the modified GTAP-AEZ model to be an extremely useful vehicle for integrating detailed emissions and abatement cost information into a global, general equilibrium framework, thereby permitting investigation of intersectoral competition for land and other inputs, as well as international competition in product markets. There are several natural extensions of this work which would be immediately useful. Firstly, apart from time and effort, there is no reason why this could not be extended to more regions. Given that the emissions and land use data bases are available for many countries, and the newest GTAP data base (version 7) is projected to have more than 100 regions, the constraining factors are just the underlying mitigation cost studies. A second extension of this approach would bring into the model non-CO<sub>2</sub> emissions from industrial and service sectors. These emissions data are also available from the EPA. In this context it would also make sense to include CO<sub>2</sub> emissions from fossil fuel combustion. This would permit a complete, multi-gas assessment of the global abatement potential in the wake of alternative carbon taxes.

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**Table 2. Total land rents at market prices by AEZ and region (million 2001 US\$)**

	USA	China	ROW	Total
AEZ1	1,590	405	5,373	7,368
AEZ2	5,340	3,352	18,309	27,001
AEZ3	3,011	6,076	44,896	53,983
AEZ4	17,669	5,550	68,465	91,684
AEZ5	7,219	9,365	43,199	59,783
AEZ6	8,465	22,631	32,908	64,005

**Table 2. Non-CO<sub>2</sub> GHG emissions by agricultural sector and emissions source and driver**

Emissions sources and drivers (drivers in parentheses) in MtCeq											
Methane (CH <sub>4</sub> )						Nitrous oxide (N <sub>2</sub> O)					Total
Enteric fermentation	Manure management	Rice cultivation	Biomass burning	Stationary and mobile combustion	Agricultural soils	Manure management	Pasture, range, and paddock	Biomass burning	Stationary and mobile combustion		
(Livestock capital stock)	(Livestock capital stock)	(Paddy rice area)	(Output)	(Output)	(Fertilizer use)	(Livestock capital stock)	(Livestock capital stock)	(Output)	(Output)		
<b>U.S.A.</b>											
Paddy Rice	0	0	2.051	0.003	0.001	0.914	0	0	0.002	0	3.0
Other Grain	0	0	0	0.085	0.012	37.557	0	0	0.05	0.004	37.7
Other Crops	0	0	0	0.129	0.013	23.485	0	0	0.075	0.004	23.7
Ruminants	30.869	5.058	0	0	0.005	0	2.913	9.932	0	0.001	48.8
Non-Ruminants	0.51	5.388	0	0	0.005	0	1.922	0.078	0	0.002	7.9
<i>Total</i>											<i>121.1</i>
<b>China</b>											
Paddy Rice	0	0	59.33	0	0.005	10.822	0	0	0	0.004	70.2
Other Grain	0	0	0	0	0.01	20.267	0	0	0	0.007	20.3
Other Crops	0	0	0	0	0.037	77.847	0	0	0	0.027	77.9
Ruminants	51.901	2.089	0	0.219	0.002	0	5.444	9.067	0.048	0.002	68.8
Non-Ruminants	2.981	4.577	0	0	0.028	0	11.928	22.351	0	0.02	41.9
<i>Total</i>											<i>279.0</i>
<b>ROW</b>											
Paddy Rice	0	0	107.957	0.437	0.016	28.783	0	0	0.159	0.012	137.4
Other Grain	0	0	0	1.136	0.095	99.65	0	0	0.413	0.069	101.4
Other Crops	0	0	0	2.862	0.244	162.894	0	0	1.04	0.179	167.2
Ruminants	380.44	25.968	0	52.962	0.071	0	17.671	141.256	11.711	0.052	630.1
Non-Ruminants	2.985	21.337	0	0	0.048	0	14.115	41.07	0	0.035	79.6
<i>Total</i>											<i>1115.7</i>
<b>World Total</b>											<i>1515.8</i>

**Table 3. Key emissions intensities (MtCeq/\$ of input)**

Emission intensities (MtCeq/\$ of input)				Forest carbon intensities* (MtCeq/\$ of land rent)		
Input	USA	China	ROW	USA	China	ROW
Fertilizer in crops production	0.0062	0.0044	0.0044	0.057	0.016	0.148
Ruminant livestock capital	0.0099	0.9562	0.0154			
Land in paddy rice	0.0040	0.0125	0.0049			

\*Adjusted forest carbon intensities to calibrate to Sohngen and Mendelsohn (2007) forest carbon response curves.

**Table 4. Elasticities of substitution: Shaded boxes denote elasticities calibrated for emissions mitigation and sequestration**

		Sectors					
		Paddy rice	Other grain	Other crops	Ruminants	Non-ruminants	Forest
Elasticity calibrated		Endowment (land)	Input (fertilizer)		Endowment (capital)	Endowment (capital)	
Intermediate input elasticities	USA	0.5	1.3	0.5	0	0	0.952**
	China	0.5	0.6	0.5	0	0	1.049**
	ROW	0.5	1.5	0.5	0	0	0.194**
Endowment elasticities	USA	1.1	0.237	0.237	0.191	2	0.2
	China	1.1	0.237	0.237	0.191	2	0.2
	ROW	1.1	0.237	0.237	0.191	2	0.2

\* \* Elasticity of substitution between own-use of forest products and land,  $\sigma_{carbon}$ , calibrated to reproduce the intensive sequestration response in forestry. Elasticity of substitution amongst intermediate inputs and value-added for crops is assumed to be equal to 0.5.

**Table 5. Carbon sequestration supply schedule\*: by category, annual equivalent abatement over 20 years (MtCeq)**

Carbon price	Extensive Margin	Intensive Margin	Wood Products	Access Margin**	Total
<b>US</b>					
5	1.672	-1.663	-0.476	0.839	0.371
10	3.509	6.802	-0.238	1.346	11.419
20	7.023	24.585	-0.084	2.866	34.390
50	17.811	73.503	-0.948	5.147	95.513
100	43.069	102.749	-0.132	9.298	154.986
200	118.287	119.006	1.667	19.931	258.893
500	270.741	286.616	0.537	25.322	583.216
<b>CHINA</b>					
5	0.440	3.018	-0.028	4.733	8.164
10	0.612	14.865	-0.282	9.966	25.161
20	1.210	26.899	-0.372	21.765	49.501
50	4.154	73.928	-1.532	53.501	130.051
100	12.797	98.522	-2.018	77.089	186.390
200	73.532	97.503	-1.325	77.089	246.799
500	108.663	202.142	-5.082	77.089	382.812
<b>ROW</b>					
5	143.218	31.572	-3.614	-19.259	151.917
10	281.670	78.626	-5.956	-2.370	351.969
20	539.266	114.936	-9.437	14.203	658.968
50	1203.164	250.691	-19.898	66.875	1500.832
100	1672.509	387.619	-29.708	80.424	2110.845
200	2189.741	366.732	-21.178	93.365	2628.660
500	2885.440	868.723	-47.496	103.227	3809.894

\* Calculated assuming a 5% discount rate using the model of Sohngen and Mendelsohn (2007)

\*\* Storage due to setting aside of forests at accessible margin in temperate and boreal regions only.

**Table 6. Percentage change in U.S.A. land rents and land use by sector following a \$100/tonne carbon tax in USA only**

<b>PANEL 1: Percentage change in land rents</b>					
	Forest	Paddy Rice	Other Grain	Other Crops	Ruminants
AEZ1	1247	-14	11	15	18
AEZ2	1244	-11	11	15	18
AEZ3	1244	-10	11	15	18
AEZ4	1246	-13	11	15	18
AEZ5	1251	-20	11	15	19
AEZ6	1259	-41	12	16	19

<b>PANEL 2: Percentage change in land use</b>					
	Forest	Paddy Rice	Other Grain	Other Crops	Ruminants
AEZ1	79	-27	-6	-2	-2
AEZ2	85	-21	-2	1	2
AEZ3	85	-21	-2	1	2
AEZ4	80	-25	-5	-2	-1
AEZ5	68	-36	-10	-7	-7
AEZ6	49	-58	-21	-18	-18

<b>PANEL 3: AEZ land rent shares</b>						
	Forest	Paddy Rice	Other Grain	Other Crops	Ruminants	Total
AEZ1	0.008	0.002	0.218	0.184	0.588	1
AEZ2	0	0.002	0.426	0.283	0.289	1
AEZ3	0	0.004	0.481	0.397	0.118	1
AEZ4	0.008	0.002	0.493	0.408	0.089	1
AEZ5	0.031	0.026	0.539	0.321	0.083	1
AEZ6	0.095	0.031	0.221	0.622	0.03	1

<b>PANEL 4: Percentage change in land use, weighted by AEZ land rent share</b>					
	Forest	Paddy Rice	Other Grain	Other Crops	Ruminants
AEZ1	2.8	-0.05	-1.16	-0.43	-1.11
AEZ2	0.14	-0.03	-0.92	0.34	0.48
AEZ3	0.15	-0.08	-0.9	0.6	0.24
AEZ4	2.99	-0.05	-2.2	-0.59	-0.09
AEZ5	8.01	-0.68	-4.48	-1.91	-0.5
AEZ6	12.88	-0.99	-3.05	-7.36	-0.37

**Table 7. Change in regional trade balances for a USA-only carbon tax**

<b>Sector</b>	<b>Net Exports (\$US million/year)</b>		
	<b>USA</b>	<b>CHN</b>	<b>ROW</b>
Rice	-203	19	181
Other Grains	-2765	118	2700
Other Crops	-2770	185	2510
Ruminants	-1755	8	1688
Non-Ruminants	-240	38	208
Other Food Products	-102	4	115
Forest Products	1485	-105	-1341
Fertilizer & Energy Intensive Manufacturing	1729	0	-1648
Other Manufacturing and Services	4906	-218	-4747
<b>Total</b>	<b>285</b>	<b>49</b>	<b>-334</b>

Figure 1. Agricultural production function

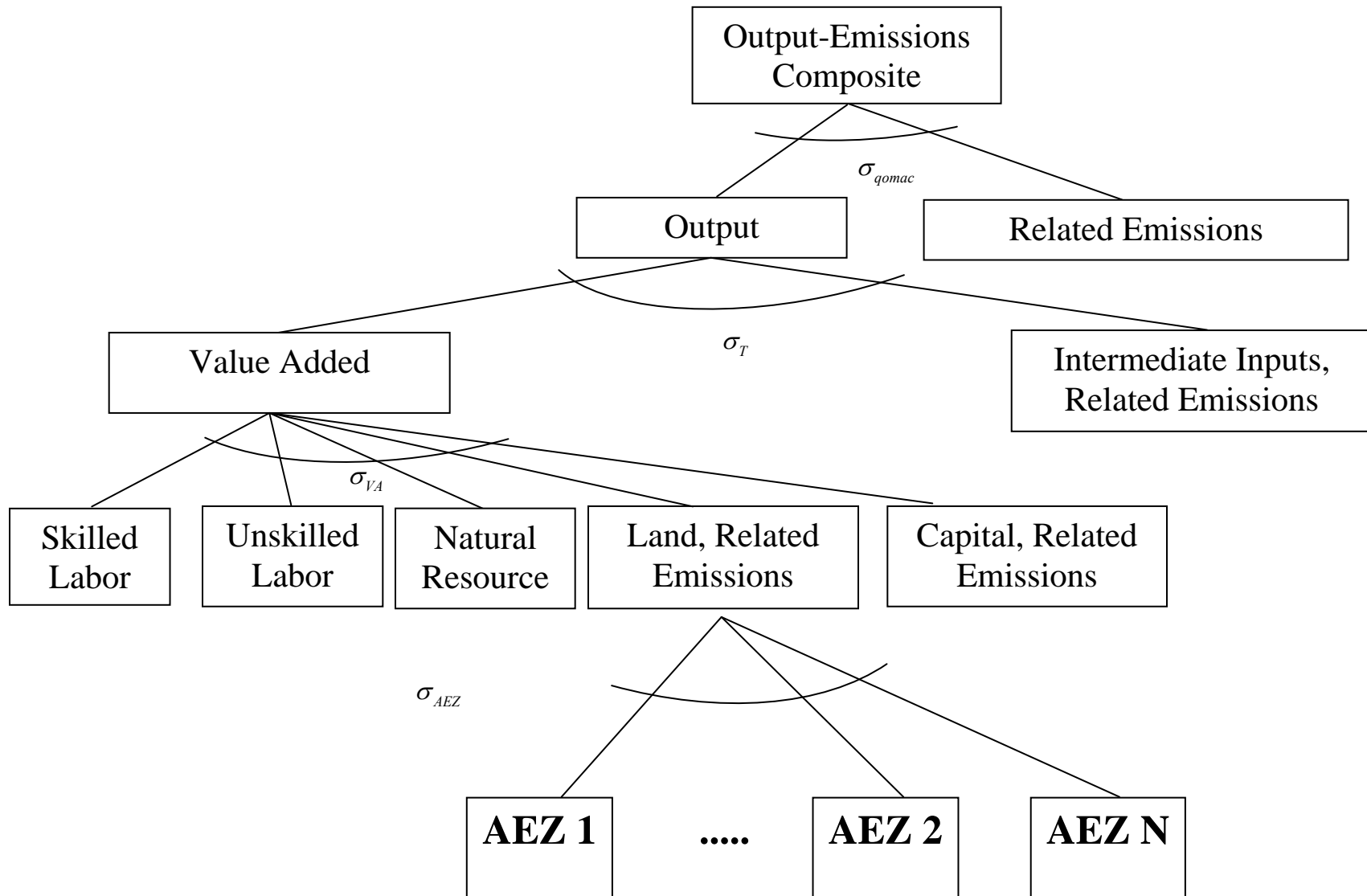
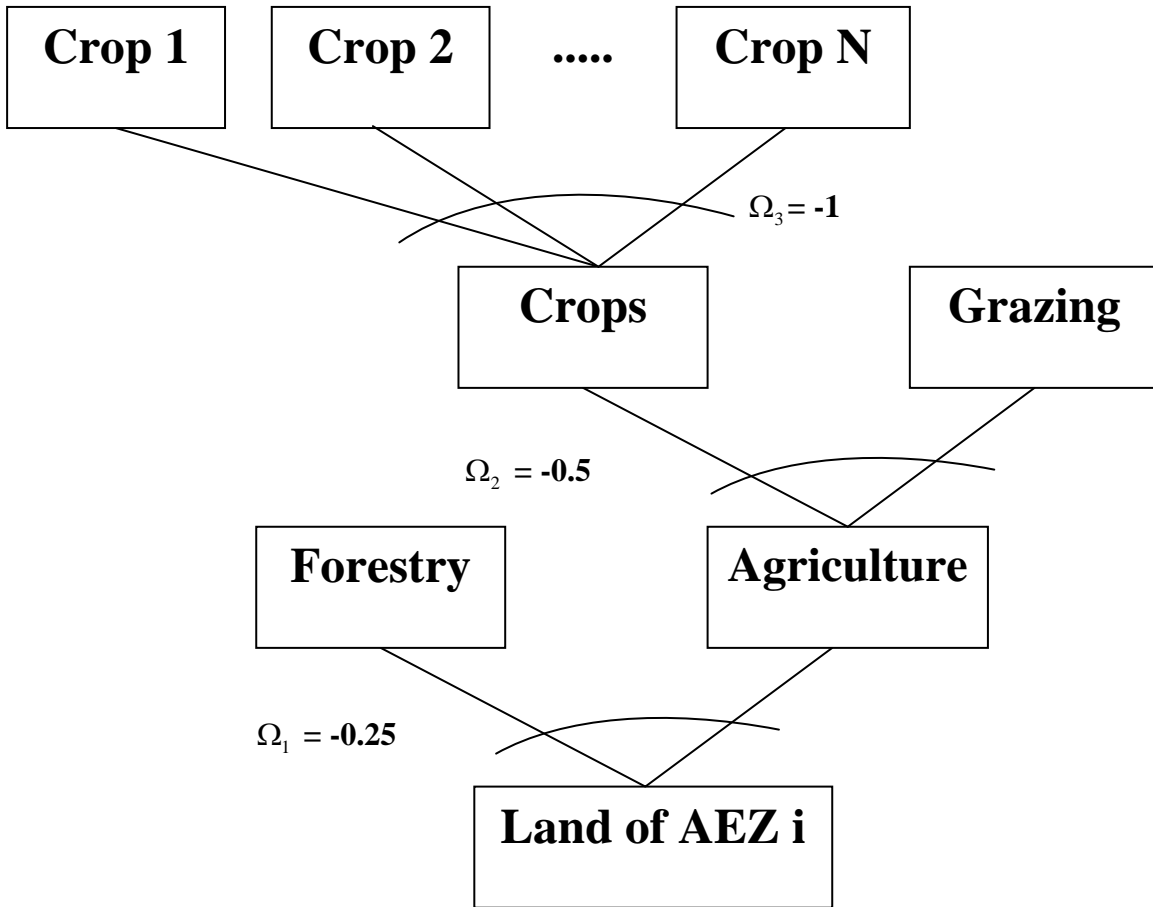
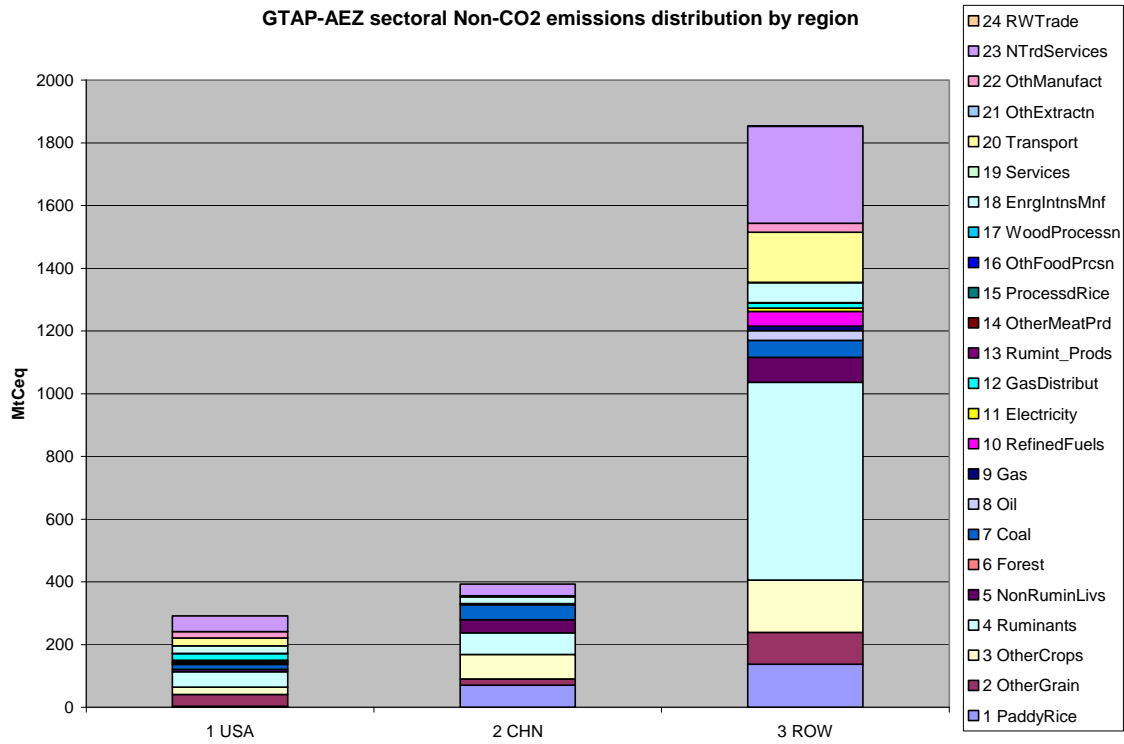


Figure 2. Three-tier structure of AEZ-specific land supply

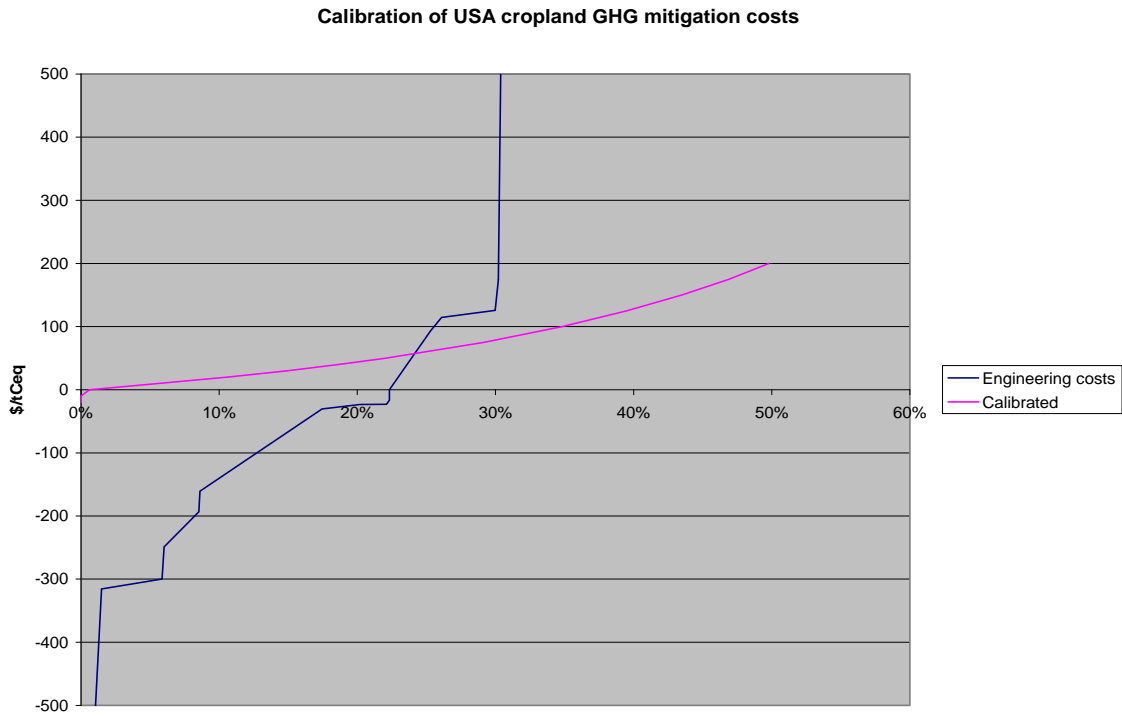




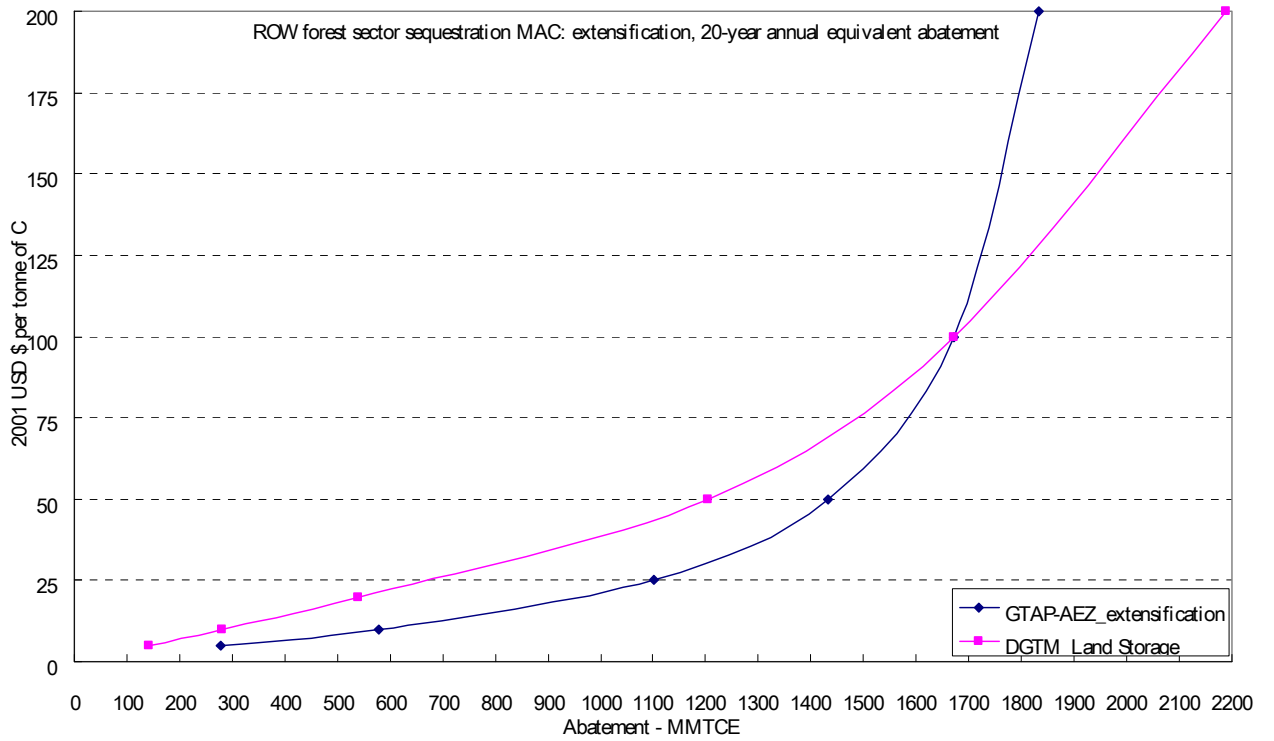
**Figure 3. Total non-CO<sub>2</sub> GHG emissions by region and sector (MtCeq)**



**Figure 4. Calibration of USA cropland GHG mitigation costs as a function of percentage abatement**



**Figure 5. Calibrated ROW forest carbon sequestration curve via extensification (20-year annual equivalent abatement)**



**Figure 6. Calibrated USA forest carbon sequestration curve via intensification (20-year annual equivalent abatement)**

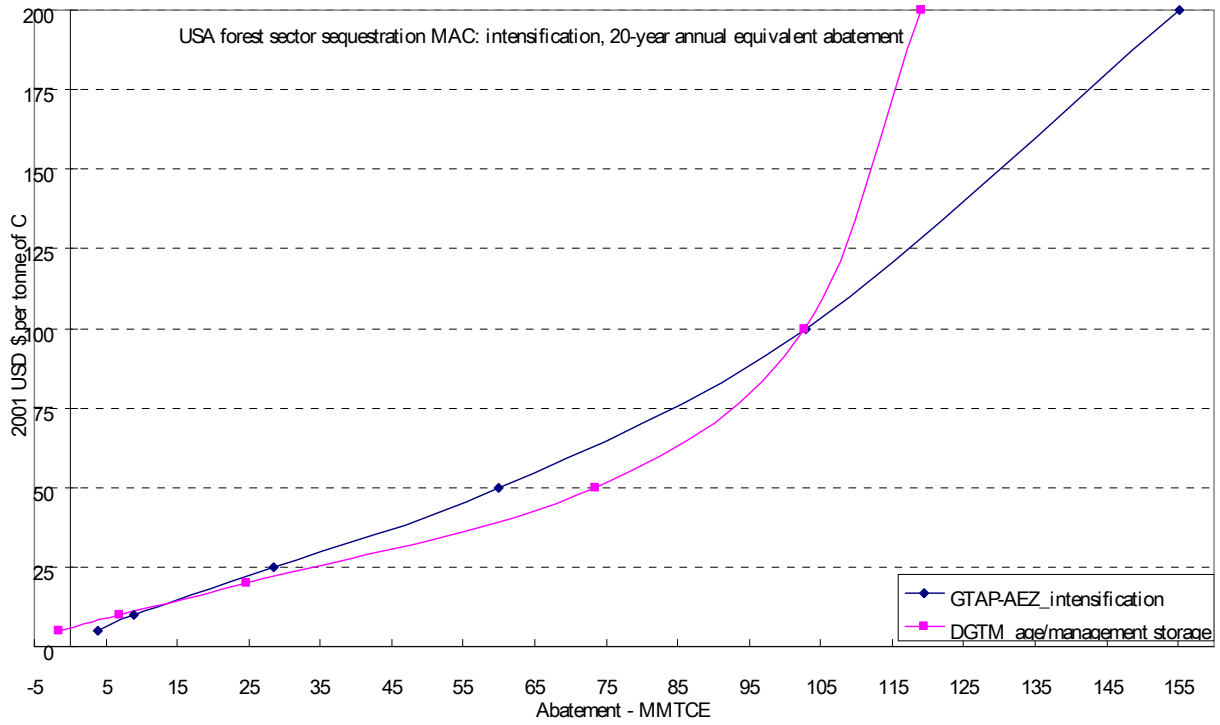
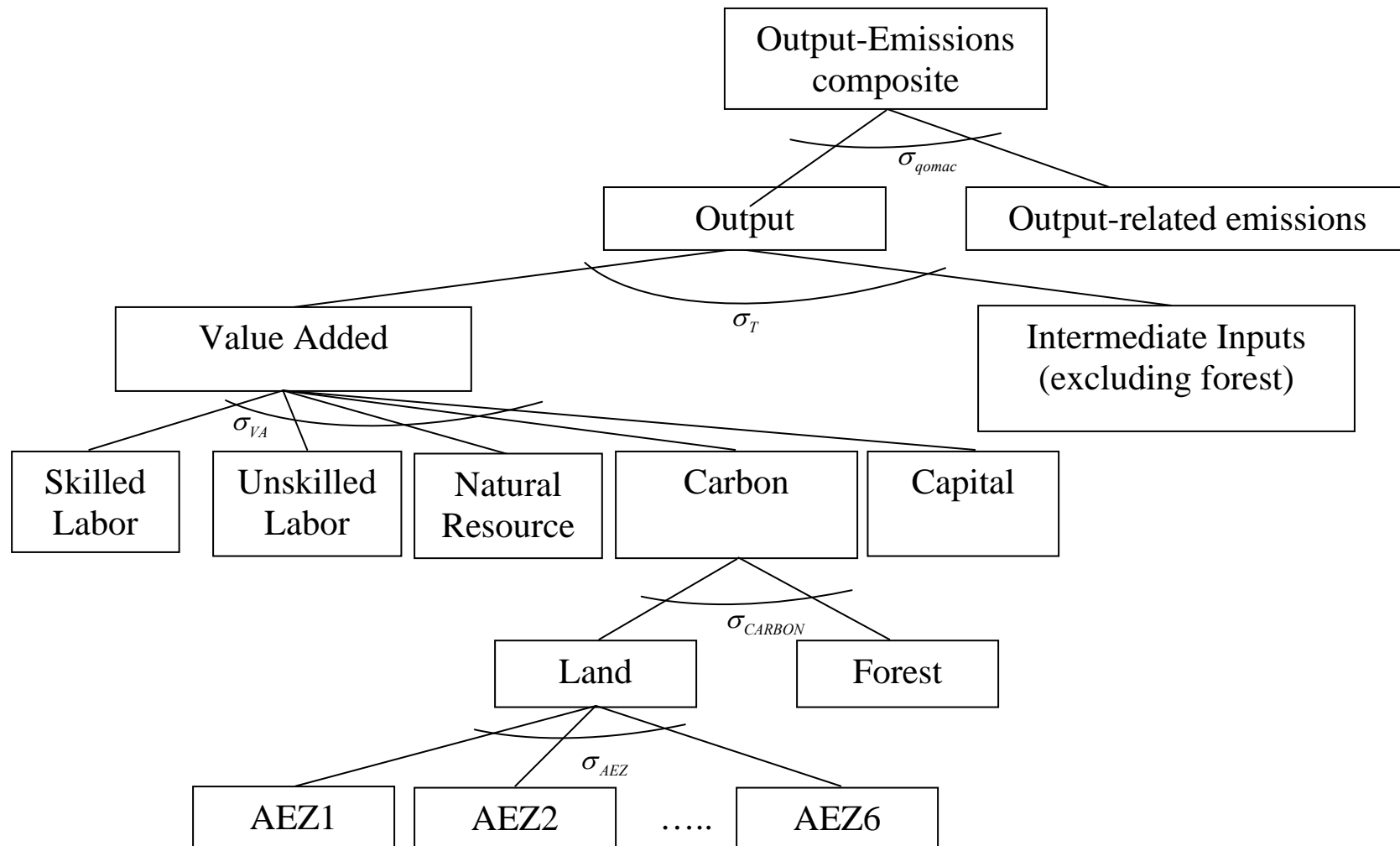
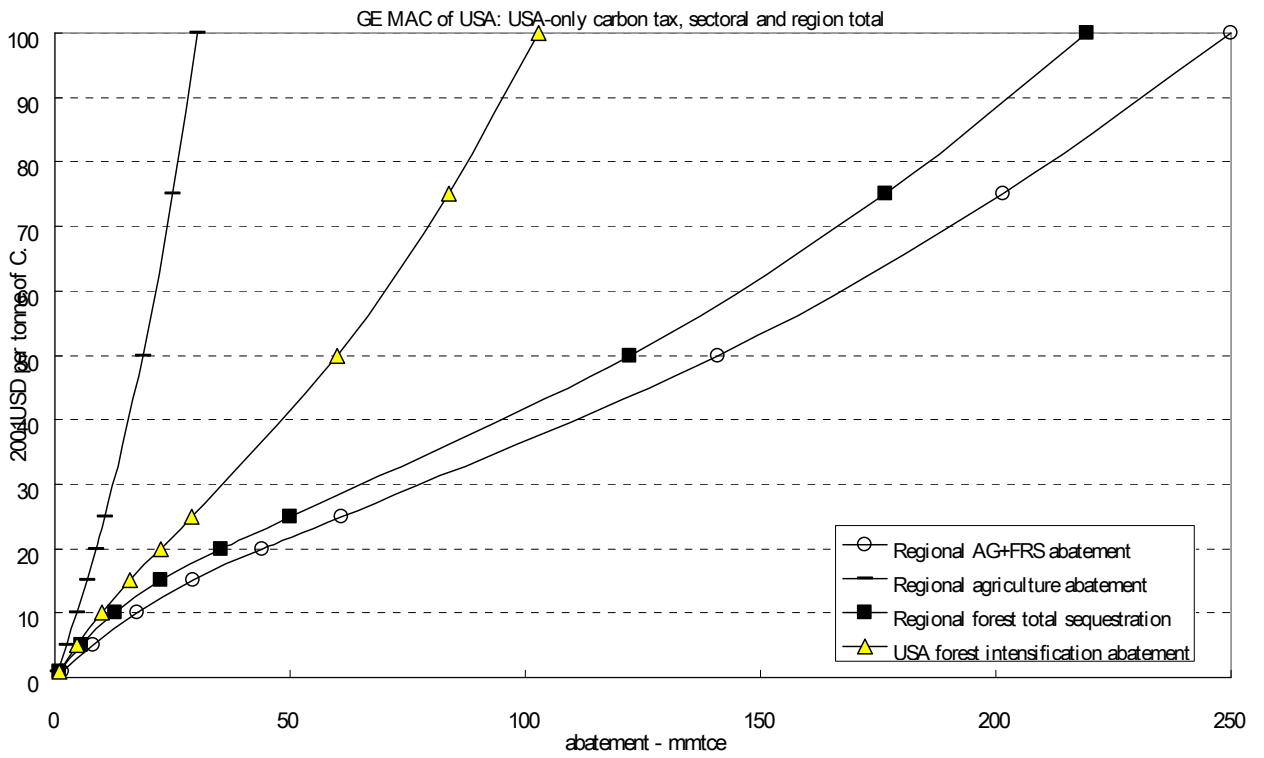


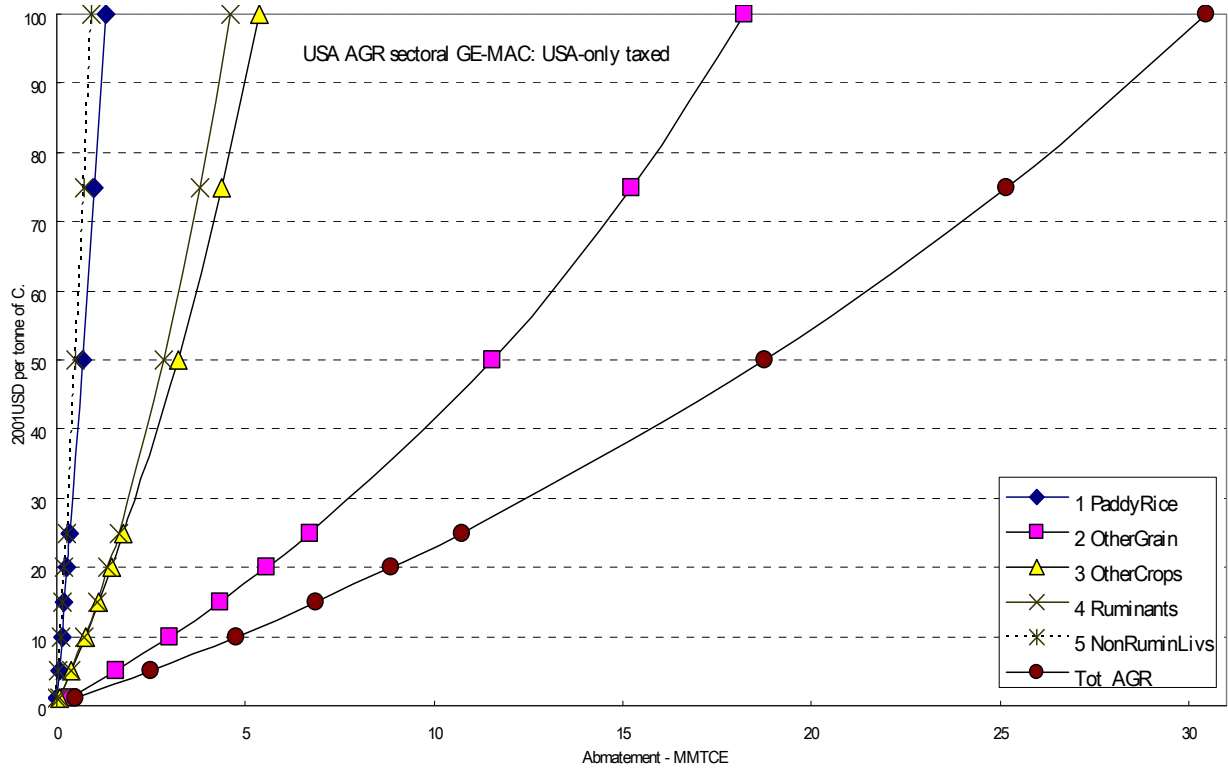
Figure 7. Production structure for the forest sector



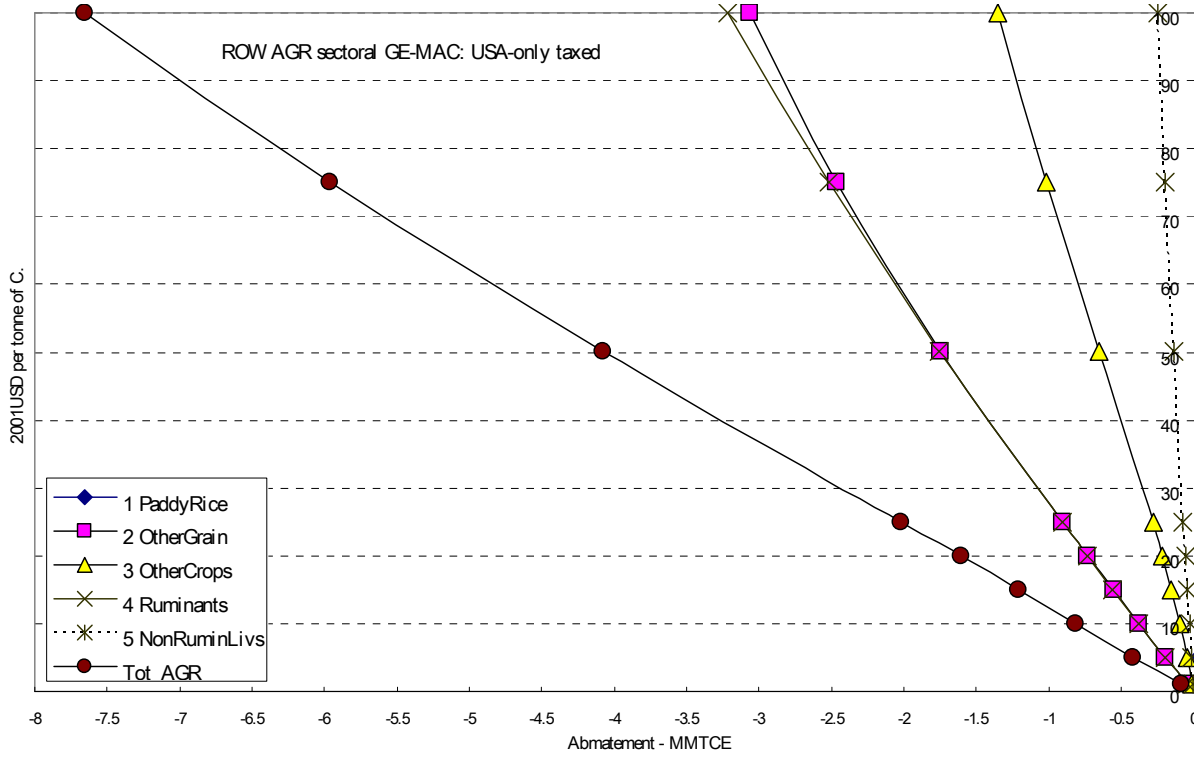
**Figure 8. USA agriculture and forestry general equilibrium GHG annual abatement supply schedules for USA-only carbon tax**



**Figure 9. USA agriculture subsector GHG annual abatement supply schedules for USA-only carbon tax**



**Figure 10. ROW agriculture subsector GHG annual abatement supply schedules for USA-only carbon tax**





**Figure 11. ROW agriculture and forestry general equilibrium GHG annual abatement supply schedules for USA-only carbon tax**

