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Thomas Hertel
Purdue University

Huey-Lin Lee
National Institute for Environmental Studies

Steven Rose
US Environmental Protection Agency

Brent Sohngen
Ohio State University

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by

Thomas Hertel[*], Huey-Lin Lee[†], Steven Rose[‡], and Brent Sohngen[§]

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[*] Center for Global Trade Analysis (GTAP), Purdue University. Corresponding author. Email: hertel@purdue.edu
[†] Center for Global Trade Analysis (GTAP), Purdue University. Email: hueylin_lee@yahoo.com
[‡] United States Environmental Protection Agency. Email: rose.steven@epamail.epa.gov
[§] The Ohio State University. Email: sohngen.1@osu.edu

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Abstract

This paper develops a CGE model with unique regional land types and detailed non-CO_2 GHG emissions which it uses to analyze the potential for reductions in land-based greenhouse gas emissions as well as forest sequestration. In our global, general equilibrium analysis of carbon taxation, we find that forest carbon sequestration is the dominant means for global GHG emissions reduction in the land using sectors. However, when compared to the rest of the world, emissions abatement in the US comes disproportionately from agriculture, and, within agriculture, disproportionately from reductions in fertilizer-related emissions (primarily in maize production). In the world as a whole, agriculture-related mitigation comes predominantly in reduced methane emissions from ruminant livestock, which is followed in relative importance by reductions in methane emissions from paddy rice. We also find significant linkages between emissions in one region and mitigation in another (i.e. leakage). For example, in the US agriculture, abatement potential 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.

JEL: Q15, Q54.
Keywords: climate change, land use change, non-CO2 greenhouse gas, marginal abatement cost, computable general equilibrium, carbon sequestration.

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1. Introduction

Changes in land use and land cover represent an important driver of net Greenhouse Gas (GHG) emissions. It has been estimated that roughly a third of the total emissions of carbon into the atmosphere since 1850 has resulted from land use change (and the remainder from fossil-fuel emissions) (Houghton, 2003). For example, in the 1990s, 6.4 Gt-C yr^{-1} was emitted to the atmosphere from industrial activities and 2.2 Gt-C yr^{-1} was emitted from tropical deforestation. In addition, agricultural land related activities are responsible for approximately 50% of global atmospheric inputs of methane (CH_4) and 75% of global nitrous oxide emissions (N_2O), for a net contribution from non-CO_2 GHGs of approximately 14% of all anthropogenic greenhouse gas emissions (USEPA, 2006a).

The policymaking community is trying to determine the potential mitigation role and implementation rules for agriculture and forestry in future climate policies, including via the Clean Development Mechanism (CDM). Land-using activities—most notably forest sequestration and dedicated biofuel production—offer considerable scope for GHG mitigation. A number of estimates have been made of the cost of abating greenhouse gas emissions through land use change and land management (Richards and Stokes, 2004; USEPA, 2006b, Chapter 5), and recent studies suggest that land-based mitigation could be cost-effective and assume a sizable share of overall mitigation responsibility in optimal abatement (Sohngen and Mendelsohn, 2003) and stabilization policies (Rose et al., 2006a). However, to date, global economic modeling of land has not been able to fully account for the opportunity costs of alternative land-uses and land-based mitigation strategies, nor the heterogeneous and dynamic environmental and economic conditions of land (e.g., Li et al., 2006; Sohngen and Tennity, 2005).

Computable general equilibrium (CGE) economic models are well suited to evaluate these kinds of tradeoffs. However, existing CGE frameworks are not currently structured to model land use alternatives and the associated emissions sources and mitigation opportunities. 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-co2 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., 2006b), as well as new engineering mitigation costs estimates (USEPA, 2006b), have provided a solid foundation for advancing global land modeling.

The focal point of our analysis will be regional and global land-use CGE GHG abatement responses. Using the newly available data, we construct a novel modeling framework to understand how different land-use opportunities for GHG abatement interact with one another on both a regional and global scale, particularly in light of global market clearing conditions for product markets. This paper extends the initial conceptual work of Lee (2004), and presents a fuller and more realistic global-scale implementation of the GTAP-AEZ 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 mitigation for CO_2 and NCGGs.

The GTAP-AEZ 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 structure, aimed at capturing key GHG emissions and sequestration activities. The model disaggregates 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. Energy producing and consuming sectors are also disaggregated. The GTAP land use database (Lee et al., 2005) enhances the standard GTAP global economic database by disaggregating land endowments and land use into 18 Agro-ecological Zones (AEZs: See FAO/IIASA, 2000, for a detailed discussion of AEZs). Second, the model incorporates newly available non-C02 emissions data from the US Environmental Protection Agency (Rose et al., 2006c). Rose et al. (2006b) has mapped the emissions data to sectors and emissions drivers in the GTAP data base, which permits us to analyze multi-gas emissions abatement scenarios in which land-using activities can both emit and sequester carbon. Third, the model's GHG mitigation responses are calibrated to source-specific GHG mitigation cost studies.

We distinguish three types of mitigation responses (costs) 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). Each individual type of response in the agricultural sector is calibrated to engineering information from the EPA, 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. 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.

Given the exploratory nature of this research, we focus our analysis on the GHG abatement schedules by sector and region for major non-CO2 GHG emissions and carbon sequestration categories associated with land-using activities, such as methane emissions from livestock production and rice cultivation, N2O emissions from nitrogen fertilizer applications, and CO2 sequestration in forestry.

Our results show that there is substantial interaction between sectors – primarily via competition for land -- and between regions in the global economy – in this case via competition in the product markets. Once GHG emissions mitigation enters the picture,

the global pattern of comparative advantage is altered, both domestically and internationally, and we observe a re-allocation of production in response to carbon prices.

Section 2 describes the GTAP-AEZ model framework, including the land use and non-CO2 GHG data bases, as well as the specification and calibration of mitigation costs. Sections 3 and 4 present the model simulation structure and results respectively. Finally, Section 5 provides summary remarks and discusses future opportunities.

2. GTAP-AEZ model

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 biophysical growing conditions and cropland and forest land use. Specifically, the database defines 18 global AEZs, as displayed in Figure 1, and identifies 2001 crop and forest extent and production for each region by AEZ for specific crop and forest types.[1] The land-use activity data was used to disaggregate the GTAP v6.0 database sectoral land rents into 18 separate AEZ land inputs. See Figure 2 for the resulting AEZ land rents by crop type. The average level of land rents on different AEZs within and across regions differs widely, based on productivity differentials; also movements in the average return to land in each AEZ will differ due to differing land allocations across commodities within AEZs. With specific land uses and values delineated by AEZ, more refined and realistic modeling of competition between different uses for land is possible.

Table 1 reports the associated land rents (at market prices) for the three regions and six aggregated AEZs. From Table 1 we can see the relative economic importance (land rental share) of each AEZ in each region of our model. For Table 1 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). From this aggregation it is clear that AEZ6 dominates the economic value of land in China, while AEZ4 dominants 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.

[1] 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 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.

The GTAP-AEZ framework retains a single, national production function for each commodity (as in the standard GTAP model), and introduces different AEZs as inputs to this national production function (see Figure 4).[2] With a sufficiently high elasticity of substitution in use (we use 20 for parameter σ_{AEZ}), we are assured that the return to land across AEZs, but 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 5), 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 US from Choi (2004), and Sohngen and Brown (2006) indicates that this elasticity averages about 0.25. Accordingly, we set the CET parameter at the bottom of this supply tree (Ω_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. 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 Ω_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

[2] The most natural approach to bringing these AEZs 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 possible, this results in a great proliferation of sectors and dimensions in the model. In an effort to simplify the model, we propose the following reasoning: if we assume that like products produced in each region are perfect substitutes, then a single commodity price will prevail. If, in addition, the production functions are similar across AEZs, and the firms face the same prices for non-land factors, then land rents in comparable activities must also move together (even if they do not share the same initial level). From the point of view of land markets, the focus of this paper, this is the key objective of our specification for land use – the returns to land on different AEZs employed in the production of the same product must move together.

parameter between these two values: Ω_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.

2.1 Model modifications associated with GHG emissions and sequestration

The model presented here considers only non-CO_2 emissions from agriculture and CO_2 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 non-CO_2 emissions and forest carbon sequestration and the potential mitigation role of land use.[3]

Emissions and Forest Sequestration

Base year non-CO2 emissions are summarized in Figure 3 for the three focus regions for this study: USA, China and the Rest Of World (ROW). From Figure 3 it is clear that non-CO_2 emissions from agriculture (crops and livestock) represent well over 50% of the China and ROW total non-CO_2 equivalent emissions and just under half of the U.S. non-CO_2 emissions. Table 2 summarizes the types of non-CO_2 emissions produced by each sector. The GTAP non-CO_2 dataset was developed from a detailed non-CO_2 greenhouse gas emissions database specifically designed for use in global economic models (Rose et al., 2006c). The USEPA 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 USEPA dataset improves modeling capacity for representing actual emitting activities and abatement strategies.[4] See Rose et al. (2006b) for a description of the methods used in mapping the USEPA non-CO_2 emissions into the GTAP version 6 database's region and sector structure. In this paper we draw only on the non-CO_2 related to drivers in the land-using sectors, since that is the focus of our paper. Similar methods

[3] We have intentionally omitted fossil fuel combustion CO_2 emissions. In addition, other CO_2 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_2 emissions are currently included.

[4] Other global emissions datasets have provided valuable regional and global estimates (e.g., USEPA, 2006a; Olivier, 2002); however, estimated emissions have been developed and presented according to IPCC source categories that aggregate across countries, and more importantly, economic sectors and activities. The USEPA database provides 2001 emissions for 29 non-CO_2 and Other CO_2 GHG emissions categories with 153 unique emissions sources (subcategories) for 226 countries. Most of the USEPA categories and subcategories were mapped into GTAP (24 categories and 119 subcategories). The excluded categories/subcategories include non-CO_2 emissions associated with biomass burning not uniquely attributable to anthropogenic activity, tropical forest fire deforestation, biomass combustion, underground storage and geothermal energy, and Other CO_2 emissions not attributable to fossil fuel combustion. The omitted emissions subcategories will be added to the database in the future as methodologies are developed and activity data becomes available. The new dataset complements the GTAP fossil fuel combustion CO_2 emissions database (Lee, 2005), and the GTAP forest carbon stock dataset (Lee et al., 2005).

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_2 emissions drivers: outputs, factor inputs (endowments), and intermediate inputs. 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_2O emissions. 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. Table 3 reports total non-CO_2 emissions by land-using sector and emissions driver category (output, endowments and intermediate inputs). From the "Region total" column, we see that the US and China together account for 28% of global non-CO_2 emissions. World-wide 26% of the emissions are tied to endowment drivers – mainly CH4 emissions from rice paddies, and CH4 and N2O from enteric fermentation and manure management. 13% of the world total non-CO2 emissions are tied to intermediate input use – for the "Other Grain" and the "Other Crops" sectors, fertilizer use is the key source of emissions.

Introducing a Specific Tax on GHG-emissions

In order to simulate potential mitigation behavior, we introduce the possibility of taxing inputs that are associated with GHG emissions. 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:

$$\Delta t_{ijr} = \Delta to_{ijr} + [\theta_{ijr} / PM_{ir}] \cdot [\Delta \tau_{ijr} - (\tau_{ijr} / PM_{ir}) \cdot \Delta PM_{ir}]$$

The left hand side of this equation represents the change in the *ad valorem* tax rate on inputs (e.g., fertilizer used in corn production). This depends on the change in the ordinary, *ad valorem*, tax, Δto_{ijr}, the change in the specific tax, $\Delta \tau_{ijr}$, and the change in the market price of the input in question: ΔPM_{ir}. Assume for the time being that the ordinary tax doesn't change and the input is in perfectly elastic supply, so the price doesn't 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: θ_{ijr}. We must divide this by the price of fertilizer, PM_{ir}, we obtain the coefficient in the equation above, which simply becomes tonnes of emissions, per dollar of fertilizer inputs purchased, valued at market prices.

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.[5] The larger this intensity, the greater the impact of a given $/tonne tax on the sector/input in question. Table 4 reports some key emissions intensities from the model for USA and China. USA has the higher emissions intensity in fertilizer, but ruminants and paddy rice show much higher emissions intensities in China. These are the activities/regions where we expect to see relatively stronger reductions in emissions following a uniform global carbon tax.

There is a closely related emissions intensity, α_{ijr} / PMC_{jr}, which measures the carbon intensity of forests (MtC/$input) and drives the incentives for carbon sequestration. In this case, sequestration is tied to the use of land, which is "taxed" input – in this case a negative tax, i.e. a sequestration subsidy. In addition to land rents, we include "own-use" of forest products by the forest sector in this composite. So PMC_{jr} reflects the combined price (rental rate) of land and own-forest use. Subsequently we will refer to this as the "carbon-augmented land" input into forestry. The reason for including own-use is that it permits us to introduce a management intensification response to the sequestration subsidy. The precise mechanism for doing so will be explained below.

The relevant equation for determining the change in *ad valorem* input tax (subsidy) in forestry follows:

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

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 augmented land. This depends on the change in the specific tax, $\Delta \tau s_{ijr}$, and the change in the price of carbon-augmented land: ΔPMC_{ir}. 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, α_{ijr} / PMC_{jr}. The calibrated intensity levels for each of the three regions is reported in Table 4. It is larger in ROW than in China and USA, therefore advantaging ROW in the matter of forest carbon sequestration. Of course, the carbon intensity of the forest is a complex function of a number of factors. For example, it depends on the age of the forest, the species selected, as well as the management practices undertaken. Optimizing all of these margins in response to a carbon sequestration subsidy is beyond the scope of the GTAP-AEZ model. Therefore, as with the other sources of mitigation response, we will adopt a "reduced form" approach to capturing the extensive and intensive margins for forest carbon sequestration – in this case drawing on results from a dyamic model of global timber markets and carbon supply (see Sohngen and Mendelsohn; Sohngen and Sedjo). Details are provided under case 3 in the next section.

Mitigation responses

[5] The tax on emissions is rebated to the regional household in the same way any tax would be re-circulated in the GTAP model.

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 the 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 for alternative abatement technologies.

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

There are many non-CO_2 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: (a) follow the approach typically used for CO_2 abatement associated with energy fossil fuel combustion and use the best possible econometric evidence on substitution elasticities, letting the GTAP-AEZ abatement response schedules fall where they may, or (b) adjusting the elasticities of substitution to give 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.

The U.S. Environmental Protection Agency (USEPA) has estimated the engineering mitigation costs and emissions implications for alternative management strategies for key non-CO_2 emissions sources and costs for significant agricultural non-CO_2 emissions sources—paddy rice, other croplands (wheat, maize, soybean), and livestock enteric and manure emissions (Delhotal et al., forthcoming; USEPA, forthcoming). From these data, we were able to construct mitigation response curves that correspond to the GTAP-AEZ region and sector structure, and can be used for calibration purposes. The second column of Table 5 indicates the drivers associated with the derived mitigation response curves by GTAP-AEZ land-using sectors.[6] For example, the methane emissions associated with paddy rice production are tied to land use, as the emissions tend to be proportional to the amount of paddy land. Nitrous oxide emissions from maize production are tied to fertilizer use. And 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.

[6] USEPA (2006b) year 2000 mitigation cost curves were used for calibrating the agriculture sectors.

The overall GTAP-AEZ production structure is illustrated in Figure 6. In calibrating to the abatement possibilities associated with input-related emissions, we utilize the two input-related elasticities of substitution: ESUBT, the elasticity of substitution between intermediate inputs, and ESUBVA, the elasticity of substitution between primary factors. For purposes of calibration, we fixed output levels in the sectors, as well as input prices to match the partial equilibrium assumptions of the engineering cost estimates. 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 5 reports the resulting elasticities of substitution among inputs obtained through this exercise.

Figure 8 illustrates the results from the calibration for USA cropland emissions mitigation response. The piecewise linear abatement cost schedule is obtained from the US EPA, while the smooth curve 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/tonne).

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 can not 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/tonne.

Case 2: Emissions not directly related to input use

In other cases, it may be difficult to tie emissions directly to input usage due to a lack of input use data or econometric production cost estimates. 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 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 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. Unlike the elasticity of substitution between capital and labor, for example, this new elasticity of substitution cannot be directly estimated. Indeed, it is a fiction invented to permit us to calibrate the model to mitigation engineering studies. The calibrated values for these elasticities of substitution are also reported in Table 5 under the column heading "output-elasticities".

Case 3: 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 (2006), we have generated regional forest carbon supply curves.[7] We refer to this model throughout as the "global timber model." In the global timber model, when incentives for carbon sequestration (carbon prices) are introduced, 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 recoreded 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 13 aggregate regions in the model, and the results are reported in Table 6. 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 first 20 years. 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.

[7] The model 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. Full detail is available in Sohngen and Mendelsohn (2006)

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 6. 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 (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 6, where the carbon storage at $5/tonne 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 cost curve for ROW is quite flat initially (see Figure 9).

The intensive margin for forest sequestration consists of several components. 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 if timberlands were managed at the age class dictated by the baseline. The algorithm used to calculate carbon due to aging does not distinguish between old and new hectares. Thus, if newly forested hectares are harvested in age classes older than the baseline age class, the component derived from aging is counted as part of the aging component rather than as part of the afforestation component. This interaction between the extensive and intensive margins can give rise to negative contributions to sequestration at very low carbon prices (see US entry for $5/tonne)

The management component is calculated similarly, that is carbon sequestered under the carbon price scenario is compared to carbon sequestered assuming the same forests are managed with the same intensity as in the baseline. 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 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 6. And Figure 10 graphs the annual total sequestration rate on this intensive margin for the USA region, in response to a carbon subsidy ranging from $1/tonne to $200/tonne. Again, remember that these annual rates have been computed using a 20 year period. (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 carbon stock is considerable —particularly in the range of interest in this paper, namely up to $100/tonne.

The remaining two columns in Table 6 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 to 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/tonne), forests in the U.S. could potentially sequester 0.4 – 95.5 million tonnes of carbon per year over the first 20 years (Table 6). These estimates are consistent with a recent detailed national assessment of U.S. sequestration potential in forestry, which suggests that for $55/tonne, 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 tones of carbon per year possible at the carbon price of $50/tonne. As prices rise above $50/tonne, 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 surprising potential to increase carbon by forest management in the near-term.

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 σ_{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). Assume first that $\sigma_{carbon} = 0$ in Figure 7. In this case, 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 we calibrate it to the $100/tonne estimates in Table 6 by adjusting the incremental annual carbon intensity of forests to the levels reported in Table 4. The higher the forest carbon intensity, the stronger the profitability and hence land area response to the sequestration subsidy. The forest carbon sequestration curve obtained from the model via extensive margin (land use) for the ROW region is reported in Figure 9. As can be seen, the GTAP-AEZ mitigation cost curve intersects that of the global timber model at the calibration point of $100/tonne. The two curves are quite similar up to the $100/tonne level. However, after that point, the calibrated MAC (dark line) has considerably more curvature than that displayed by the

global timber model. 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 analysis to carbon prices to be below $100/tonne.

In contrast to the extensive margin just explored, we might consider fixing the total land in forestry (set $\Omega_1 = 0$ in Figure 5), introducing $\sigma_{carbon} > 0$ in 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 the intermedidate forest product input 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), and thereby increasing the carbon intensity per unit of 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 σ_{carbon} until GTAP-AEZ produces the desired level of carbon sequestration at the $100/tonne level of subsidy. The calibrated forest carbon sequestration supply curve via the intensive margin is the dark curve shown in Figure 10 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/tonne.

This completes our discussion of the general equilibrium model, and the associated data base and parameters which aim to accurately reflect partial equilibrium abatement possibilities in land using sectors. We now turn to an analysis which highlights the general equilibrium interactions between these land-using sectors, both through the land market and through global product markets.

3. Results

Method for Analysis

The focal point of our analysis will be the regional and global GTAP-AEZ GHG abatement supply schedules. Having calibrated the model to a range of partial equilibrium abatement cost curves, each of which assumes that conditions in the other sectors do not change, we seek to understand how these different sources of abatement interact with one another – particularly given the regional constraints on land use, by AEZ, as well as the global constraint that product supply equals demand. Accordingly, we estimate general equilibrium abatement schedules by region and sector. This is done by varying the per unit carbon tax systematically from $1/tonne to $100/tonne, each time re-solving the general equilibrium model and observing the sources and extent of abatement in the land using sectors. We are keenly interested in. In order to better understand the competition between sectors for land, as well as the global general equilibrium effects, we conduct several intermediate simulations to help us isolate the various effects at work before considering the global impacts of a global carbon tax.

We begin our analysis by exploring the domestic resource implications of carbon taxes *applied in the US only*. This allows us to trace out the USA-only general equilibrium abatement response schedules. In this case, we focus on competition for land in the US, as forest carbon sequestration encourages an expansion of forest land at the expense of other activities. Of course changes in the supply of forest and agriculture products in the US has an impact on world markets, and therefore on the relative incentives to produce in China and ROW. Thus, we can expect spillover effects from the US-based carbon taxes. For example, a carbon tax that reduces fertilizer use in the US will have an impact on world prices for crops and fertilizer. In particular, lower usage of fertilizer in the US will cause world fertilizer prices to fall, and crops prices to rise. Thus there is an incentive for producers in other regions to increase fertilizer use and crops output, unless of course they too are subject to the tax. By examining the impact of a US only tax initially, we can identify the magnitude of regional emissions leakage effects in non-CO_2 gas abatement stemming from the shifting of global production in land-using sectors, in response to regional taxes. We then perform a similar experiment, only now levying the tax on the rest of the world (omitting the US). This generates abatement in ROW, and leakage (increased emissions) in the US. Finally, we put these pieces together and examine the impact of a global tax on carbon – both on the USA and on the world as a whole.

General Equilibrium Abatement Cost Schedules and Leakage

Figure 11 portrays the general equilibrium, mitigation responses for forestry and for the aggregate agriculture sector, respectively, in the wake of carbon price policies implemented *in the US only*. At $5/tonne of carbon, forestry and agriculture appear to be of equal importance. However, from there, the two abatement curves begin to diverge, as the agriculture abatement schedule becomes more inelastic and the forestry sequestration schedule becomes more elastic. By $10/tonne, forest sequestration accounts for double the abatement of agriculture, and by the time the carbon price reaches $50/tonne, it is roughly four times as large.

Figure 11 also reports the portion of forest sequestration in the US that is attributable to the intensification effect. I.e., this is the amount of sequestration that would occur if no additional land moved into forestry. Clearly the potential for carbon sequestration through changes in management is substantial (recall also Table 6 and Figure 10), accounting for half of total forest sequestration at the $50/tonne tax rate. Of course the remaining portion of the general equilibrium sequestration is due to an expansion in forested land area. This forest extensification effect 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, we have ascertained 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 shown in Figure 11, the abatement is more substantial in agriculture.

In summary, our results for the U.S. indicate that about 20 million t Ceq. can be abated each year in the agricultural sector and about 120 million t Ceq can be sequestered in the forestry sector for $50/t Ceq. It is instructive to compare these estimates to other estimates in the literature, For similar prices, Murray et al. (2005) find that approximately 9 million t Ceq of CH4 and NO2 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 considers only the United States, with few 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 regional only model of Murray et al. (2005), where no such responses are possible, one would expect stronger price changes, and consequently higher marginal costs for abatement and sequestration. For example, we expect that our marginal costs for the U.S. under a global carbon tax would lead to higher marginal costs (see analysis below).

Now turn to the disaggregation of the US abatement schedule for agriculture, by sub-sector, as reported in Figure 12. As noted above, emissions from paddy rice, ruminant and non-ruminant livestock are largely methane, while emissions from other grains and other crops are dominanted by NO_2 associated with fertilizer applications. As can be seen from this figure, farm sector abatement in the US is dominated by other grains (largely maize) in the US. This is followed by other crops and ruminants. Abatement in rice and non-ruminants is quite modest in the US, even at our calibration point of $50/tonne, in response to a US-only carbon tax.

Now turn to the impact of this same USA-only carbon tax policy on emissions in ROW. We begin our analysis of this leakage effect by examining the trade impacts, as reported in the first three colulmns of Table 7. These results, under the “USA only” header, reports the net trade (change in *fob* exports less change in *cif* imports) impacts of the US-only tax (at a carbon price of $100/tonne). Here, we see that net exports of crop and livestock products fall sharply in the wake of the carbon tax. The largest drop is for the heavily traded other grains and crops sectors, followed by ruminant products. This decline in net exports is made up in the US by increased exports of forestry and wood products, as well as fertilizer and energy intensive manufactures, and other manfactures and services. 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 do sum to zero (subject to rounding error) due to the general equilibrium requirement of global trade balance.

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-CO2 emissions in ROW. This leakage effect in ROW in the case of agriculture sectors, following the US-only carbon tax, is displayed in Figure 13. 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. Finally, note that there is actually a small reduction in ROW emissions of methane from rice production (negative leakage, or abatment). 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 14 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/tonne, 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/tonne carbon tax is only about one MMTCeq. – or about 5% of the leakage in ROW following the US only tax. Figure 14 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 actually encourages less carbon-intensive production techniques in ROW. However, this effect reaches its maximum at the $50/tonne carbon price, after which all of the forestry leakage is through reductions in forest land area (the extensive component).

Similarly, we can examine the impact of a carbon tax applied in non-US regions on USA emissions. For example, Figure 15 displays the resulting impact on US emissions, when taxes are applied in the ROW region. (As with the impact of US taxes on emissions in China, the increase in emissions in the US when a tax in applied in China is very small – on the order of 1 MMtCeq.) The leakage to USA from ROW carbon taxes is over 25 MMtCeq. Indeed, the total magnitude of the leakage to USA as a result of a carbon tax in ROW is nearly the same as the leakage to ROW as a result of a USA carbon tax. However, *the composition is quite different*. Whereas forestry dominated the leakage to ROW following the USA tax, agriculture is much more important when the tax is levied in ROW and the leakage occurs in the USA market. Indeed, above $50/tonne, leakage through expansion in USA agriculture dominates that through expansion in USA forestry

following a carbon tax in ROW. And the intensification component of forestry leakage is very small in this case (Figure 15).

We can gain some insight into the strong agricultural leakage from ROW to USA, following the carbon tax in ROW, by referring once again to Table 7 – this time shifting our attention to the second group of columns. Here, we see very large reductions in net exports for agricultural products in the ROW region – indeed the reduction in net exports of rice is five times as large as that arising in the US under the US only tax. The bulk of these reductions are made up by increases in USA net exports – particularly for ruminants and other grains. Meanwhile, the incentive to produce and sell forest products in the US falls, thereby encouraging the movement of land out of forestry and into agriculture in USA.

Figure 16 reports the composition of leakage to US emissions in response to the ROW only carbon tax. In contrast to the ROW leakage in response to the US tax, this figure shows that other grains (maize) dominates the leakage story, accounting for about half of the total. This is due to the very strong trade effects (Table 7), coupled with the relatively high emissions intensity for this producct (i.e., fertilizer applications). Ruminants and other crops are a distant second and third in importance, with negligible leakage arising through the response of rice production in the US.

Next, we turn to the impacts of a global carbon tax. The impact on US emissions over a range of carbon prices is reported in Figure 17. *A priori* we expect the impact on US GHG emissions to be roughly equal to the combined effect of the USA-only tax on US emissions and the ROW-only tax on US emissions. Indeed the curves in this figure are similar to the general equilibrium abatement response for the USA when the tax is applied only in the USA – with the curves shifted to the left to account for USA response to the ROW and China taxes. Note that the US abatement in agriculture is only about half a large, for a given carbon tax, under the global vs. the unilateral tax policy. Thus the impact of global trade is very significant in the case of emissions from US agriculture. These leakage effects also diminish the overall importance of ruminants, relative to crops in the global abatement schedules.

Figure 18 reports the aggregate agriculture abatement schedule, along with that for forestry and the total abatement schedule from land using activities. Whereas leakage cuts the US abatement from agriculture in half when we move from the US-only to the global carbon tax, the impact on forest sequestration is quite modest. This is to be expected given that the forest response in the GTAP-AEZ model is calibrated on results from a global timber market model that already accounts for price changes globally. The global tax thus implies that the *relative importance of agriculture in total abatement diminishes* when considering a global carbon tax versus a regional carbon tax. This figure also shows the forest sequestration abatement at the intensive margin, which, as before, accounts for about half of the total sequestration in the US. This stands in sharp contrast to forest sequestration in ROW in the wake of a global carbon tax (Figure 19), where the role of forest carbon sequestration is even more dominant. Most sequestration in ROW

occurs at the extensive margin – both through a reduction in the rate of deforestation and as well as and expansion of forest lands.

Figure 20 aggregates across regions the sources of agriculture emissions reductions in response to a global carbon tax. In contrast to the US, the greatest scope for agriculture-based emissions reductions globally is in ruminants, followed by rice. Whereas the wheat and coarse grains ("other grains") sub-sector was the most important source of agriculture-based emissions reductions in the US, it is only half as important as paddy rice, and one-third as important as ruminant livestock production, in the world as a whole.

Figure 21 reports the global abatement response to a global carbon tax. Not surprisingly, global abatement is dominated by ROW, which also comprises the bulk of the world's land area and forests. The aggregate abatement schedules for land using activities in US and China are remarkably similar, with slight differences in neighborhood of $50/tonne carbon price.

Competition for Land

A key feature of these results is the within-region competition for land, by AEZ. In order to better understand this, we focus on one specific simulation, namely the $100/tonne carbon equivalent tax *in the USA alone*. The resulting change in land rents, by AEZ and sector, is reported at the top of Table 8. Note, first of all, that the change in land rents, in a given use, across AEZs, is nearly identical. This is due to our assumption of very high substitutability (σ_{AEZ} = 20) between AEZs in a given use, which is in turn motivated by the fact that the final products produced on different AEZs face a common price. The latter fact dictates a common movement in land rents, provided the underlying technologies are similar, as assumed here.

The second point to note from Table 8 is that the returns to land in paddy rice production fall sharply. The tax on methane emissions from rice production hits returns to land in this use very hard. Returns to land in other land-using sectors, including: other grains, other crops, forestry, and grazing uses, rise. The rise in forestry land rents is a direct consequence of the CO_2 sequestration subsidy which lowers the cost of land to forestry, thereby boosting its use and hence 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 GTAP data base. More recent estimates suggest that this share is a substantial under-estimate. Making this adjustment will, 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 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 other inputs, including land, for the taxed input, the cost of which has risen substantially.

These changes in land rents dictate changes in land use, by sector, which are reported in the next panel of Table 8. Here, we see that commercial forestry increases its use of land

substantially, while paddy rice dramatically reduces its use of land in response to the GHG emissions tax. Other crops and ruminants increase their use of the shorter length of growing period AEZ land types (2 and 3) and decrease their demand for longer length of growing period AEZ land (5 and 6) where forestry is more dominant. The latter action provides GHG emissions benefits, while the former offsets lost production.

Of course, there can be a large percentage change in a variable with relatively little economic importance, and so the simple percentage change in land use is a bit misleading. The most natural way to scale the percentage change in land use is to pre-multiply it by the share of a given AEZ's land rents generated by each activity in the base period data. The third panel in Table 8 does so, using the AEZ land rent shares reported at the bottom of Table 8 (fourth panel). Now we see 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. Therefore, in these AEZs, the basic story is one of cropland moving primarily into grazing activities. On the other hand, the direction of the land movement differs in the longer length of growing period AEZs (5 and 6). Here, grazing is relatively less important, while forestry becomes much more important (particularly in AEZ 6 where land rents from forestry reach about 10% of total land rents).

A Global Perspective on Emissions Taxation: Competition in International Markets

Taxes on emissions of greenhouse gases have important international ramifications. Recall from the abatement schedules presented above that, while the US reduces emissions in response to the US-only carbon tax, the ROW region takes full advantage of the opportunity presented to them, increasing emissions and so partially offsetting the US reductions. This emissions leakage is the result of the ROW region picking-up production in response to decreased US output. In this section, we try to elucidate these regional net emissions responses by providing a matrix of results showing the full set of interactions across regions and sectors. Table 9a offers such a view of the global interactions between emissions taxes (sequestration subsidies) in one region and emissions (sequestration) in another region. The table presents a decomposition of the effects of a global tax into the individual taxes/subsidies within each region, all based on results for the $100/tonne carbon-equivalent tax.

For the simulation underpinning Table 9a, we utilize the numerical integration technique proposed by Harrison, Horridge and Pearson (2000, henceforth HHP) to apportion the impact of each group of instruments on total emissions in each region. This permits us to identify, for example, the contribution of the $100/tonne tax on paddy rice related emissions in USA on total emissions in ROW. The great virtue of the HHP decomposition technique is that all of the individual numbers add up in the end to the total impact. This would not be the case if we simply ran each group of policies separately and added up the resulting numbers. (The difference between the sum of the individual effects and the total effect is a measure of the interaction between policies.)

The columns in Table 9a refer to emitting regions. So the percentage change in total emissions in USA amounts to a reduction of 76% in the wake of a $100/t C global tax

(Table 9a, Total Impact row, USA column). On the other hand, total emissions in ROW fall by about 140%. What explains this difference? For this we need to refer to the individual elements in each column. Together, they sum to the total emissions response given at the bottom of the table. The rows in this table show the breakdown (numerical decomposition) of the total mitigation impact – by type of instrument and region. So, for example, the impact of a $100/tonne tax on purchased input related emissions in USA on total USA emissions is -8.27%. On the other hand, the same tax in USA, leads to slightly higher aggregate emissions in ROW (+0.61%). As expected, the diagonal elements in each block of the table are negative, indicating that a tax on emissions in a particular region lowers *overall* emissions in that region.

Identical carbon taxes in different regions can lead to very different responses in aggregate emissions. For example, while the $100/tonne purchased input-related emissions tax (i.e. fertilizer use in crops) in USA reduces total USA emissions by more than 8%, the same tax in ROW reduces total emissions in ROW by just 2.54% (ROW row, ROW column – purchased input related emissions). A $100/tonne Ceq tax on paddy rice and ruminant livestock production in China (i.e., primary factor taxes), results in a 13% reduction in total emissions, while the comparable reduction in USA is just 2%. This is a direct consequence of the differential emissions intensities in these countries (recall Table 4 which showed these two sectors to be very emissions intensive in China). Similarly, the $100/tCeq forest sequestration subsidy results in a substantial increase in ROW forest carbon stocks – enough to reduce overall non-CO2 emissions and increase forest carbon in that region by more than 100% -- while the comparable reductions in USA and China are just 75% and 42% respectively.

The off-diagonal elements of Table 9a tend to be positive, indicating that there is generally some “leakage” as other (untaxed) regions respond by increasing emissions of the activity on which the tax has been levied in one region – e.g., fertilizer use in crops, or paddy rice cultivation. Overall, the leakage effects are small, and the U.S. tends to have the largest leakage effects. In particular, leakage in the U.S. is potentially significant with respect to forest sequestration in ROW. As forestry activity expands in ROW, agricultural output falls and US farm production expands to fill the void. The total impact at the $100/tonne sequestration subsidy is enough to boost USA land-based emissions by about 6%. In every case, the diagonal elements are dominant, indicating that the most important impact of a given carbon tax/sequestration subsidy is to reduce net emissions in the region where it is levied.

It is also instructive to look at the abatement *levels* (vs. percentages). Table 9b shows how the composition of the abatement portfolio can vary from one region to the next. While forest sequestration is the dominant strategy in all regions, additional sequestration in ROW dwarfs that in other regions at around 2438 million t. Ceq. Paddy rice and livestock mitigation are a more important part of the mitigation portfolios in China and ROW in the face of a $100/tonne carbon price, while the fertilizer tax is relatively more important in USA.

4. Conclusions

We have developed a computable general equilibrium model with unique regional land types and detailed non-CO_2 GHG emissions, with particular emphasis placed on land-based greenhouse gas emissions and forest sequestration. Using this framework, we are able to evaluate the relative importance of non-CO_2 mitigation and forest carbon sequestration in different economic sectors and regions. We found that biophysical and economic characteristics can create comparative abatement advantages for GHG mitigation, both across sectors within a given country, and between the same sector in different countries. These comparative advantages result in intra- and inter-regional re-allocations of production in response to carbon prices. We observe these general equilibrium effects in terms of emissions reductions/increased sequestration as well as production and land-use. We also find that international trade structure influences regional mitigation responses, as well as international GHG emissions leakage in land-based activities in response to a regional carbon policy and profitable production increases despite increasing emissions subjected to a carbon tax.

We base our assessment of partial equilibrium, mitigation possibilities in agriculture on detailed engineering and agronomic studies commissioned by the US Enviromental Protection Agency. 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 (2006). In our global, general equilibrium analysis of carbon taxation, we find that forest carbon sequestration is the dominant means for global GHG emissions reduction in the land using sectors. However, when compared to the rest of the world, emissions abatement in the US comes disproportionately from agriculture, and, within agriculture, disproportionately from reductions in fertilizer-related emissions (primarily in maize production). In the world as a whole, agriculture-related mitigation comes predominantly in reduced methane emissions from ruminant livestock, which is followed in relative importance by reductions in methane emissions from paddy rice. We also find significant linkages between emissions in one region and mitigation in another (i.e. leakage). For example, in the US agriculture, abatement potential 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 the analysis, we we explore two avenues for carbon sequestration: intensive and extensive responses. We capture the former effect 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. When the two are combined in our global general equilibrium simulations, the intensive margin accounts for about half the sequestration response in the US, but its relative importance in the rest of the world is smaller.

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 two 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 countries, the constraining factors are just the GTAP data base itself, as well as the underlying mitigation cost studies. A second extension of this approach would bring into the model non-CO2 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 CO2 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 1: Land rent at market price 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-CO2 emissions categories and associated economic drivers (activities)

GHG/category GTAP-AEZ sector	Paddy rice	Other grain	Other crops	Ruminant livestock	Non-ruminant livestock	Forest	Ruminant animal products	Other meat products	Processed rice	Other food processing	Wood processing
Methane (CH_4)											
Enteric fermentation				x	x						
Manure management				x	x						
Rice cultivation	x										
Biomass burning	x	x	x	x							
Other industrial non-agriculture											x
Stationary and mobile combustion	x	x	x	x	x	x	x	x	x	x	x
Nitrous oxide (N_2O)											
Agricultural soils	x	x	x								
Manure management				x	x						
Pasture, range, and paddock				x	x						
Biomass burning	x	x	x	x							
Other industrial non-agriculture											x
Stationary and mobile combustion	x	x	x	x	x	x	x	x	x	x	x

Table 3: Non-CO_2 GHG emissions by sector and emissions driver category

			Sectors:						Region total
			Paddy Rice	Other Grain	Other Crops	Ruminants	Non-Ruminants	Forest	
Total non-CO_2 emissions (MtCeq)		USA	2.971	37.707	23.707	48.778	7.904	0.002	566.332
		China	70.160	20.284	77.911	68.773	41.884	0.017	576.044
		ROW	137.364	101.363	167.219	630.131	79.590	0.079	2916.635
		World	210.495	159.354	268.837	747.682	129.378	0.097	4059.011
Share of sectoral emissions by driver (%)	Output	USA	0	0	1	0	0	0	75
		China	0	0	0	0	0	0	51
		ROW	0	2	2	0	0	0	60
		World	0	1	2	0	0	0	61
	Endowment	USA	69	0	0	100	100	0	10
		China	85	0	0	100	100	0	30
		ROW	79	0	0	100	100	0	28
		World	80	0	0	100	100	0	26
	Intermediate input	USA	31	100	99	0	0	100	14
		China	15	100	100	0	0	100	20
		ROW	21	98	98	0	0	100	11
		World	19	99	98	0	0	100	13

Table 4: Key emissions intensities (MtC/$ of input, where MtC = 1000 Kg C)

	Emission intensities (MtC/$ of input)			Forest carbon intensities (MtC/$ 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			

Table 5: Elasticities of substitution 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)	
Output elasticities	USA	0	0	0	0	0	0
	China	0	0	0	0	0	0
	ROW	0	0	0	0	0	0
Intermediate input elasticities	USA	0.5	1.3	0.5	0	0	0
	China	0.5	0.6	0.5	0	0	0
	ROW	0.5	1.5	0.5	0	0	0
Endowment elasticities	World	1.1	0.237198	0.237198	0.191	2	0.2

* Adjusted the forest carbon intensities to calibrate to Sohngen (2005) forest carbon response curves.

Table 6: Carbon sequestration supply schedule: by category, annual equivalent abatement over 20 years (MMTCE)**

Carbon price	Extensive Margin	Intensive Margin	Wood Products	Access Margin**	Total
US					
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
CHINA					
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
ROW					
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

Source: Results based on model described in Sohngen and Mendelsohn (2006).
* Calculated assuming a 5% discount rate.
** Storage due to setting aside of forests at accessible margin in temperate and boreal regions only

Table 7: Change in regional trade balances due to unilateral carbon taxes: $100/t.

	USA only			ROW only			China only		
Sector	USA	CHN	ROW	USA	CHN	ROW	USA	CHN	ROW
Rice	-203	19	180	798	540	-1331	34	-241	192
OtherGrain	-2765	118	2700	5593	885	-6488	263	-600	323
OtherCrops	-2770	185	2510	4244	2857	-6991	97	-929	828
Ruminants	-1756	8	1689	5333	175	-5390	21	-181	157
NonRuminants	-240	38	208	1122	558	-1633	122	-548	426
OthFood	-102	4	115	1539	206	-1343	100	-627	539
Forest Prdts	1486	-105	-1340	-3142	-1103	4592	-154	726	-590
Fertilizer & Engy Int Mnfcs	1729	0	-1648	-3553	284	4474	-319	2126	-1727
OtherMnfcSves	4907	-218	-4747	-16237	-5610	19630	133	-760	589
Total	285	49	-334	-4303	-1207	5519	297	-1034	738

Table 8: Percentage change in U.S.A. land rents and land use by sector following a $100/tonne Carbon tax in USA only

	Percentage change in land rents					
	Forest	Paddy Rice	Other Grain	Other Crops	Ruminants	
AEZ1	1225.70	-21.39	10.13	14.08	17.59	
AEZ2	1224.09	-19.40	9.93	13.88	17.38	
AEZ3	1223.97	-19.18	9.91	13.86	17.36	
AEZ4	1225.44	-20.85	10.07	14.02	17.53	
AEZ5	1228.88	-25.59	10.41	14.36	17.91	
AEZ6	1235.81	-38.88	11.19	15.16	18.71	
	Percentage change in land use					
	Forest	Paddy Rice	Other Grain	Other Crops	Ruminants	
AEZ1	78.66	-29.03	-4.77	-1.84	-1.48	
AEZ2	83.04	-25.16	-1.89	1.10	1.44	
AEZ3	83.33	-24.79	-1.62	1.37	1.77	
AEZ4	79.31	-27.99	-3.95	-1.00	-0.60	
AEZ5	70.20	-35.04	-8.56	-5.70	-5.80	
AEZ6	52.94	-51.45	-19.02	-16.33	-16.21	
	Percentage change in land use, weighted by AEZ land rent share					
	Forest	Paddy Rice	Other Grain	Other Crops	Ruminants	
AEZ1	2.23	-0.06	-0.98	-0.32	-0.84	
AEZ2	0.10	-0.04	-0.79	0.31	0.42	
AEZ3	0.11	-0.09	-0.77	0.54	0.21	
AEZ4	2.38	-0.05	-1.85	-0.39	-0.05	
AEZ5	6.96	-0.73	-3.95	-1.57	-0.42	
AEZ6	12.61	-1.05	-3.05	-7.22	-0.37	
	AEZ land rent shares					
	Forest	Paddy Rice	Other Grain	Other Crops	Ruminants	Total
AEZ1	0.008	0.002	0.218	0.184	0.588	1
AEZ2	0.000	0.002	0.426	0.283	0.289	1
AEZ3	0.000	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	0.030	1

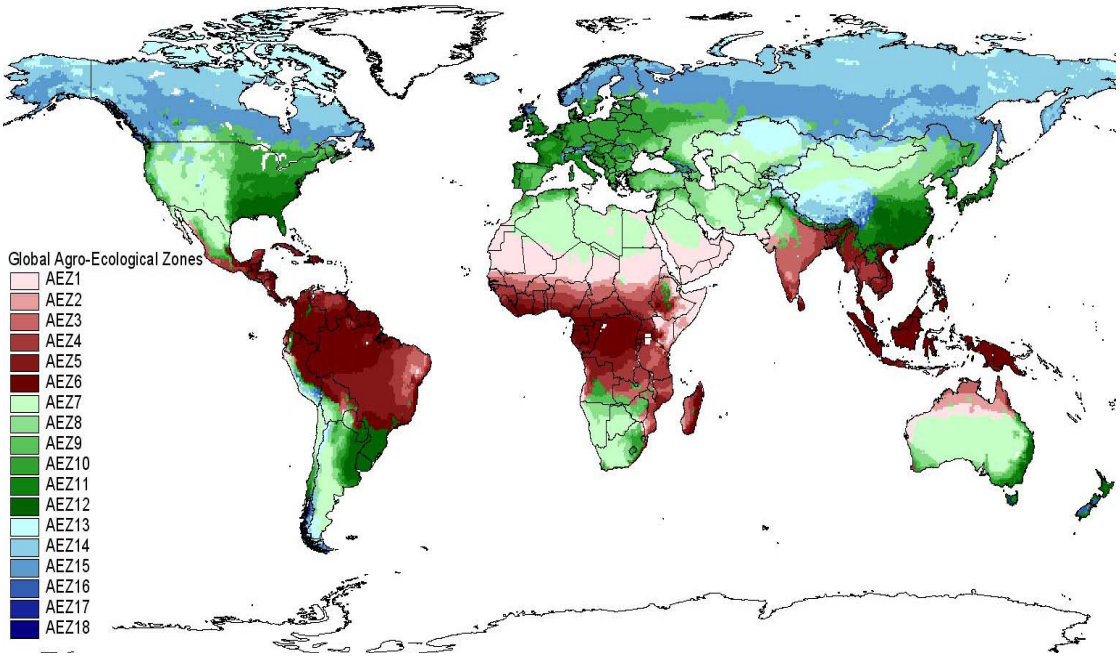
Table 9a: General equilibrium impact of emissions taxes on net emissions in each region following a global tax of $100/tCeq (percentage change)

Type/region of taxation		Emissions/sequestration change from region (%)		
		USA	CHN	ROW
Output related emissions	USA	-0.01	0	0
	CHN	0	0	0
	ROW	0.03	0.01	-0.02
Purchased input related emissions	USA	-8.27	0.08	0.61
	CHN	0.28	-4.26	0.32
	ROW	1.73	0.27	-2.54
Primary factor related emissions	USA	-1.98	0.01	0.19
	CHN	-0.04	-12.88	-0.04
	ROW	0.79	0.15	-7.41
Forest sequestration	USA	-75.37	0.04	0.6
	CHN	0.09	-42.96	0.18
	ROW	6.27	0.9	-131.58
Total Impact		-76.48	-58.63	-139.69

Table 9b: General equilibrium impact of emissions taxes on net emissions in each region following a global tax of $100/tCeq (levels change)

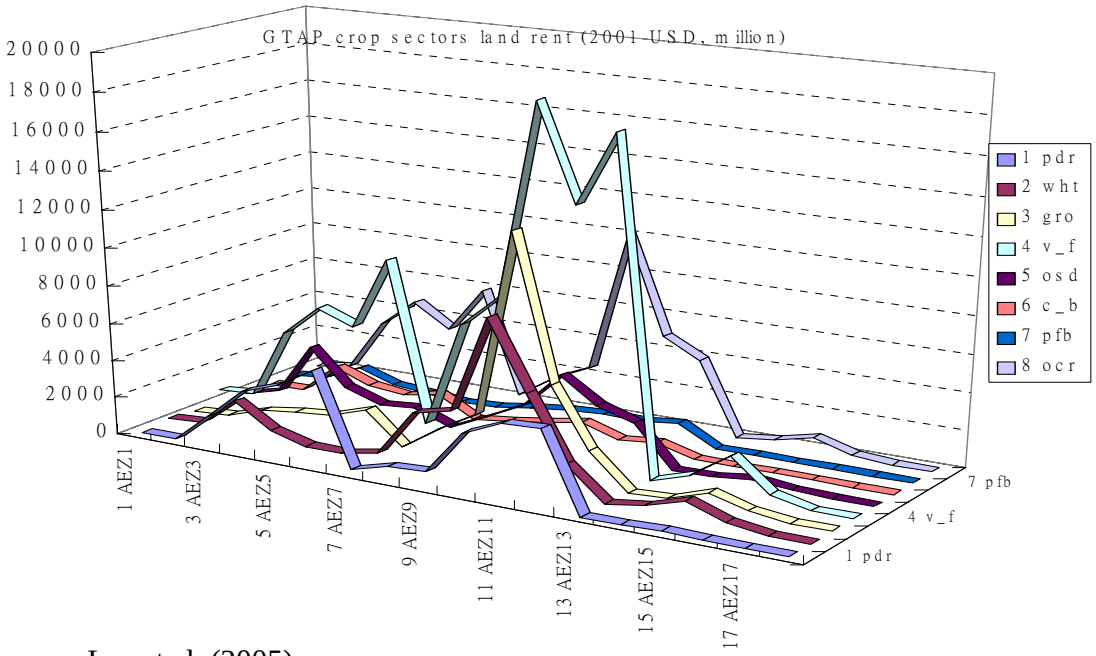
Type/region of taxation		Emissions change from region (MtCeq)		
		USA	CHN	ROW
Output related emissions	USA	-0.03	0.00	0.00
	CHN	0.00	0.00	0.00
	ROW	0.09	0.04	-0.37
Purchased input related emissions	USA	-24.07	0.31	11.30
	CHN	0.81	-16.75	5.93
	ROW	5.04	1.06	-47.06
Primary factor related emissions	USA	-5.76	0.04	3.52
	CHN	-0.12	-50.64	-0.74
	ROW	2.30	0.59	-137.30
Forest sequestration	USA	-219.38	0.16	11.12
	CHN	0.26	-168.90	3.34
	ROW	18.25	3.54	-2438.11
Total Impact		-222.61	-230.5	-2588.32

Figure 1: GTAP's 18 Agro-Ecological Zones



Source: Lee et al. (2005)

Figure 2: Cropland land rents by AEZ



Source: Lee et al. (2005)

Figure 3: Total non-CO_2 GHG emissions by region and sector (MtCeq)

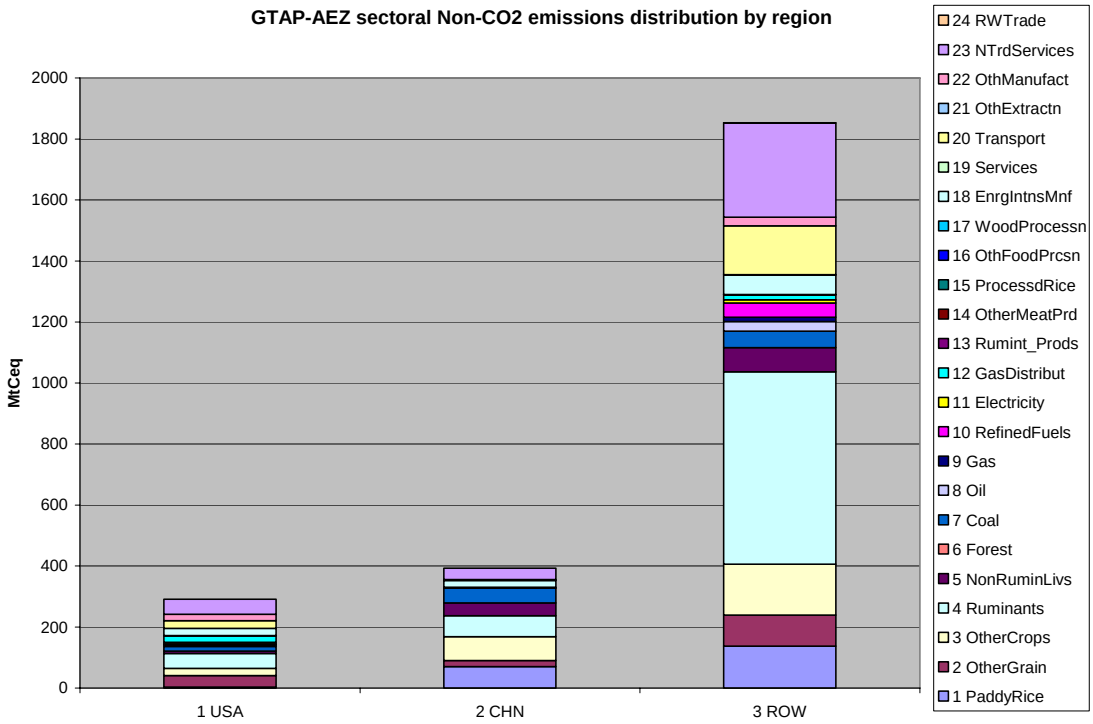


Figure 4: Sector-specific CES structure for AEZ land demand

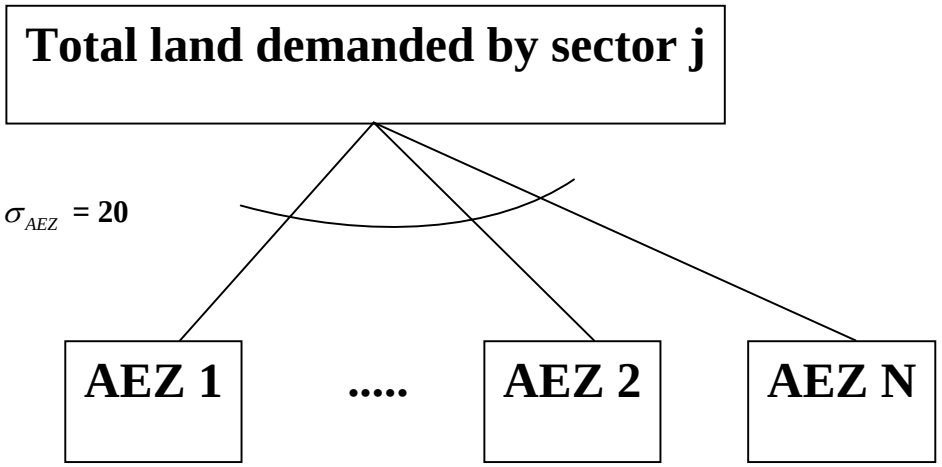


Figure 5: Three-tier structure of AEZ-specific land supply

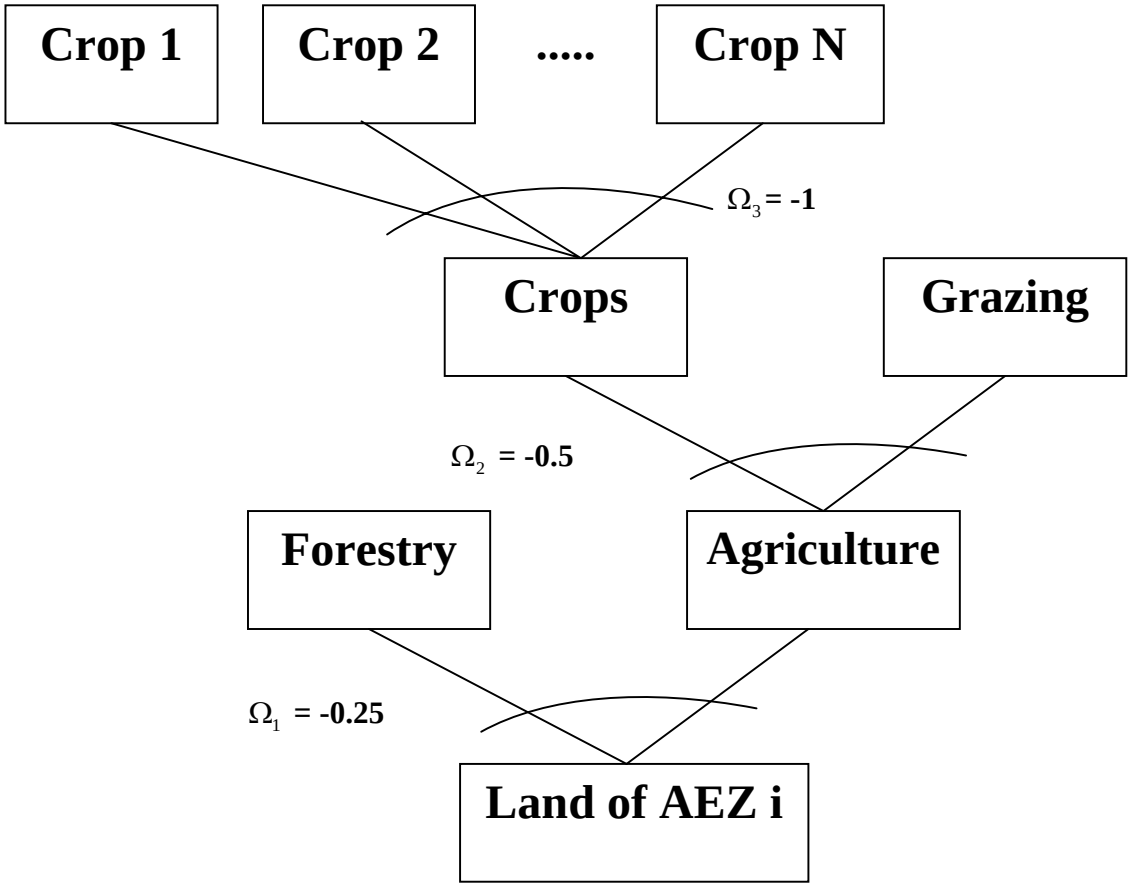


Figure 6: Production structure: with output related emissions included

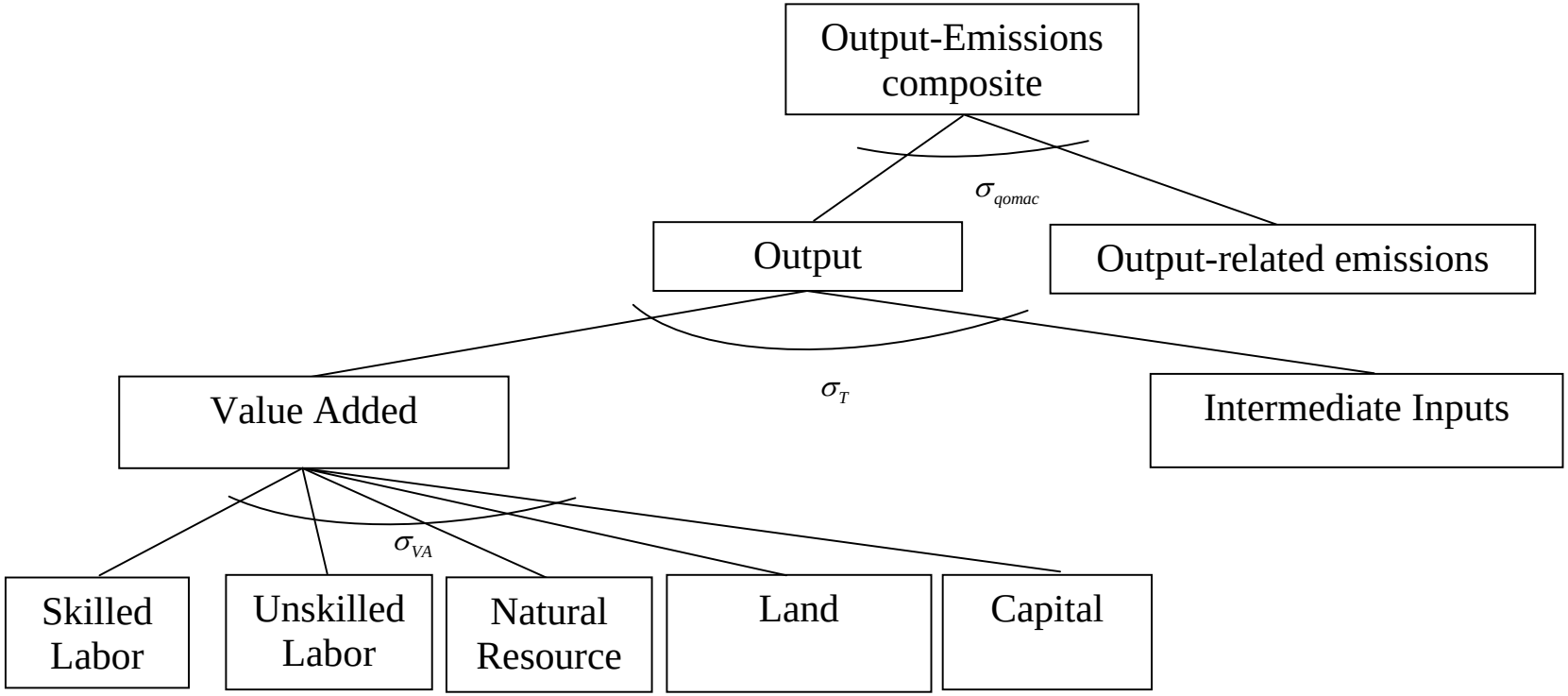


Figure 7: Production structure for the forest sector

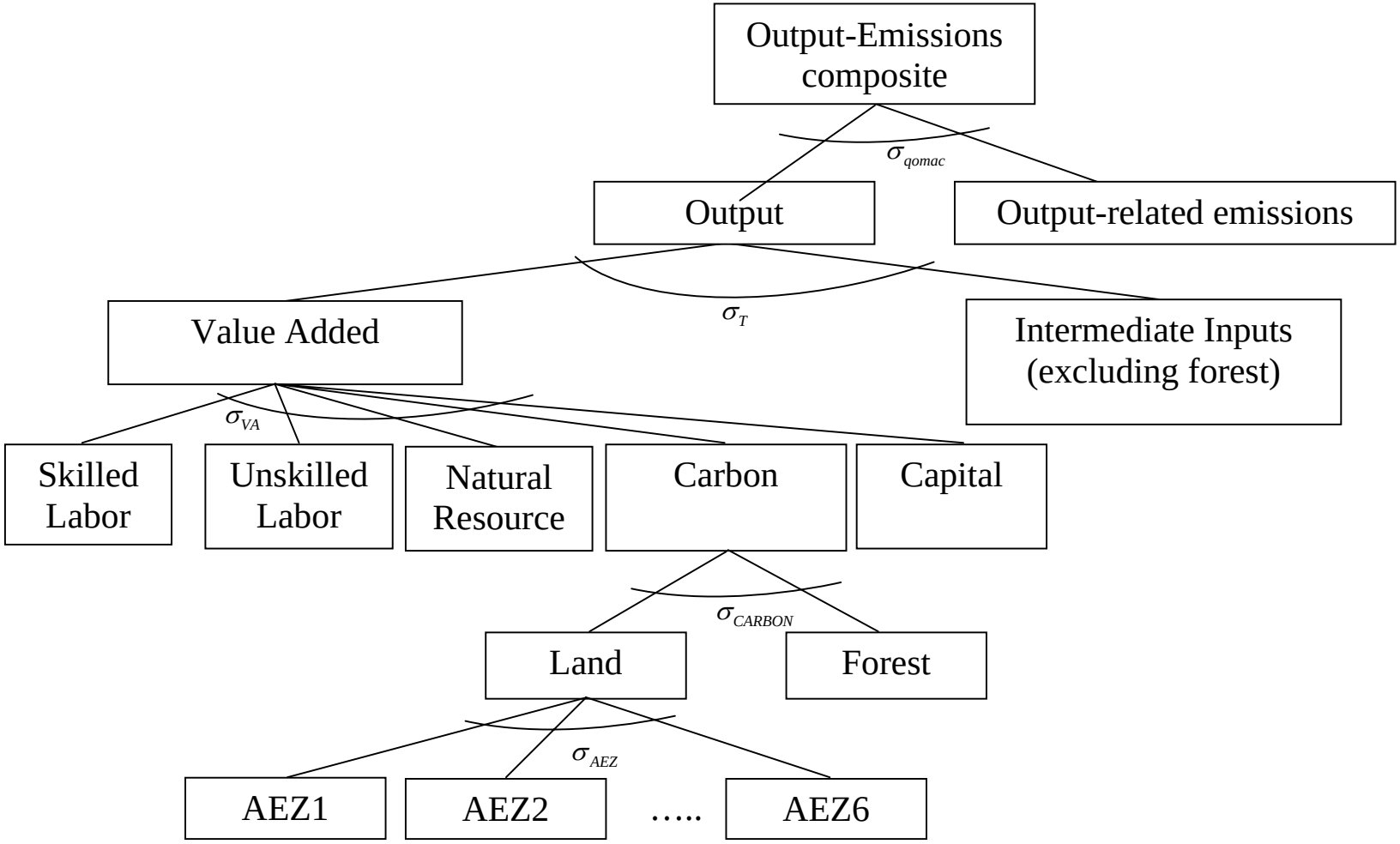


Figure 8: Calibration of USA cropland GHG mitigation costs

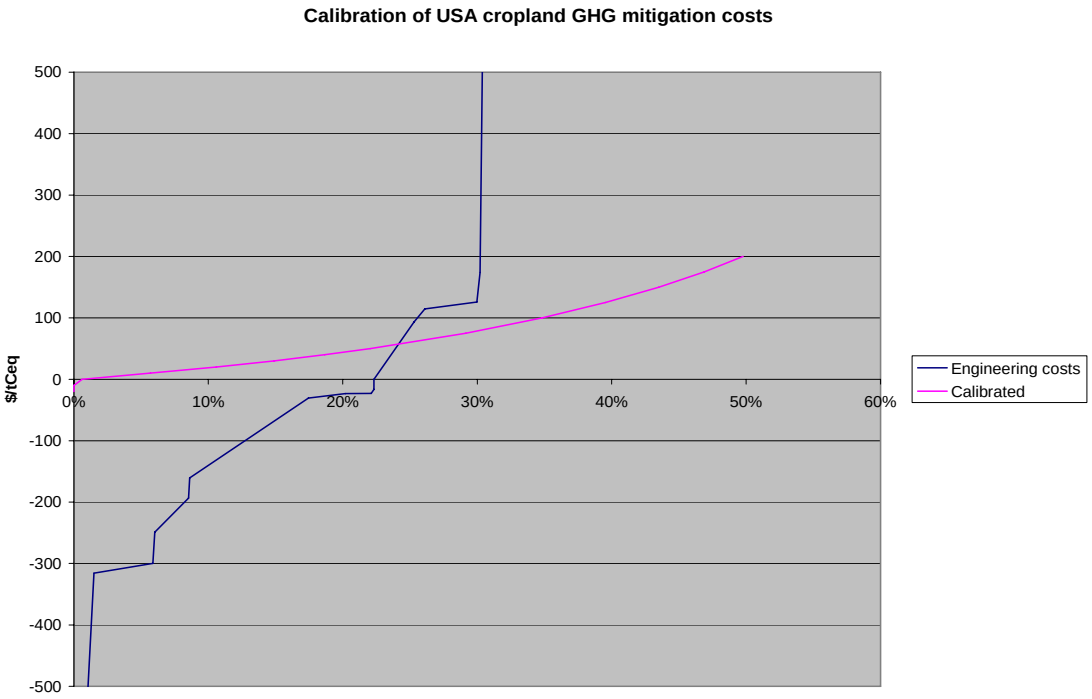


Figure 9: Calibrated ROW forest carbon sequestration curve via extensification (20-year annual equivalent abatement)

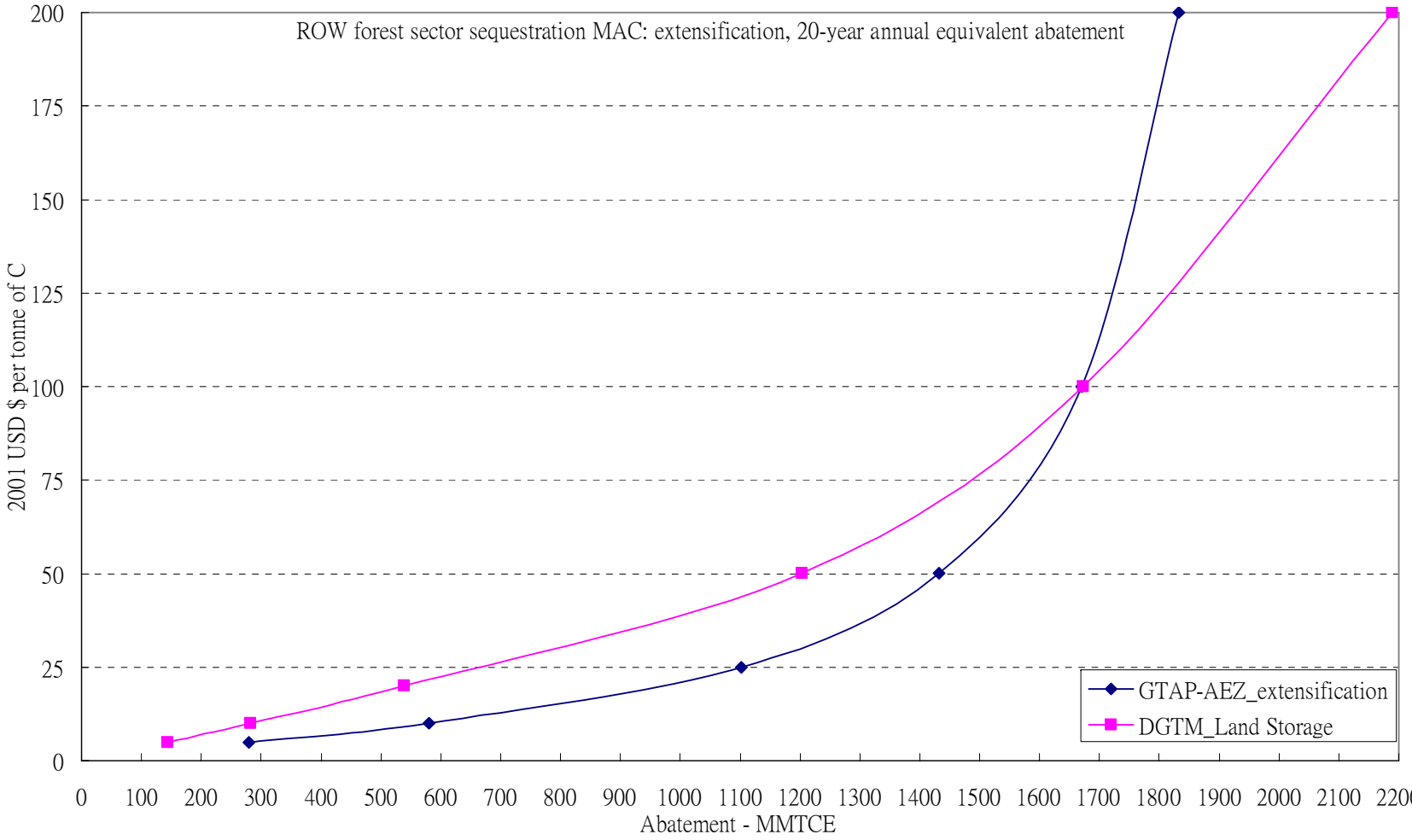


Figure 10: Calibrated USA forest carbon sequestration curve via intensification (20-year annual equivalent abatement)

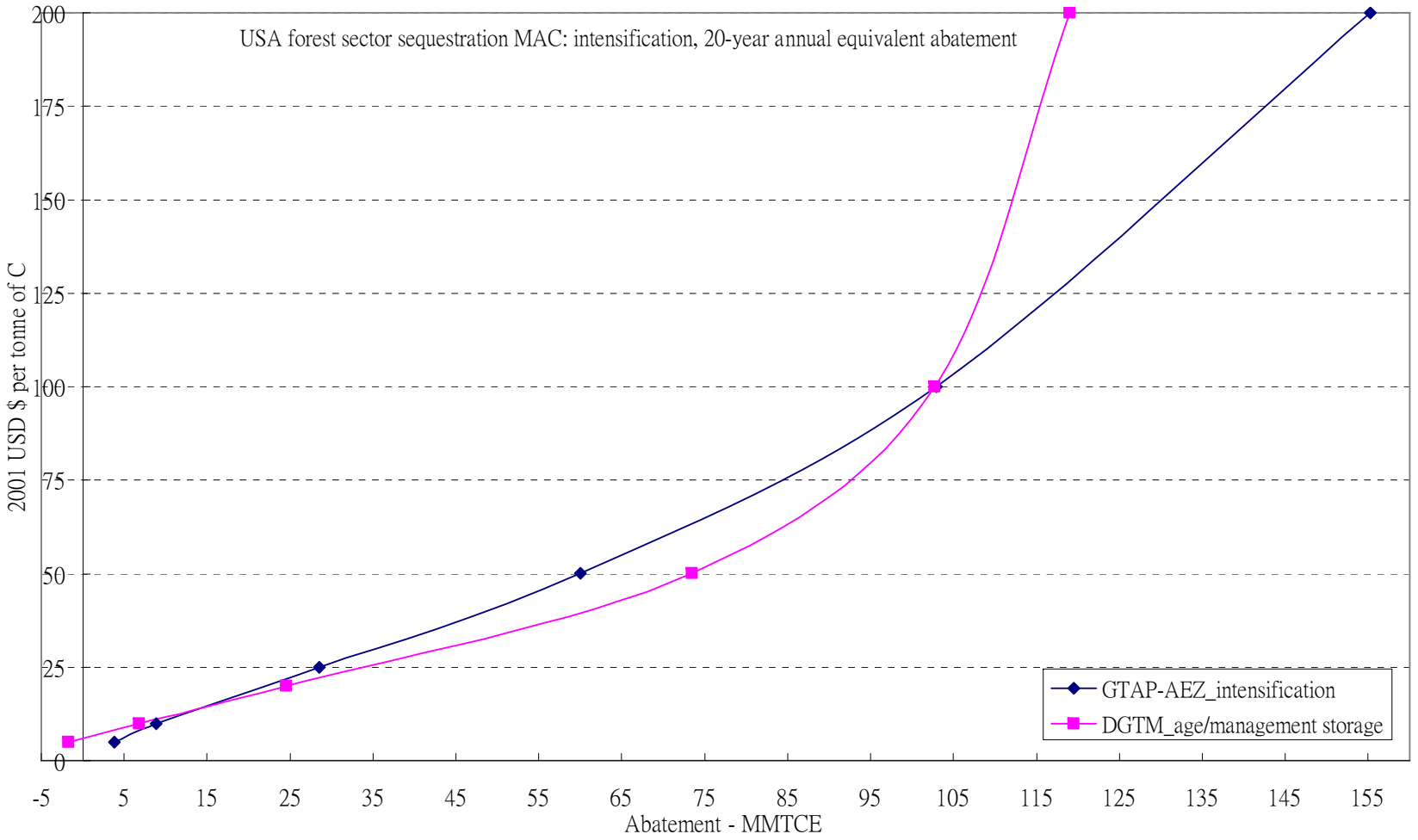


Figure 11: USA agriculture and forestry general equilibrium GHG abatement supply schedules for USA-only carbon tax

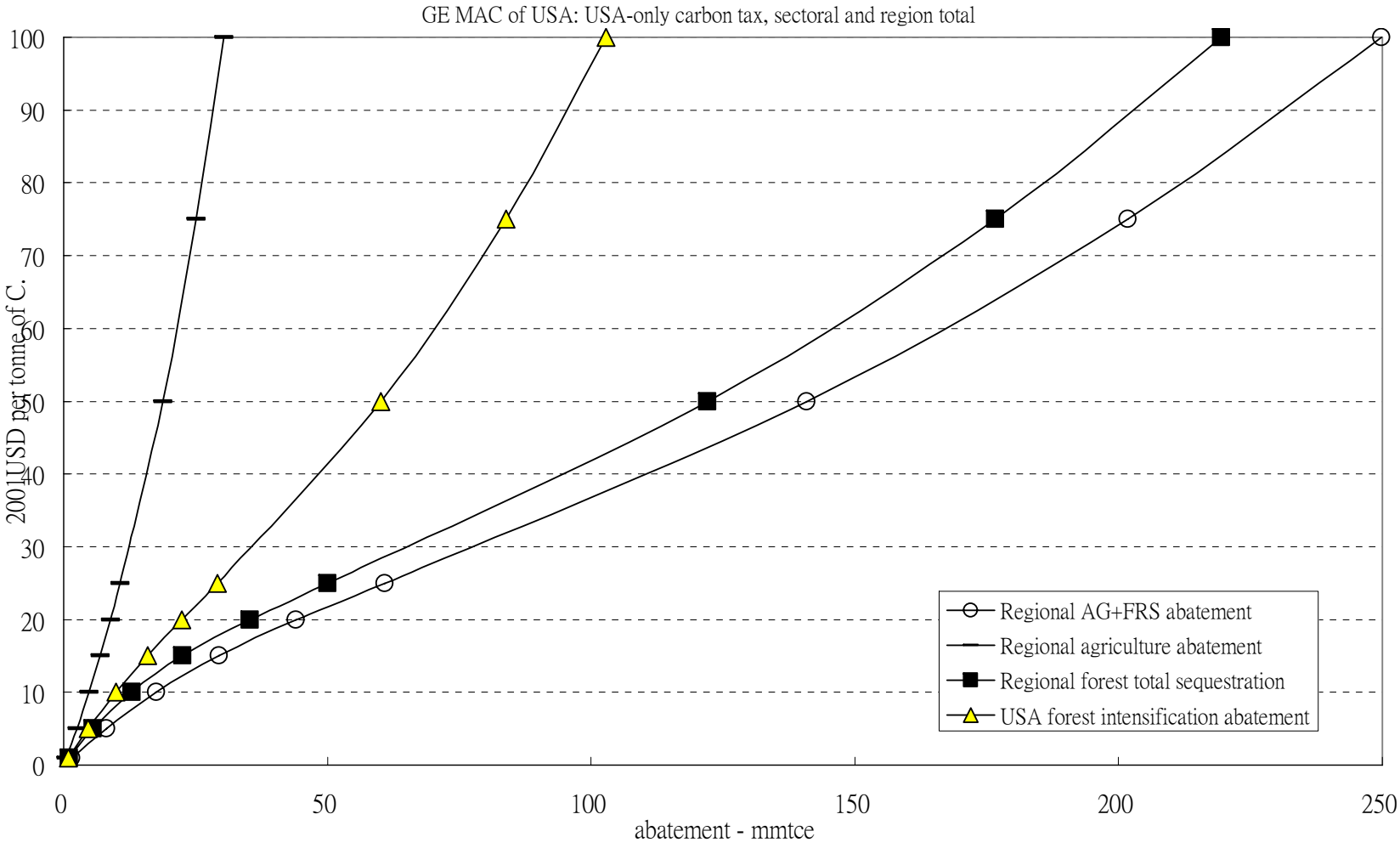


Figure 12: USA agriculture subsector GHG abatement supply schedules for USA-only carbon tax

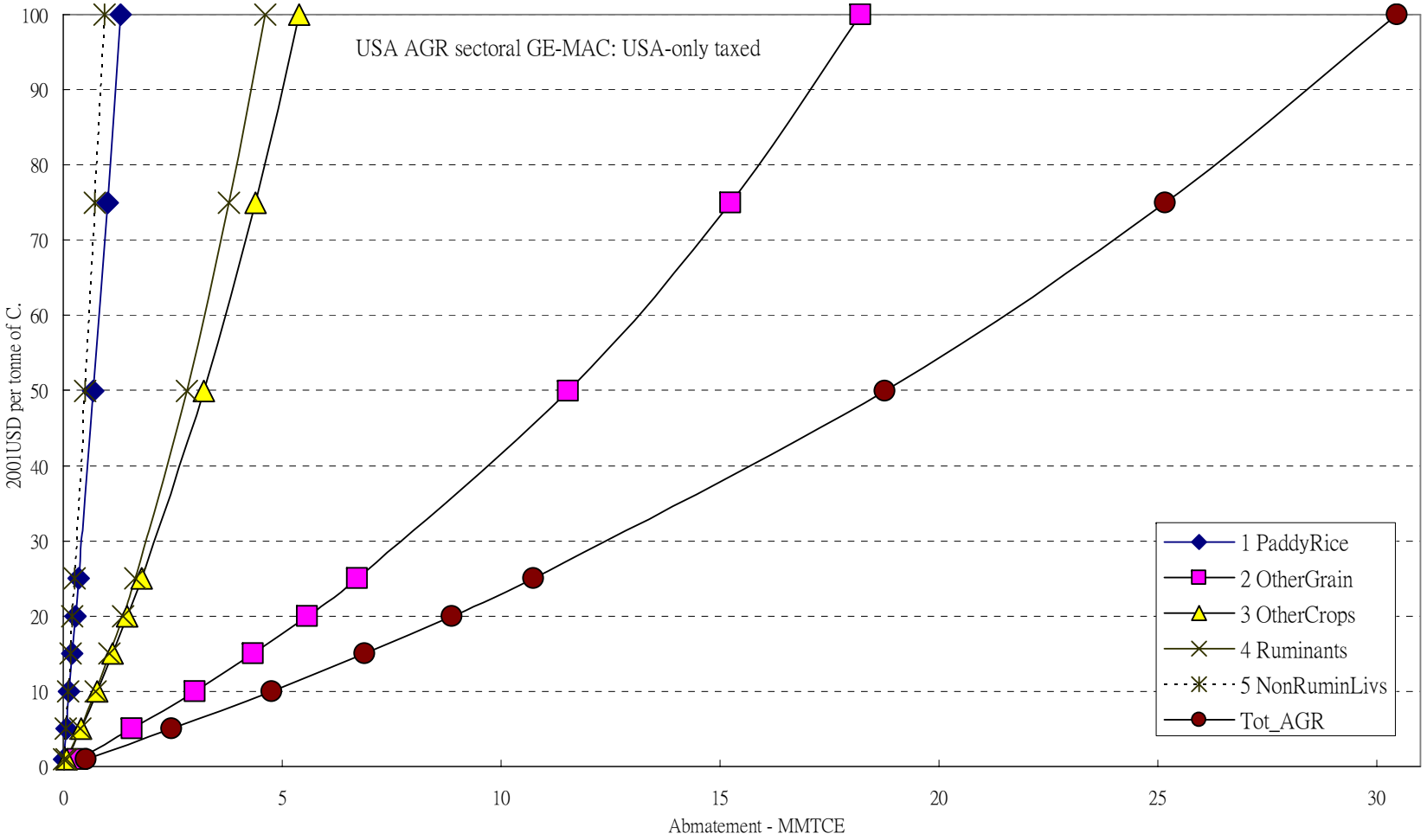


Figure 13: ROW agriculture subsector GHG abatement supply schedules for USA-only carbon tax

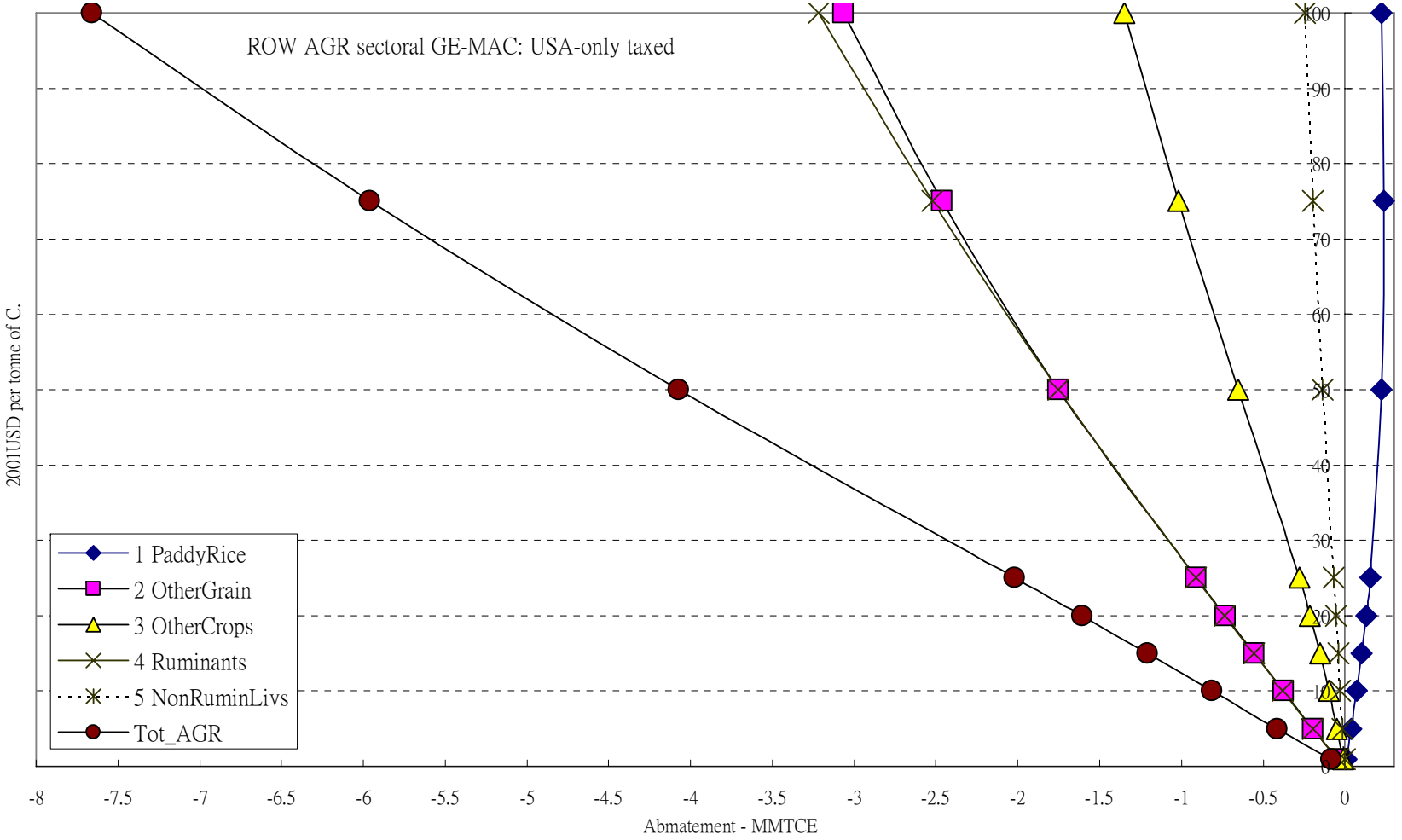


Figure 14: ROW agriculture and forestry general equilibrium GHG abatement supply schedules for USA-only carbon tax

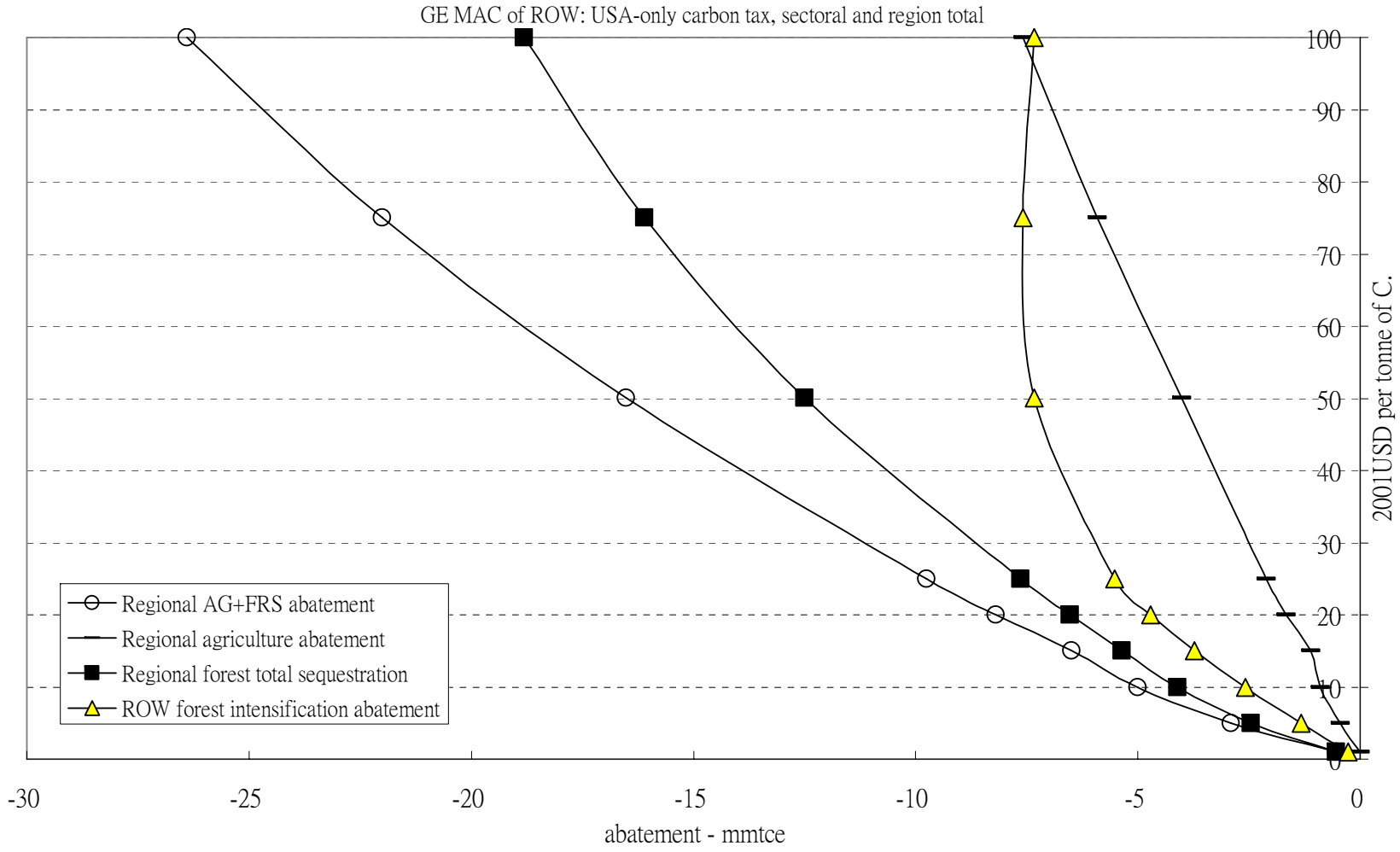


Figure 15: USA agriculture and forestry general equilibrium GHG abatement supply schedules for ROW-only carbon tax

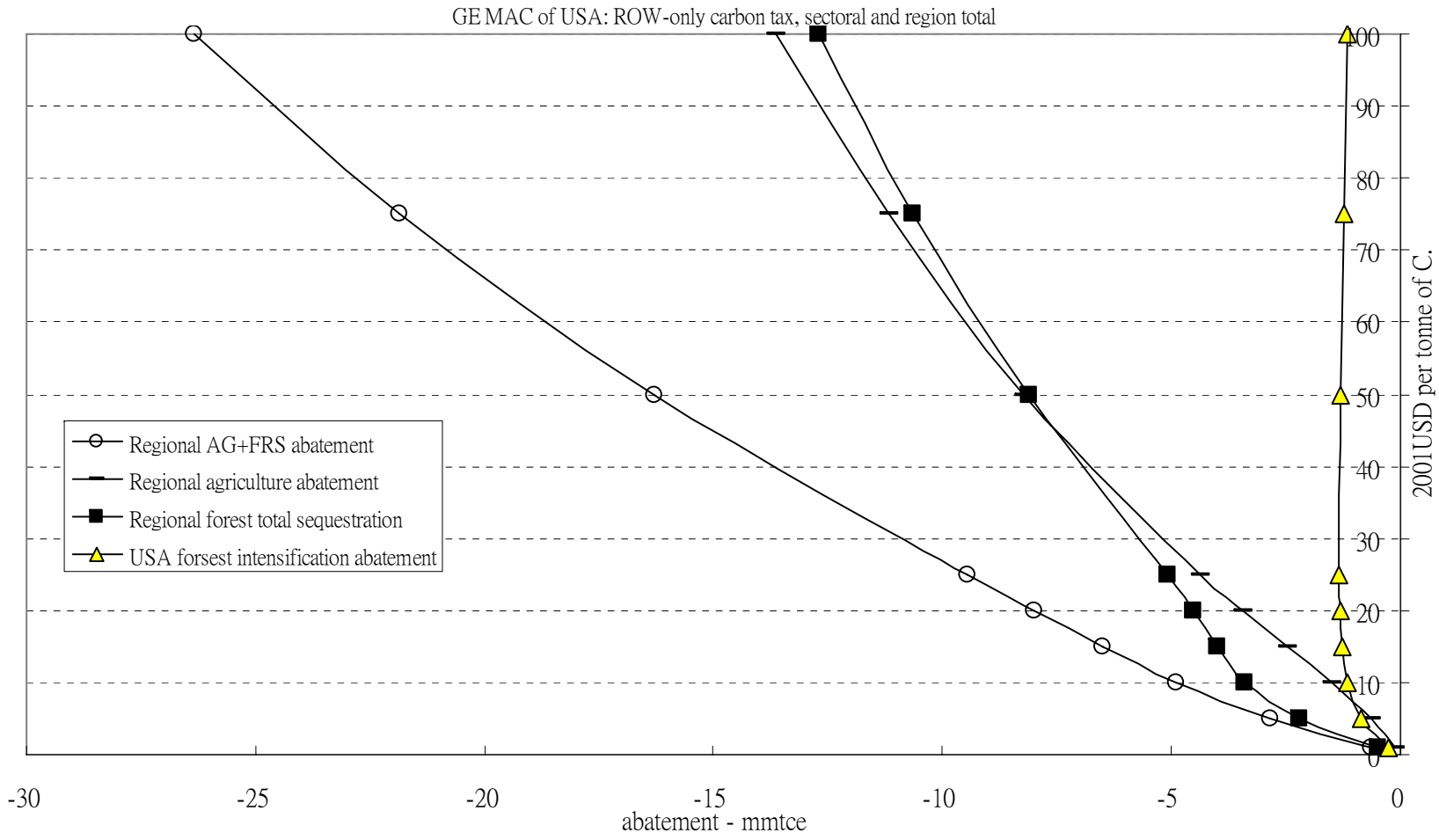


Figure 16: USA agriculture subsector GHG abatement supply schedules for ROW-only carbon tax

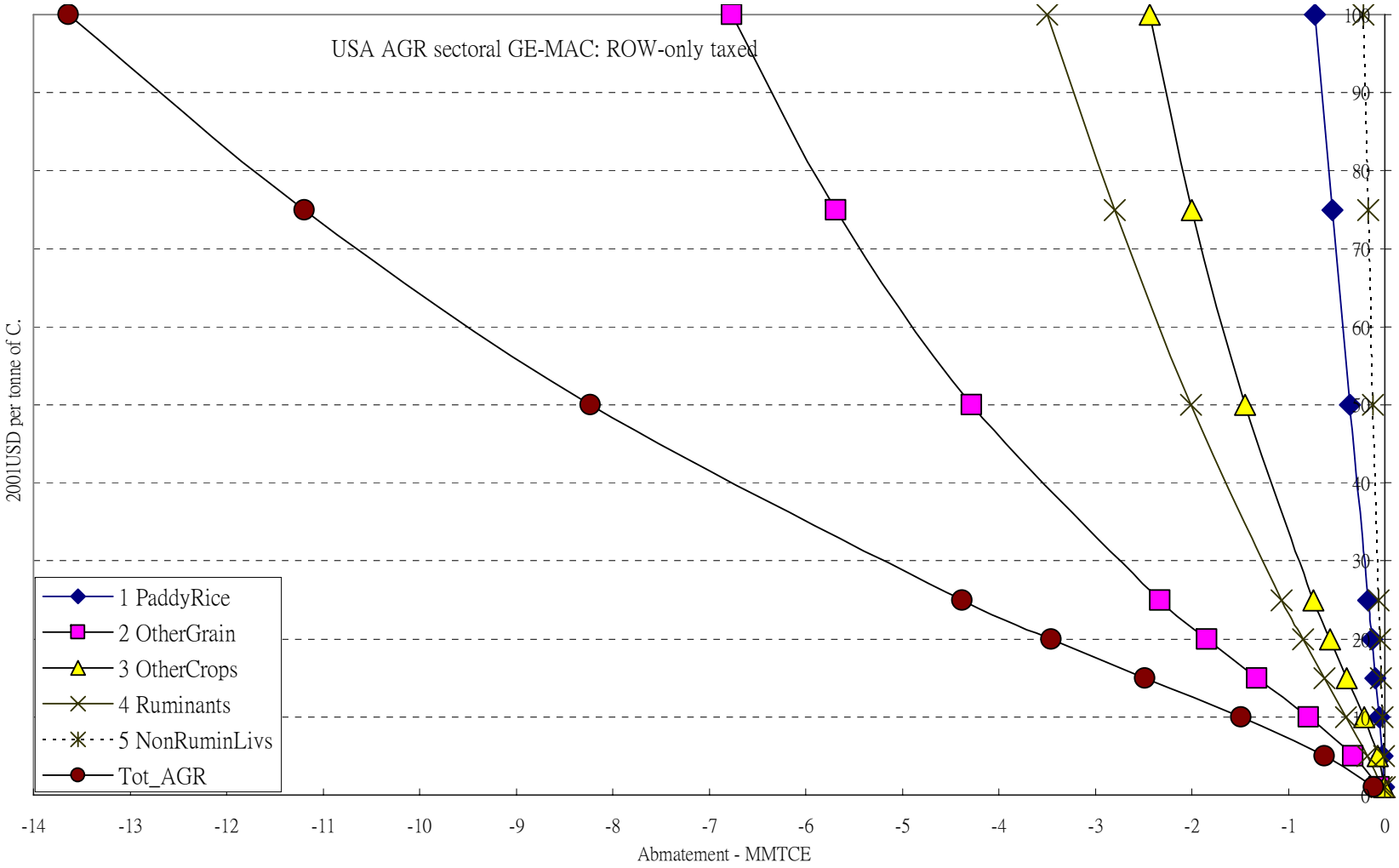


Figure 17: USA agriculture subsector GHG abatement supply schedules for global carbon tax

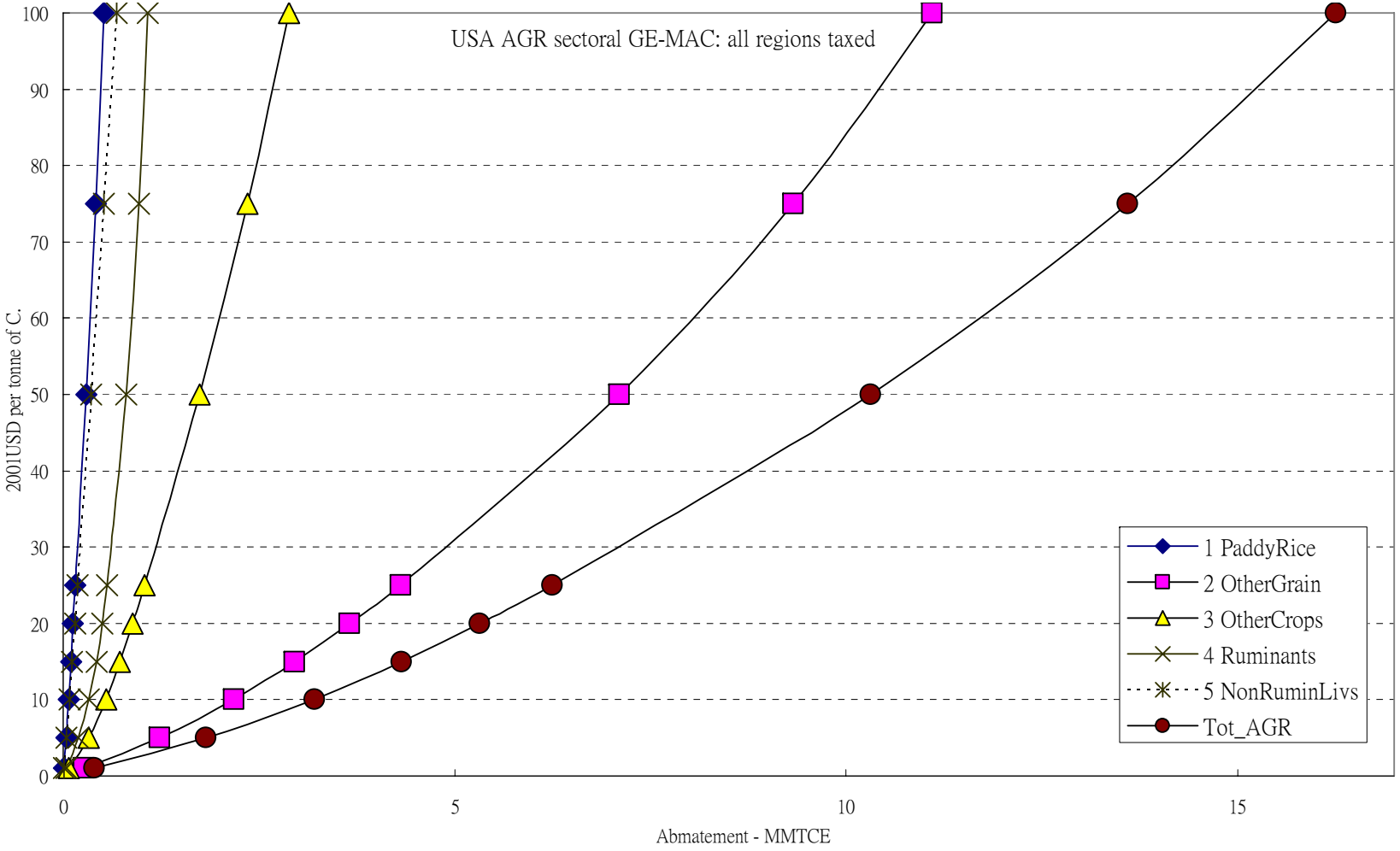


Figure 18: USA agriculture and forestry general equilibrium GHG abatement supply schedules for global carbon tax

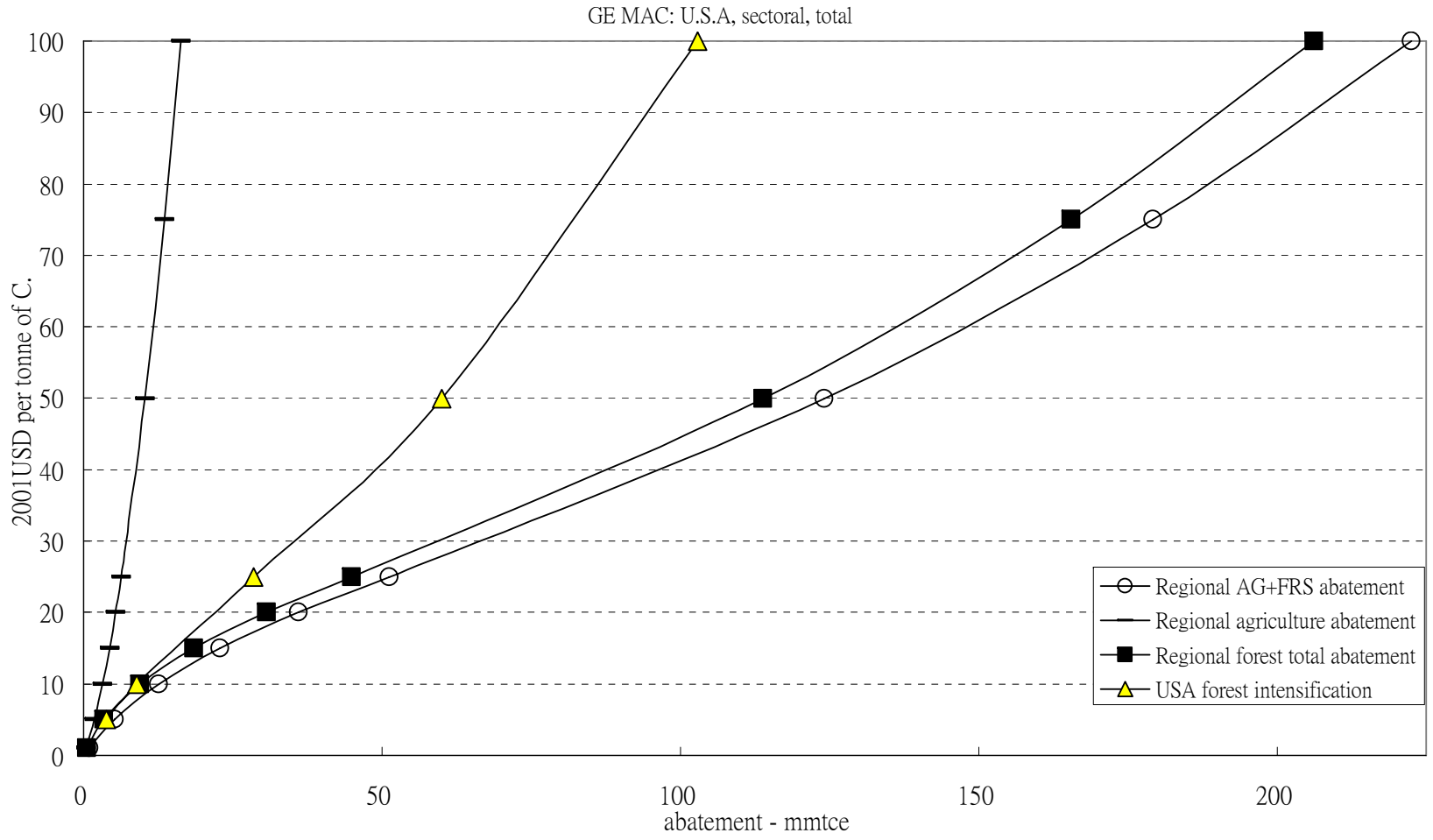
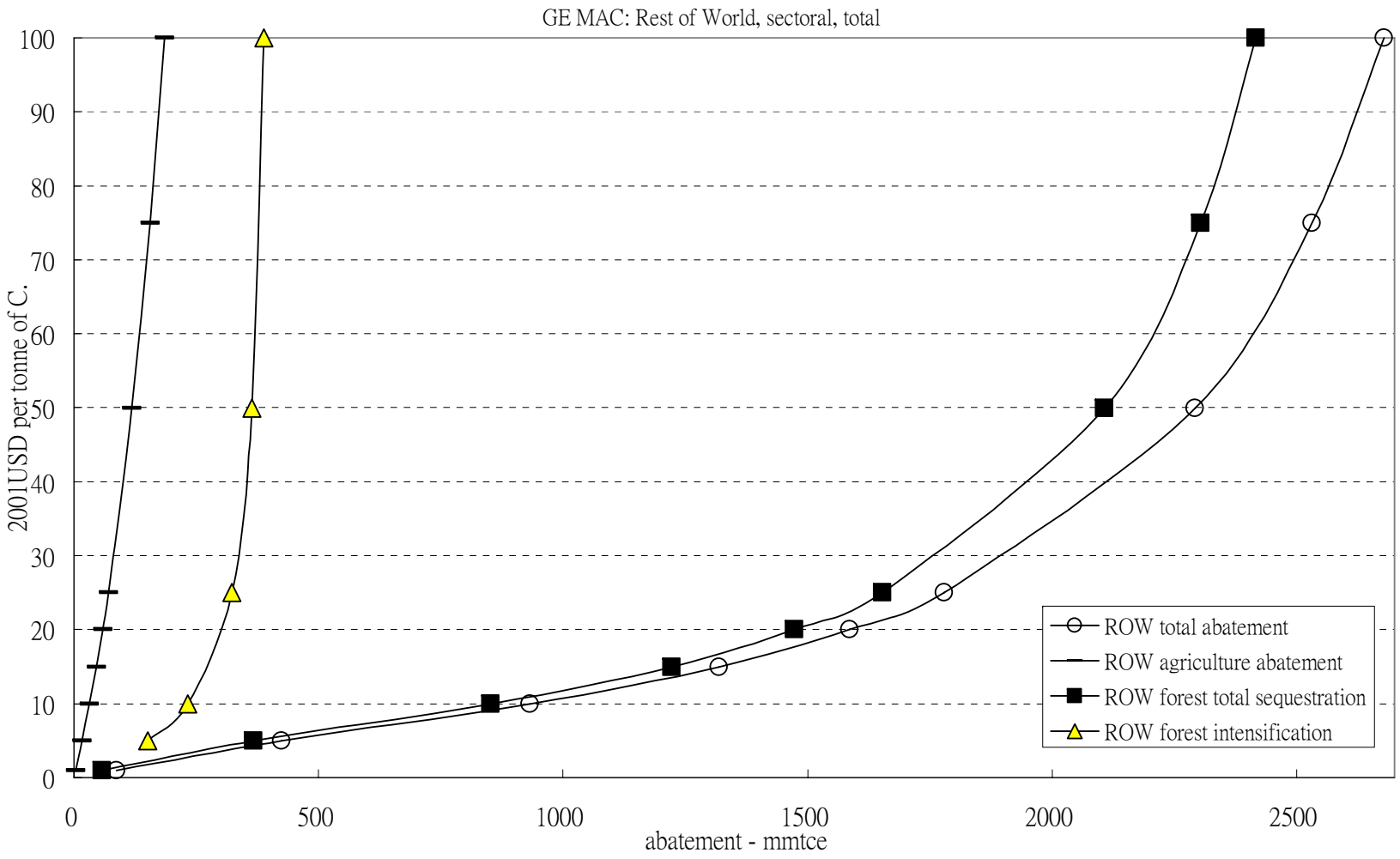


Figure 19: ROW sectoral general equilibrium GHG abatement supply schedules for global carbon tax



Figures 20: Global agriculture subsector GHG abatement supply schedules for global carbon tax

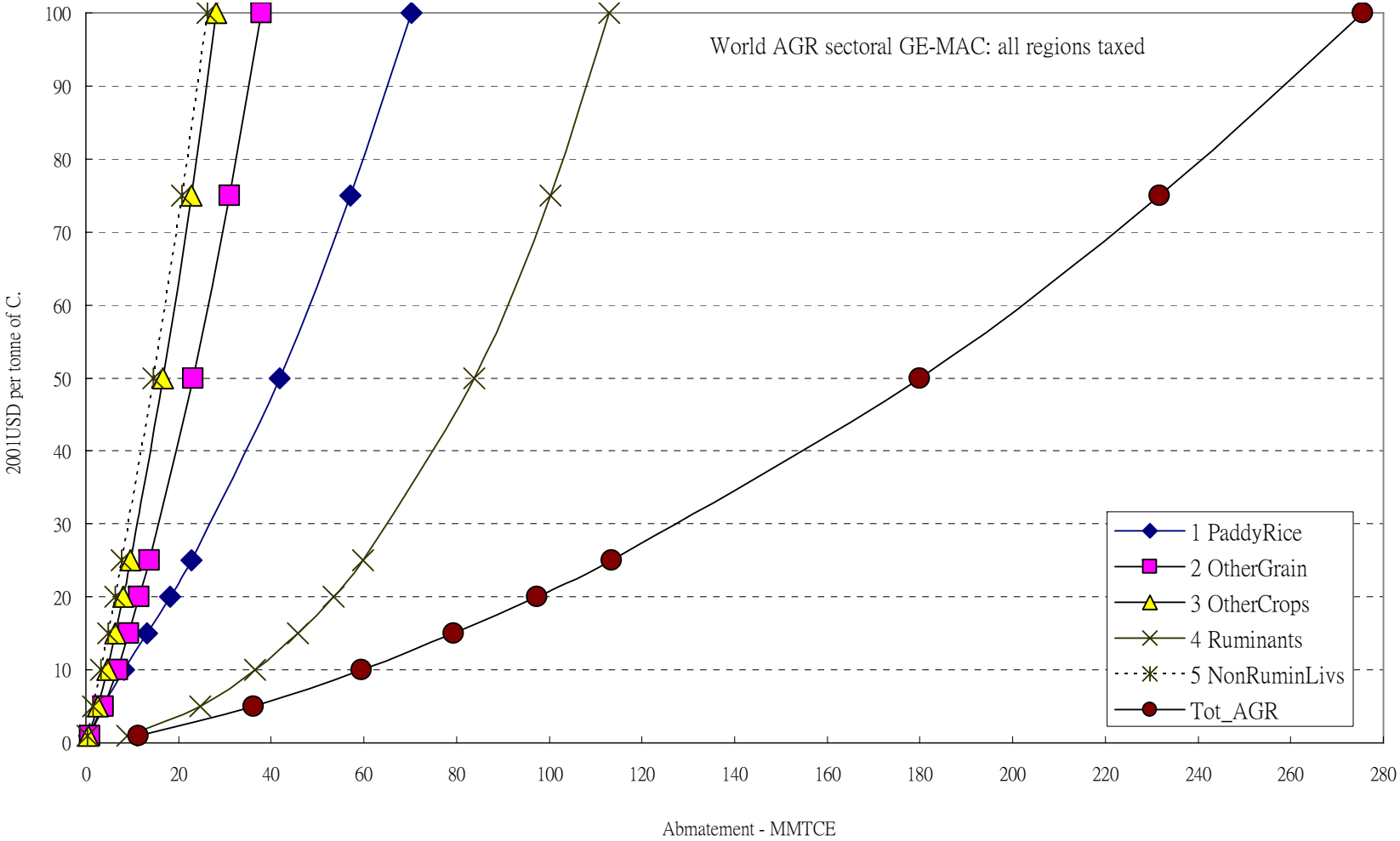


Figure 21: Regional general equilibrium GHG abatement supply schedules for global carbon tax (HL: all prod_comm taxes)