“Land heterogeneity in determining climate change mitigation costs”

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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 management activities are responsible for approximately 50% of global atmospheric inputs of methane (CH_4) and agricultural soils are responsible for 75% of global nitrous oxide emissions (N_20), for a net contribution from non-CO_2 GHGs of approximately 14% of all anthropogenic greenhouse gas emissions (USEPA, 2006a).

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). Partial and general equilibrium and integrated assessment frameworks are currently being developed to more careful study climate change policy and the role of land in mitigating climate change. Until recently, this work has been hindered by the lack of a consistent global land resource database 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.

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. Focusing on the USA and China, and taking into account both CO2 and non-CO2 gases, she computes the cost of achieving various national abatement targets in the absence of land mobility within agriculture and between agriculture and forestry. She then compares this cost to that obtained when the potential to move land across uses, within AEZs, is taken into account. Lee finds that the failure to account for land mobility is likely to result in a potentially large overstatement of the marginal cost of mitigation.

The GTAP-AEZ derivative developed in this paper implements new global data and constructs a CGE model with heterogeneous land factor inputs and detailed land related GHG emissions. With this tool, we begin to explore the role of land in GHG mitigation. Specifically, 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 climate price policies.

Our model employs the newly available GTAP land database (Lee et al., 2005). The land database enhances the standard GTAP global economic database by disaggregating land endowments and use into 18 Agro-ecological Zones (AEZs). Second, the model incorporates newly available non-C02 emissions data for the year 2001 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 engineering cost studies. Finally, we work with a more disaggregated model structure, aimed at capturing key GHG emissions and sequestration activities. There are 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.

In addition, we bring to bear additional information aimed at better informing the issue of land mobility within national AEZs. In the new GTAP-AEZ model, land is imperfectly mobile across uses, with the degree of land mobility depending on the extent of heterogeneity within that particular national AEZ. Heterogeneity is measured along five different dimensions: (1) accumulation of days with temperature values above 5 degree Celsius, (2) moisture availability (ratio of actual evapotranspiration to potential evapotranspiration), (3) soil carbon density in the top 30 cm. of the soil, (4) Soil pH in the top 30 cm. of the soil, and (5) topography.

We distinguish three types of mitigation responses (costs) in our analysis: those associated with sectoral outputs (e.g., methane emissions from landfills), 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 ladn cover). Each individual type of response 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 elasticity of substitution in production.

Given the exploratory nature of this research, we focus our analysis on the marginal cost of abatement schedules by sector and region, for net emissions from non-fossil fuel combustion activities. This puts the emphasis front and center on emissions and sequestration 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 and between regions in the global economy. We found comparative abatement advantages for land endowments, both domestically and internationally, that result in re-allocations of production in response to carbon prices. We also found that the regional profitability of production can improve due to general equilibrium effects despite increasing emissions subjected to a carbon tax.

Section 2 describes the GTAP-AEZ model framework, including the land, GHG, and land heterogeneity data, as well as the mitigation cost calibration. 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 heterogeneous land. We do this by bringing climatic and agronomic information to bear on the problem – introducing Agro-Ecological Zones (AEZs) (Lee et al., 2005).

The most natural approach to bringing these AEZs into the GTAP model would be to have a different activity for each AEZ/product combination, with the resulting outputs (e.g., wheat) competing in the product markets. Presuming like products produced in each region are perfect substitutes, then a single price will prevail. If the production functions are similar, and the firms face the same prices for nonland factors, then land rents in comparable activities must also move together. From the point of view of land markets – the focus of this paper – this is the key result – the returns to land on different AEZs employed in the production of the same product must move together. Now this result can be obtained in a variety of ways. The first is to incorporate separate production functions for each AEZ/product combination. With as many as 18 AEZs possible, this results in a great proliferation of sectors and dimensions in the model. An alternative is to retain a single, national production function for each commodity, but to introduce the different AEZs as inputs to this national production function. With a sufficiently high elasticity of substitution in use (we use 20), we are assured that the return to land across AEZs, but within a given use, will move closely together. This is the approach taken here. A natural way to constrain land supply within an AEZ is via the Constant Elasticity of Transformation (CET) frontier. This is the approach taken in the standard GTAP model (Hertel, 1997), and it is effective at restricting land mobility. In this specification, the absolute value of the CET pararmeter represents the upper bound (the case of a tiny rental share) 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).

Of course, given the rather coarse grouping of land into AEZs, there is still considerable heterogeneity within these units, and this, in turn, is likely to limit the mobility of land across uses within an AEZ. Of course, there are many other factors, beyond those reflected in the AEZs, that limit land mobility. These include: costs of conversion, managerial inertia, un-measured benefits from crop rotation, etc.

We measure heterogeneity along five different dimensions: (1) accumulation of days with temperature values above 5 degree Celsius, (2) moisture availability (ratio of actual evapotranspiration to potential evapotranspiration), (3) soil carbon density in the top 30 cm. of the soil, (4) Soil pH in the top 30 cm. of the soil, and (5) topography. Each dimension is represented by an index. The standard deviations of these indices within a given national AEZ are computed, normalized to the (0,1) interval, and then averaged to obtain a unique index of land heterogeneity by AEZ (Figure 1).

Calibration of the constant elasticity of transformation land supply functions in the model is such that the aggregated national supply of land to different activities within the country replicates econometric evidence in land supply within cropping activities, while permitting mobility to vary across national AEZs depending on the heterogeneity index. We adjust the elasticity of transformation for each region/AEZ, to account for the measure of AEZ heterogeneity such that land mobility is lower, the more heterogeneous the endowment. Specifically, we treat the (positive) land supply elasticity parameter as a decreasing function of the heterogeneity of AEZs, with land supply reaching its minimum value (zero) in the most heterogeneous AEZ. The slope is determined such that the line passes through the point determined by the global average heterogeneity index and the global average supply elasticity.

The estimated elasticities of transformation amongst crops are reported in Table 1. Note that it varies considerably across AEZs and regions. It is also lower in USA and China than in ROW. This is because the ROW elasticities are dictated by the measure of heterogeneity at the country level. Since most countries in the world are smaller, and more homogeneous than China and USA, their AEZs are more homogeneous and they are therefore expected to exhibit higher supply elasticities within a given AEZ. The greatest degree of heterogeneity in both USA and China is in AEZ 1, whereas AEZ 6 in both countries has much less heterogeneity, and therefore a larger elasticity of transformation across uses within the AEZ.

While the elasticities of transformation amongst crops in Table 1 are in line with the econometric evidence, less information is available on the mobility of land between crops and grazing land, and between agriculture and foretry uses. However, we expect these values to be lower in absolute value than the supply response amongst crops. Here, we follow the nested CET approach of ABARE (Ahammad, 2006). In this framework, 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. The elasticities of transformation between crops and livestock are set at half the value in Table 1, and half again for the elasticities of land transformation between forestry and agriculture, within AEZs.

2.1 Model modifications associated with GHG emissions

Emissions

In order to model GHG emissions and the marginal cost of abatement, we have modified the standard model further in a number of ways. We model three categories of non-CO2 emissions drivers: outputs, factor inputs, and intermediate inputs. Emissions fluctuate in proportion to changes in the driver. For comparative static analyses, this proportional relationship is acceptable. However, dynamic models should consider adjustments to emissions factors over time, especially over long time horizons, as emissions conditions evolve (e.g., autonomous trends towards more efficient and lower emitting technologies, technologic diffusion and adoption, and air quality policies with GHG implications). Table S1 presents the GTAP-AEZ mapping of emissions categories to drivers.

Structurally, the model has only been altered to accommodate emissions associated with output. In this case, we have introduced an additional input, GHG emissions, at the top of the production tree. This approach is drawn from Hyman et al. (2003), who showed that sectoral abatement responses could effectively be modeled as a process of substituting normal production inputs for emissions in a CES production function. As the elasticity of substitution between normal inputs and emissions increases, the MAC becomes flatter. This offers a natural vehicle for calibration.

Emissions pricing

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. The following equation, drawn from the TAB file, illustrates how this works:

```
Equation CHNGETAXFD
# eq'n computes change in power of the tax on emissions #
(all,i,TRAD_COMM)(all,j,PROD_COMM)(all,r,REG)
    del_TFD_L(i,j,r) = del_TFDO_L(i,j,r)
+ [UNITDEMIT(i,j,r)/PM_L(i,r)] * [c_TAUIEMIT(i,j,r)
                      - (PM_L(i,r)*AVEDTAUI(i,j,r)/100) * pm(i,r)];
```

The left hand side of this equation represents the (absolute) change in the ad valorem power of the tax rate on inputs (e.g., fertilizer used in corn production). This depends on the change in the power of the ordinary tax, `del_TFDO_L(i,j,r)`, the change in the specific tax, `c_TAUIEMIT(i,j,r)`, and the change in the price of the input in question: `pm(i,r)`. 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 tax on fertilizer use in corn production depends on the change in the 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:

```
Formula (all,i,TRAD_COMM)(all,j,PROD_COMM)(all,r,REG)
    UNITDEMIT(i,j,r)  = QFDEMIT(i,j,r)/QFD_L(i,j,r) ;
```

If we multiply the denominator by the price of fertilizer, `PM_L(i,r)`, 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.[1] The larger this intensity, the greater the impact of a given $/tonne tax on the sector/input in question. Table 3 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 for a given carbon tax.

There is a closely related emissions intensity which applies in the case of carbon sequestration in forestry. Here, we assume that increasing the amount of land in forestry, in a given country/AEZ pair, boosts sequestration by an equal proportion. So the critical intensity is the amount of carbon stock per unit of land rents. Table 3 reports this ratio. It is larger in ROW than in China and USA.

Mitigation responses

In keeping with most CGE analysis, our 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 great deal of conservation. If it is small, then the opposite will apply. These elasticities of substitution are therefore key in determining the marginal abatement cost for emissions from various activities in our model. This section discusses how the GTAP-AEZ marginal GHG abatement response schedules are derived and how they are calibrated to engineering cost estimates for alternative abatement technologies.

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

There are many non-CO2 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 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)

[1] The cost of emissions is rebated to the regional household in the same way any tax would be re-circulated.

follow the approach typically used for energy fossil fuel combustion CO2 abatement 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 the desired 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 this later approach.

The USEPA has estimated the engineering mitigation costs and emissions implications for alternative management strategies for key non-CO2 emissions sources (Delhotal et al., forthcoming; USEPA, forthcoming), including cost for significant agricultural non-CO2 emissions sources—paddy rice, other croplands (wheat, maize, soybean), and livestock enteric and manure emissions. From this data, we were able to construct mitigation response curves for calibration that correspond to the GTAP-AEZ region and sector structure. Unfortunately, mitigation cost estimates were not available for all non-CO2 sources (though additional estimates, such as for F-gas sources, are forthcoming). The first column of Table 4 indicates where the derived mitigation response curves were applied to GTAP-AEZ sectors.[2]

Given the GTAP-AEZ structure, we calibrated the two main input substitution elasticities for each region and relevant sector—the elasticity of substitution between intermediate inputs and the elasticity of substitution between primary factors (Table 4). For the calibration, we fixed production and input prices to match the partial equilibrium assumptions of the engineering cost estimates. We then varied 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 was adjusted so that the model would mimic the estimated emissions reduction proportions from the derived engineering based response curve. In particular, we targeted the calibration of the response at $50/tCeq. Figure 2 illustrates the results from the calibration for the USA cropland mitigation response.

Figure 2 illustrates a number of 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. Like others (Hyman et al., 2003), we assume that unaccounted for costs and barriers are preventing their implementation and their associated emissions reduction benefits are not available. Another issue is that the USEPA estimates represent a finite set of discrete technologies. This creates two problems for this sort of calibration: sections of the cost response curves are non-monotonic and eventually all mitigation options are exhausted. The substitution elasticities can not account for either of these characteristics. Instead, the elasticities provide smooth monotonic mitigation responses that impose a calibration tradeoff, especially for flatter engineering response curves, of whether to match the lower price or higher price mitigation reductions.

[2] USEPA (2006b) year 2000 mitigation cost curves were used for calibrating the agriculture sectors. However, year 2000 curves were not available for the non-ag sectors. Therefore, the projected 2010 cost curves were used for these sectors.

These issues raise the question of whether one should employ fixed reduction shocks in the GE model for carbon prices higher than the point where the engineering studies suggest that additional abatement options are no longer available. Furthermore, an inherent danger in adjusting the elasticity of substitution between intermediate inputs and the elasticity of substitution between primary factors is that we may end up distorting the production functions such that they make little economic sense, or fly in the face of econometric work in that area. Hyman et al. (2003) avoid this issue by tying emissions directly to output. However, this approach prevents analysis of input allocation and substitution of recognized input drivers of emissions. We discuss alternatives for modeling input associated emissions and abatement further in the Conclusion.

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 (e.g., landfill CH4 emissions and fugitive CH4 emissions from oil and gas industry non-combustion activities). Here, it is most natural to tie emissions to the aggregate output of the sector. However, if we simply tax output, the only vehicle for emissions reduction is to reduce the total production in the sector. However, engineering analyses suggest that – for a cost – emissions per unit of output can often be reduced, i.e., the abatement response curve is rarely entirely vertical. In order to capture this, 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 production. 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 energy 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 engineering studies. Therefore, we are free to pick this elasticity for a given GHG in a given industry (see Table S2 for our output CES substitution elasticities).

Case 3: Modeling the marginal costs of forest carbon sequestration

Forest carbon stocks can be increased by increasing the biomass of existing forest acreage or by converting non-forest lands to forests. Sohngen (2005) has generated regional forest carbon supply curves using his detailed model of global timber markets and forest carbon stocks. The curves are good summary representations of the cost-effective mix of forest mitigation strategies—both forest land management and land-use change— and the market feedbacks. We calibrate the model's regional AEZ forest acreage responses (i.e., carbon stock changes) to Sohngen's regional responses.[3] At the moment we are using the forest carbon intensity as our calibration lever. This was

[3] As a result, we are implicitly attributing all of Sohngen's increased sequestration response from a carbon price to additional forest acreage. This clearly isn't the case and likely biases are forest carbon responses upward. We are exploring refinements that will allow us to identify the land-use change share of Sohngen's estimated responses.

necessary because the base year forest carbon stocks include both managed and unmanaged forests and produces inflated forest carbon intensities. Understanding the implications of adjusting the forest carbon intensities for calibration requires further analysis. Ultimately, we will circumvent this issue by delineating managed and unmanaged land in the data base.

2.2 Land, emissions, and sequestration data

Land

As described in Lee et al. (2005), a land-use and land cover database was recently developed 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 Agro-Ecological Zones (AEZs, see Figure 3) and identifies 2001 crop and forest extent and production for each region by AEZ for specific crop and forest types. These AEZs represent six different lengths of growing period (6 x 60 day intervals), spread over three different climatic zones (tropical, temperate and boreal). Furthermore, the land-use activity data was used to disaggregate the GTAP v6.0 database sectoral land rents into 18 AEZ factor inputs. Figure 4 portrays the resulting cropland AEZ land rents. With specific land uses and value delineated by AEZ, more refined and realistic modeling of alternative land uses and the relative role of heterogeneous lands is possible.

This database enhances the standard GTAP global economic database by disaggregating land endowments into 18 AEZs. These 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, the length of growing period depends on temperature, precipitation, soil characteristics and topography. This approach evaluates the suitability of each AEZ for production of alternative crops and livestock 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.

Lee et al. (2005) first allocate global land area by AEZ and country. They then associate different production activity levels (physical outputs and yields) with each national/AEZ pair. When combined with price data from the FAO, these different production activities are translated into value terms, and these value shares are ultimately used to allocate land rents from each land-using activity across AEZs within the GTAP data base. If we aggregate the land rents on each AEZ, in each region of our aggregation, then we can compute the relative economic importance (land rental share) of each AEZ in each region of the model. Table 5 reports the associated land rents (at market prices) for the three regions and six AEZs. Note that land rents in USA and China have comparable land rents in total. However, whereas AEZ6 dominates in China, AEZ4 is the economically dominant one in USA. In ROW, the land rents are more evenly spread across AEZs, with AEZs3 – 6 all generating significant economic activity.

Greenhouse gas emissions

The US Environmental Protection Agency has developed a detailed non-CO2 and non-fossil fuel combustion CO2 (“Other CO2”) greenhouse gas emissions database specifically for use by global economic models (Rose et al., 2006c). The dataset’s disaggregated emissions structure maps directly to countries and economic sectors and facilitates utilization of available input activity quantity data, such as energy volumes and land-use acreage. Rose et al. (2006b) carried out this mapping.

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; thereby, making it difficult to model actual emitting activities and abatement strategies. The 2001 base year of the new dataset corresponds to the GTAP version 6 database base year. The database provides emissions for 27 non-CO2 and Other CO2 GHG emissions categories with 153 unique emissions sources (subcategories) for 226 countries. Annex 1 emissions were extracted from national UNFCCC Common Reporting Framework and National Inventory submissions. Non-Annex 1 emissions were drawn and, if necessary, disaggregated from available National Inventories, the EDGAR 3.2 database by RIVM/TNO [4] (biomass burning, Other CO2), ALGAS country reports,[5] or estimated using IPCC inventory methods or extrapolated from 2000 estimates.

Each of the 153 emissions sources was individually mapped to the GTAP version 6 database’s country and sector structure (226 countries, 57 sectors). The relevant emitting GTAP sectors were identified for each emissions sub-category. Many emissions subcategories mapped directly to individual GTAP sectors for each country. However, disaggregation methodologies were required for subcategories that mapped to multiple GTAP sectors and/or there were multiple emitting activities (e.g,, CH4 and N2O emissions from combustion of coal, natural gas, and oil in GTAP energy sectors col, oil, gas, p_c, ely, and gdt). Where possible, GTAP input activity data was exploited for subcategory emissions disaggregation across sectors in order to integrate the datasets for greater consistency across data.

The new dataset complements the GTAP fossil fuel combustion CO2 emissions database (Lee, 2005). Therefore, the full GTAP GHG emissions database provides country-level CO2, non-CO2, and Other CO2 GHG emissions and sequestration by emissions category and gas for each sector. The detailed structure vastly improves emissions modeling opportunities.

The model presented here considers only non-CO2 emissions and forest carbon sequestration. Given our interest in land-use modeling and land’s majority share of global CH4 and N2O emissions, the absence of CO2 emissions allows us to emphasize and focus on the evaluation of the non-CO2 emissions and mitigation role of land

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[4] EDGAR (Emission Database for Global Atmospheric Research), Version 3.2 (Olivier, 2002)
[5] ALGAS (Asia Least-Cost Greenhouse Gas Abatement Strategy)

heterogeneity. GTAP-AEZ uses an aggregated non-CO2 emissions structure (Figure 5) with CO2 equivalent non-CO2 emissions by sector. Non-CO2 emissions from agriculture (crops and livestock) represent well over 50% of the China and ROW total non-CO2 equivalent emissions and just under half of the U.S. non-CO2 emissions.

Forest carbon stocks

Forests are both a large potential source of carbon emissions and an opportunity for mitigation through carbon sequestration. However, it is difficult for static or myopic intertemporal models to reasonably represent the dynamic forest capital growth implications of alternative management strategies for existing forests. For the static model developed here, it is simply impractical to attempt to model the age composition of forests. Therefore, static and myopic models must instead define a representative forest (e.g., Sands and Leimbach, 2003).

Lee et al. (2005) have implemented the Sohngen and Tennity (2005) global forest carbon stock data that provides 2000 estimates of above-ground forest carbon stocks by regionally unique forest management types and age cohorts within each AEZ for each GTAP region. Using biophysical details from Sohngen and Tennity, we derived an average forest and carbon stock condition for each AEZ in each region. While we are able to model the most significant drivers of forest carbon changes—deforestation and afforestation, this construction prevents us from modeling more subtle forest carbon management strategies, such as longer rotation lengths, thinning practices, and fertilizer applications.[6]

3. Analysis

The focal point of our analysis will be the derived GTAP-AEZ abatement supply schedules. We estimate abatement schedules by region and sector by varying the per unit carbon tax systematically from $1/tonne to $100/tonne. We are keenly interested in land allocation decisions and general equilibrium effects. First, to help us define relative sector abatement potential, we explore the domestic resource implications of carbon taxes applied to the US under partial equilibrium (PE) and general equilibrium (GE) conditions. Second, we investigate the competition for land between sectors in general and in more detail with respect to a single carbon price ($50/tCeq) to see how the different land-using sectors with differing emissions profiles and AEZ distributions respond.

Third, recognizing that a US carbon tax increases US costs of production, we look for the global effects and explore the implications of the regionally applied carbon tax by comparing abatement schedules from the carbon tax applied to the US to schedules from a tax applied globally. For example, a carbon tax that reduces fertilizer use in China, will have an impact on world prices for crops and fertilizer. Lower usage of fertilizer in China will cause world fertilizer prices to fall, and crops prices to rise. Thus there is a tendency

[6] A global soil carbon dataset that will complement the existing emissions and sequestration datasets is under development.

for producers in other regions to want to increase fertilizer use and crops output unless they, too, are subject to the tax. The abatement supply comparison will allows us to identify overall regional emissions leakage effects in non-CO2 gases and the corresponding global production and land re-allocations. Finally, we dig deeper to investigate the roles of the individual carbon taxes. Specifically, we decompose the regional effects of a global carbon tax into emissions responses for each tax instrument applied regionally, i.e., the unique abatement attributable to each of output, endowment, intermediate input, and forest sequestration carbon taxes.

4. Results

Competition for mitigation and competition in the land market

We can look at any single region and ask how might that region address non-CO2 GHG emissions and forest carbon? In this case, we looked at the US region. Figures 6 and 7 portray the PE and GE sectoral mitigation responses respectively for carbon prices that are applied only to the US. The importance of GE effects is readily apparent. The PE schedules suggest a larger mitigation response than realized under GE conditions for any given carbon price. With inelastic production and perfectly elastic inputs, the PE schedules are biased upward for each sector and for the entire region. For example, the USA regional PE abatement response to a $50/tCeq tax is twice that of the GE response (approximately 120 versus 250 MtCeq).

The GE affects on the sectors varies, as does the effect on the relative ordinal mitigation contribution of each sector. For example, PE estimates imply that the industrial sector will generate the largest level of abatement for any carbon price. However, that is not the case in GE settings where, at low carbon prices, industry abatement assumes the majority of the mitigation responsibility, but the forestry sector dominates mitigation from $5/tCeq on, and agricultural mitigation in GE is now relatively more appealing than services based abatement. The costs of abatement in industry and services have proven to be more expensive than suggested by the PE estimates as international substitutes are not as readily available as they are in the forestry and agriculture sectors. Production increases, in particular in ROW forestry and agriculture, lead to increased emissions in the other regions (Figure 8). Under both PE and GE, agriculture based mitigation (rice, grains, and livestock) plays a more modest role than forestry that increases in absolute terms, but its share of total abatement is decreasing.

What are the mitigation implications for regional land use? A key feature of our analysis is the competition for land, by AEZ. In order to better understand this, we focus on the case of a $50/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 6. 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 between AEZs in a given use, which in turn is motivated by the fact that the final products produced on different AEZs face a common price.

The second point to note from Table 6 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 sectors rise, especially other grains, other crops, forestry, grazing uses. The rise in forestry land rents is a direct consequence of the CO2 sequestration subsidy which lowers the cost of land to forestry, thereby boosting its use. The size of the increase in forest land rents is a bit of a curiosity that requires further investigation. The rise in other grains, other crops, and ruminant land rents is a consequence of the increased demand for land by the forest sector and the carbon tax being applied directly to non-land input use, e.g., fertilizer and ruminant capital. In the case of the later effect, producers respond by substituting other inputs, sometimes land, for the taxed input, the cost of which has risen substantially.

These changes in land rents, in turn, give rise to changes in land use, by sector, which is also reported in Table 6. The next panel in the table reports the simple percentage change in land use, by activity. Here, we see that forestry increases its use of land, while paddy rice dramatically reduces its use of land. Other grain production, other crops, and ruminants increase their use of the low AEZ land types and decrease their demand for higher AEZ land (5 and 6). The later action providing 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 is a bit misleading. The most natural way to scale the percentage change in land use, is to premultiply it by the share of a given AEZ's land rents generated by this activity in the base period data. The third panel in Table 6 does so, using the AEZ shares reported at the bottom of Table 6 (forth panel). Now we see that the expansion in ruminant land use is relatively more important in the shorter growing period AEZ land classes. Therefore, in these AEZs, the basic story is one of crop land moving primarily into grazing activities. On the other hand, the nature of the land movement differs in the longer 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. From Figure 8, we see that, while the US is reducing emissions in response to the US only carbon prices, the ROW region (and the China region slightly) is taking full advantage of the opportunity with increases in emissions at all prices that partially offset the US reductions. This emissions leakage is the result of the ROW region picking-up production in response to decreased US output. A comparison of Figures 8 and 9 illustrates how dramatic the leakage effect is. Figure 9 depicts the regional abatement schedules for globally applied carbon taxes. The carbon tax transforms the ROW region into the clearly dominant abatement region as tropical deforestation in particular is decreased. The US mitigation role is redefined as well by the globally applied tax. Most notably, the mitigation responses in all the US sectors are diminished as the cost of US mitigation rises with higher world prices (Figure 10); thereby, improving the overall profitability of production despite the costs associated with GHG emissions.

Next, we try to elucidate these regional net emissions responses by identifying the individual components. Table 7 offers one view of the global interactions between emissions taxes in one region and emissions in another region. This table is constructed by simulating the impact of $50/tonne Ceq taxes on all of the emissions categories considered above (including sequestration subsidies of $50/tonne) in all three regions of the world. Over the course of the simulation, we utilize the numerical integration technique proposed by Harrison, Horridge and Pearson 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 $50/tonne tax on output 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 had simply run 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.)

First of all, an orientation to Table 7 is in order. The columns in this table refer to emitting regions. So the percentage change in total emissions in USA amounts to a reduction of 36.96% in the wake of this global tax (Table 7a). On the other hand, emissions in ROW fall by about 58%. What explains this difference? For this we need to refer to the individual elements in each column. Together, they sum to the total emissions given at the bottom of the table. The rows in this table show the breakdown – or decomposition of the total tax impact – by type of instrument and region. So, for example, the impact of a $50/tonne tax on output related emissions in USA on USA emissions is -10.8%. On the other hand, this same tax raises emissions in China by 0.2% (USA row, China column). In general, note that the diagonal elements in each block of the table tend to be negative, such that a tax on emissions in a particular region lowers overall emissions in that region.

Identical taxes in different regions can lead to very different responses. A $50/tonne Ceq tax on paddy rice and ruminant livestock production in China (primary factor taxes), results in a 12.64% reduction in total emissions, while the comparable reduction in ROW is 5.69% and in the USA 1.41%. Similarly, the $50/tCeq forest sequestration subsidy results in a 49% increase in ROW forest carbon stocks, but 24% and 22% increases in the USA and China respectively.

The off-diagonal elements of Table 7 tend to be positive, indicating that there is 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. There are a few negative off-diagonal elements, but they are quite small – e.g., the impact on USA and ROW emissions to a tax on primary factor related emissions in China. In general, the off-diagonal entries are also dominated by their on-diagonal counterparts.

It is also instructive to look at the abatement levels (vs. percentages). Table 7b shows how the composition of the abatement portfolio can vary from on region to the next. While forest sequestration is the dominant strategy in all regions, additional sequestration in ROW dwarfs that in other regions at almost 900 MtC. Paddy rice and livestock mitigation are a more important part of the mitigation portfolios in China and ROW, while industry and services are relatively more important in USA.

5. Conclusions

We developed a computable general equilibrium model with unique regional land types and detailed non-CO2 GHG emissions, in particular land based greenhouse gas emissions, and forest sequestration and GHG abatement. We were able to evaluate the non-CO2 and sequestration mitigation roles of economic sectors and, more importantly given our focus, the role of heterogeneous land. We found that biophysical and economic land characteristics can create comparative abatement advantages for land endowments, both domestically and internationally. The comparative advantages can result in intra- and inter-regional re-allocations of production in response to carbon prices. We observed these general equilibrium effects in terms of emissions reductions/increased sequestration as well as production and land-use. We also found that international market 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.

Additional analysis is planned for this paper, including exploring the importance of general equilibrium effects on relative regional and sectoral land utilization. In addition, we may pursue more substantial analyses, considering alternative model structures for incorporating input related emissions and abatement, and further analyzing the role of heterogeneity via land mobility and within AEZ heterogeneity. We discuss each of these in turn a bit more below.

Not all emissions fit neatly into the input and output driver characterizations used here. For example, N2O emissions from fertilizer use can be reduced without altering the total amount of fertilizer applied, by moving to a slow release fertilizer product. In this case, there are really two margins for abatement. The first involves using less fertilizer overall, while the second involves changing the quality of the fertilizer input, thereby reducing emissions per unit of fertilizer. This requires some sort of blend of the output and input approaches. A natural way to handle this is to "take a page" from Hyman et al. (2003), and introduce (some, maybe all) of the N2O emissions associated with fertilizer usage as an input to production, which is nested with fertilizer in the production function. When emissions are taxed, the first thing the firm attempts to do is "substitute" fertilizer for emissions – i.e., more to a higher quality fertilizer (e.g., slow-release formulation), in a effort to abate emissions. To the extent this substitution is limited in scope (i.e., less than infinite), the tax will also raise the aggregate cost of fertilizer, thereby inducing some substitution of other inputs for fertilizer.

One clear advantage of this approach is that it gives us more flexibility in calibration. We can achieve a desired calibrated mitigation response without totally undermining the production function of the sector in question. For example, consider the case of fertilizer use in corn production. The econometric evidence suggests that the elasticity of substitution between fertilizer and land in the aggregate is around 1.0 for the United States. What if this gives an aggregate emissions reduction to a $50/ton carbon tax that is only half what is suggested by the EPA-commissioned studies? Do we double this value – thereby effectively doubling overall supply response or corn? Having another margin for abatement would permit us to hit the overall calibrated mitigation target without significantly altering the aggregate production function.

In order to isolate the impact of land heterogeneity on our findings, we restrict the model in the follow ways. Firstly, we can ignore heterogeneity within national AEZs, so that acreage response is the same across all AEZs. In a second step, we can aggregate AEZs so that there is only one type of land in each region. This would correspond to the specification in the standard GTAP model, and it permits competition for land amongst all activities within each region, regardless of soils, precipitation or topography. By comparing the cost of mitigation under these different scenarios, we are able to evaluate the economic importance of land heterogeneity in attempts to limit greenhouse gas emissions.

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Table 1: Elasticities of transformation amongst crops

	USA	China	ROW
AEZ1	-0.5656	-0.6424	-1.0651
AEZ2	-0.6170	-0.7759	-1.0002
AEZ3	-0.4085	-0.6762	-1.1086
AEZ4	-0.7115	-0.7748	-1.0646
AEZ5	-0.9059	-0.7324	-1.1207
AEZ6	-0.9508	-0.9958	-1.0666

Table 2: Non-CO2 GHG emissions by sector and emissions driver category

					Share of sector emissions by type of emissions driver											
Sector	**Total non-CO2 GHG emissions (MtCeq)**				**Output**				**Endowment**				**Intermediate input**			
	USA	China	ROW	World	USA	China	ROW	World	USA	China	ROW	World	USA	China	ROW	World
1 PaddyRice	2.971	70.160	137.364	210.495	0%	0%	0%	0%	69%	85%	79%	80%	31%	15%	21%	19%
2 OtherGrain	37.707	20.284	101.363	159.354	0%	0%	2%	1%	0%	0%	0%	0%	100%	100%	98%	99%
3 OtherCrops	23.707	77.911	167.219	268.837	1%	0%	2%	2%	0%	0%	0%	0%	99%	100%	98%	98%
4 Ruminants	48.778	68.773	630.131	747.682	0%	0%	0%	0%	100%	100%	100%	100%	0%	0%	0%	0%
5 NonRuminLivs	7.904	41.884	79.590	129.378	0%	0%	0%	0%	100%	100%	100%	100%	0%	0%	0%	0%
6 Forest	0.002	0.017	0.079	0.097	0%	0%	0%	0%	0%	0%	0%	0%	100%	100%	100%	100%
7 Coal	15.284	48.317	54.138	117.739	100%	100%	100%	100%	0%	0%	0%	0%	0%	0%	0%	0%
8 Oil	4.650	0.117	31.526	36.292	100%	75%	99%	99%	0%	0%	0%	0%	0%	25%	1%	1%
9 Gas	2.096	0.012	14.090	16.199	100%	33%	99%	99%	0%	0%	0%	0%	0%	67%	1%	1%
10 RefinedFuels	1.619	1.157	46.828	49.603	7%	26%	83%	79%	0%	0%	0%	0%	93%	74%	17%	21%
11 Electricity	53.879	14.287	91.773	159.939	98%	94%	96%	96%	0%	0%	0%	0%	2%	6%	4%	4%
12 GasDistribut	21.791	0.041	16.089	37.921	100%	17%	99%	99%	0%	0%	0%	0%	0%	83%	1%	1%
13 Rumint_Prods	0.022	0.001	0.068	0.091	0%	0%	0%	0%	0%	0%	0%	0%	100%	100%	100%	100%
14 OtherMeatPrd	0.005	0.002	0.027	0.034	0%	0%	0%	0%	0%	0%	0%	0%	100%	100%	100%	100%
15 ProcessdRice	0.000	0.013	0.016	0.029	0%	0%	0%	0%	0%	0%	0%	0%	100%	100%	100%	100%
16 OthFoodPrcsn	0.084	0.044	0.281	0.409	0%	0%	0%	0%	0%	0%	0%	0%	100%	100%	100%	100%
17 WoodProcessn	0.142	0.041	0.365	0.547	0%	0%	6%	4%	0%	0%	0%	0%	100%	100%	94%	96%
18 EnrgIntnsMnf	236.161	191.091	1032.969	1460.222	100%	100%	100%	100%	0%	0%	0%	0%	0%	0%	0%	0%
19 Services	0.112	0.039	0.983	1.134	0%	0%	0%	0%	0%	0%	0%	0%	100%	100%	100%	100%
20 Transport	25.466	0.932	159.809	186.207	43%	75%	88%	81%	0%	0%	0%	0%	57%	25%	12%	19%
21 OthExtractn	0.004	0.064	0.399	0.467	0%	0%	0%	0%	0%	0%	0%	0%	100%	100%	100%	100%
22 OthManufact	34.336	3.423	41.806	79.564	99%	89%	96%	97%	0%	0%	0%	0%	1%	11%	4%	3%
23 NTrdServices	49.520	37.421	309.160	396.101	100%	100%	100%	100%	0%	0%	0%	0%	0%	0%	0%	0%
24 RWTrade	0.093	0.014	0.562	0.670	0%	0%	0%	0%	0%	0%	0%	0%	100%	100%	100%	100%
25 CGDS	0.000	0.000	0.000	0.000	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Total	566.332	576.044	2916.635	4059.011	75%	51%	60%	61%	10%	30%	28%	26%	14%	20%	11%	13%

Table 3: Key emissions intensities (tonnes/$ of input)

Emission intensities (MtC/$ of input)		
Input	**USA**	**China**
Fertilizer in crops production	0.0061	0.0043
Ruminant livestock capital	0.0099	0.9562
Land in paddy rice	0.0040	0.0125

Forest carbon intensities (MtC/$ of land rent)		
USA	**China**	**ROW**
0.185	0.198	0.271

Table 4: Elasticities of substitution calibrated for emissions mitigation & sequestration

	Elasticity calibrated	Output elasticities			Intermediate input elasticities			Endowment elasticities
		USA	China	ROW	USA	China	ROW	World
1 PaddyRice	Endowment (land)	0	0	0	0.5	0.5	0.5	1.1
2 OtherGrain	Input (fertilizer)	0	0	0	1.3	0.6	1.5	0.237198
3 OtherCrops		0	0	0	0.5	0.5	0.5	0.237198
4 Ruminants	Endowment (capital)	0	0	0	0	0	0	0.191
5 NonRuminLivs	Endowment (capital)	0	0	0	0	0	0	2
6 Forest *		0	0	0	0	0	0	0.2
7 Coal	Output	0.0205	0.021	0.018	0	0	0	0.2
8 Oil	Output	0.004	0.009	0.0075	0	0	0	0.2
9 Gas	Output	0.0049	0.0081	0.0061	0	0	0	0.2
10 RefinedFuels		0	0	0	0	0	0	1.26
11 Electricity		0	0	0	0	0	0	1.26
12 GasDistribut		0	0	0	0	0	0	1.26
13 Rumint_Prods		0	0	0	0	0	0	1.12
14 OtherMeatPrd		0	0	0	0	0	0	1.12
15 ProcessdRice		0	0	0	0	0	0	1.12
16 OthFoodPrcsn		0	0	0	0	0	0	1.12
17 WoodProcessn		0	0	0	0	0	0	1.26
18 EnrgIntnsMnf	Output	0.119	0.119	0.119	0	0	0	1.26
19 Services		0	0	0	0	0	0	1.290463
20 Transport		0	0	0	0	0	0	1.68
21 OthExtractn		0	0	0	0	0	0	0.2
22 OthManufact		0	0	0	0	0	0	1.26
23 NTrdServices	Output	0.0165	0.0125	0.012	0	0	0	1.26
24 RWTrade		0	0	0	0	0	0	1.68
25 CGDS		0	0	0	0	0	0	1

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

Table 5: Land rents at market prices by AEZ and region (millions 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 6: Percentage change in land rents and land use by sector following a $50/tonne Carbon tax: USA only

Percentage change in land rents

	Forest	PaddyRice	OtherGrain	Other Crops	Ruminants
AEZ1	253.5	-15.9	2	3.3	5.1
AEZ2	254.3	-15.3	1.9	3.2	5.1
AEZ3	236.9	-15.5	1.9	3.2	5.1
AEZ4	267.5	-15.5	2	3.2	5.1
AEZ5	295.2	-16.5	2	3.3	5.2
AEZ6	320.2	-20.2	2.3	3.6	5.4

Percentage change in land use

	Forest	PaddyRice	OtherGrain	Other Crops	Ruminants
AEZ1	18.3	-11.3	-1	-0.3	0
AEZ2	20.3	-11.3	-0.5	0.2	0.6
AEZ3	12.6	-7.7	-0.3	0.2	0.4
AEZ4	25.2	-13.3	-0.9	0	0.4
AEZ5	33.3	-18.7	-2.4	-1.3	-1.1
AEZ6	30.5	-26.7	-7.2	-6.1	-5.7

Percentage change in land use, weighted by AEZ land rent share

	Forest	PaddyRice	OtherGrain	Other Crops	Ruminants
AEZ1	0.286	-0.023	-0.211	-0.05	0
AEZ2	0.013	-0.017	-0.226	0.068	0.162
AEZ3	0.009	-0.029	-0.131	0.098	0.053
AEZ4	0.427	-0.026	-0.431	-0.003	0.034
AEZ5	2.134	-0.412	-1.215	-0.391	-0.084
AEZ6	5.604	-0.626	-1.366	-3.242	-0.153

AEZ land rent shares

	Forest	PaddyRice	OtherGrain	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 7a: General equilibrium impact of emissions taxes on total emissions in each region following a global tax of $50/tCeq (percentage change)

Type/region of taxation		Emissions change from region (%) USA	CHN	ROW
Output related emissions	USA	-10.80	0.02	0.01
	CHN	0.02	-8.96	0.02
	ROW	0.02	0.11	-5.49
Purchased input related emissions	USA	-5.14	0.10	0.52
	CHN	0.19	-2.26	0.24
	ROW	1.36	0.32	-1.10
Primary factor related emissions	USA	-1.41	0.02	0.13
	CHN	-0.04	-12.64	-0.03
	ROW	0.49	0.13	-5.69
Forest sequestration	USA	-23.71	0.04	0.16
	CHN	0.09	-21.66	0.09
	ROW	2.03	0.60	-48.54
Total Impact		-36.96	-41.82	-58.12

Table 7b: General equilibrium impact of emissions taxes on total emissions in each region following a global tax of $50/tCeq (levels change)

Type/region of taxation		Emissions change from region (MtCeq) USA	CHN	ROW
Output related emissions	USA	-31.45	0.07	0.12
	CHN	0.05	-35.21	0.36
	ROW	0.05	0.43	-101.77
Purchased input related emissions	USA	-14.97	0.38	9.58
	CHN	0.56	-8.87	4.51
	ROW	3.96	1.24	-20.40
Primary factor related emissions	USA	-4.12	0.06	2.49
	CHN	-0.12	-49.71	-0.48
	ROW	1.44	0.50	-105.36
Forest sequestration	USA	-69.03	0.14	3.01
	CHN	0.26	-85.18	1.71
	ROW	5.92	2.37	-899.36
Total Impact		-107.45	-173.77	-1105.59

Figure 1 - AEZ Heterogeneity, by Country (zero = lowest, 1.0 = highest)

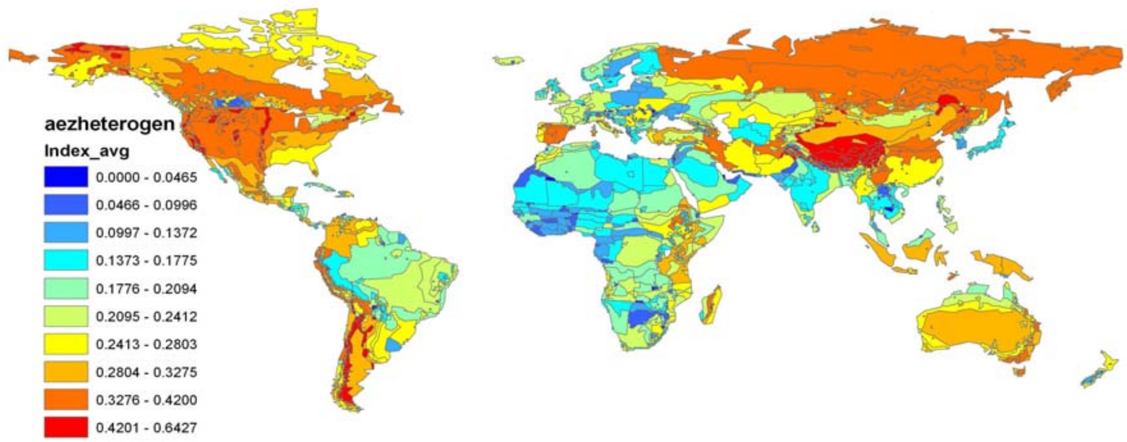


Figure 2

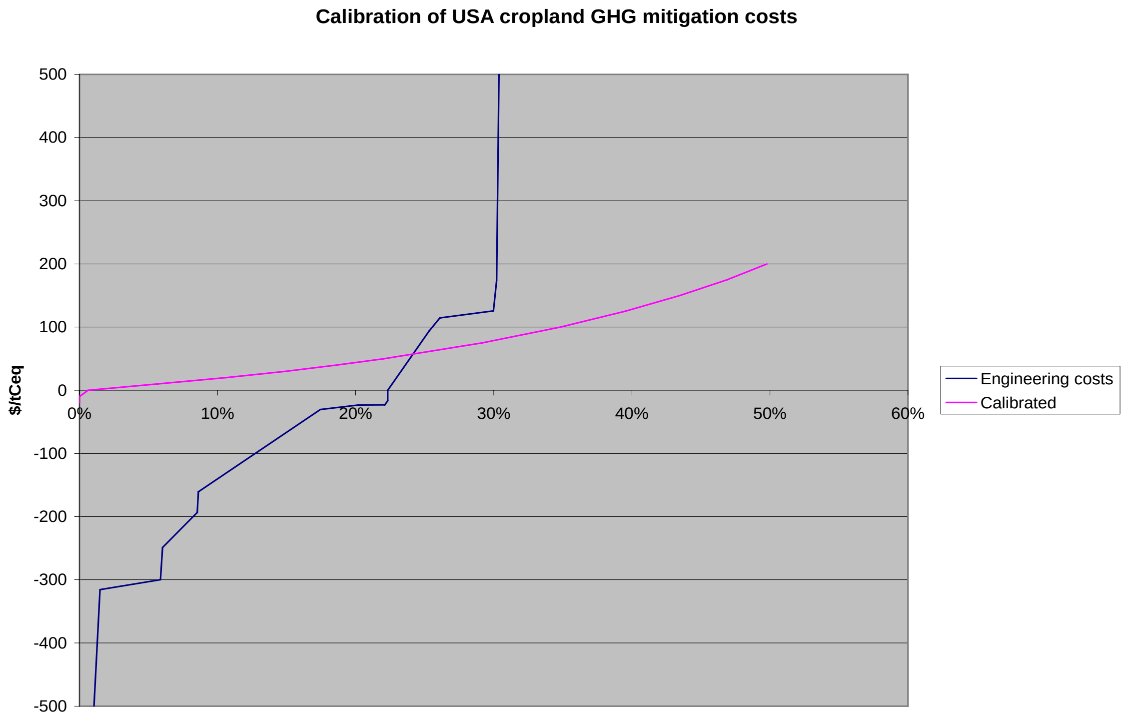
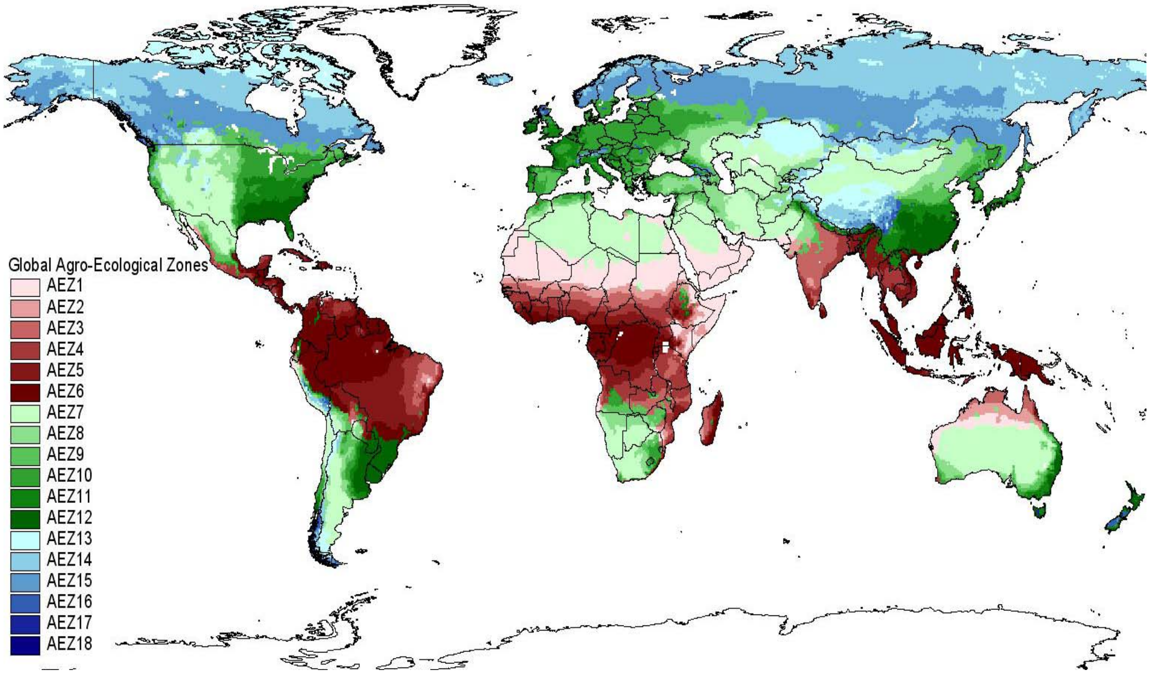
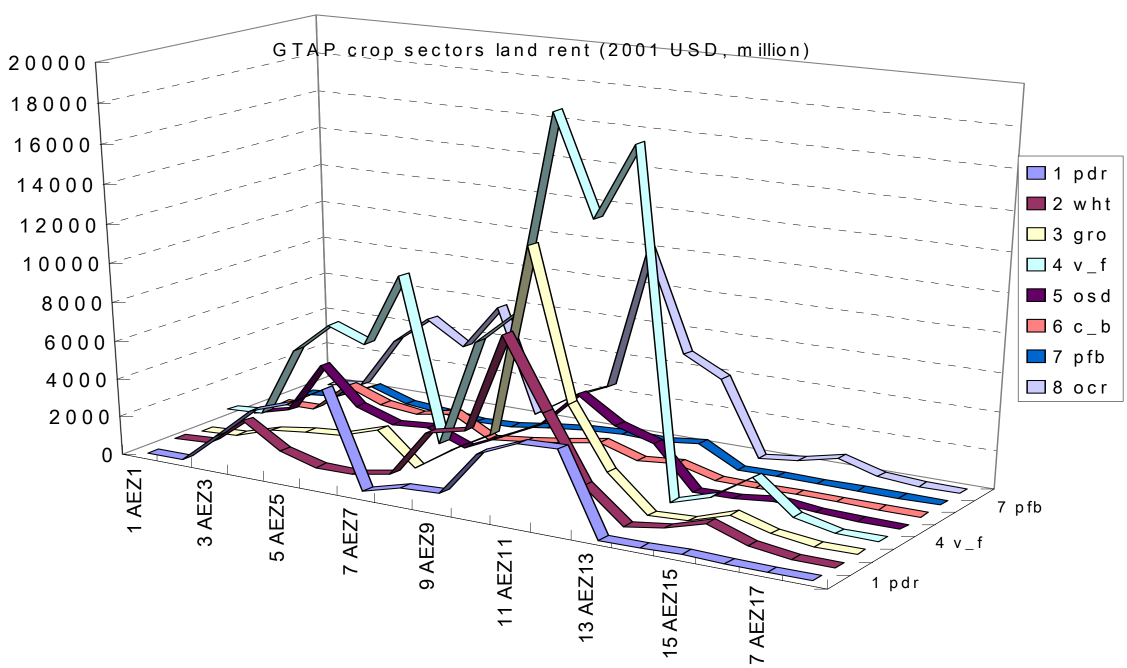


Figure 3 – GTAP's 18 Agro-Ecological Zones



Source: Lee et al (2005)

Figure 4 – Cropland land rents by AEZ



Source: Lee et al. (2005)

Figure 5: Total non-CO2 GHG emissions by region and sector (MtCeq)

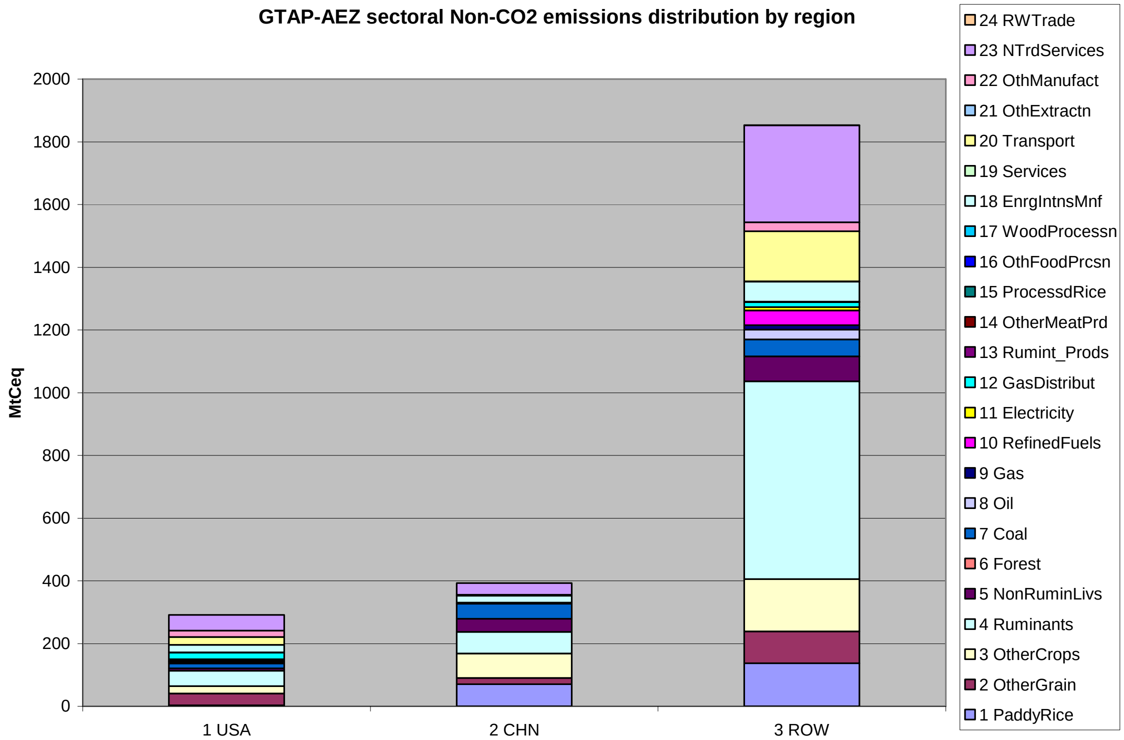


Figure 6: USA sector partial equilibrium GHG abatement supply schedules

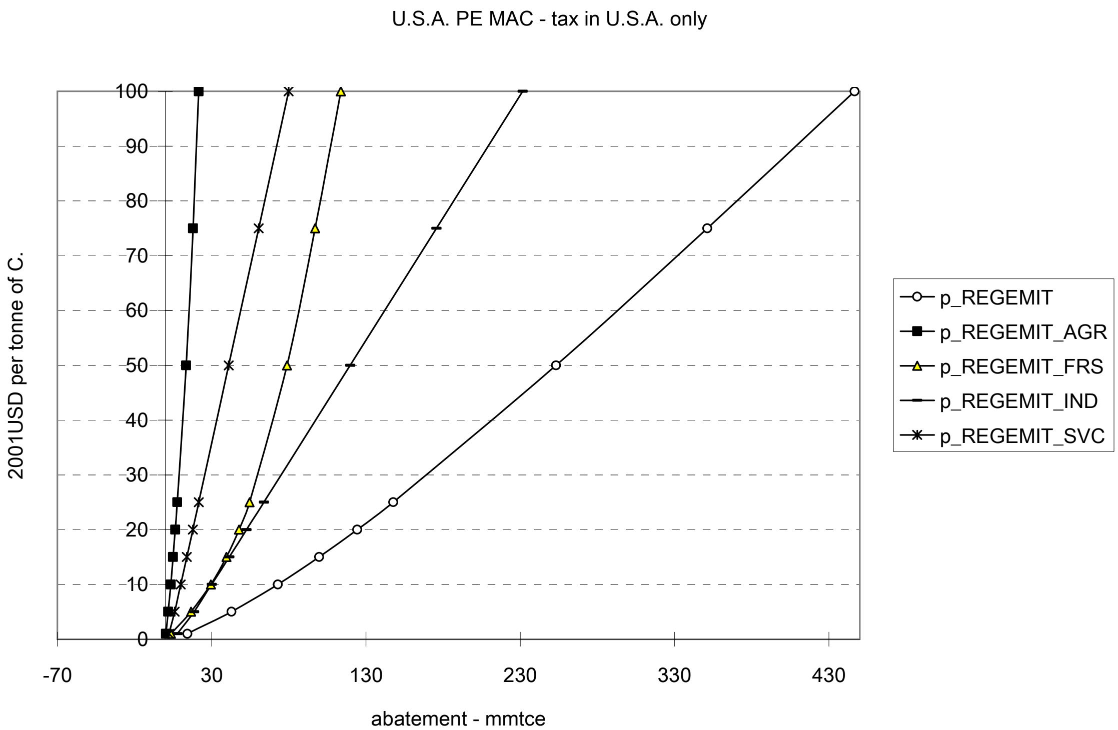


Figure 7: USA sector general equilibrium GHG abatement supply schedules for USA only carbon tax

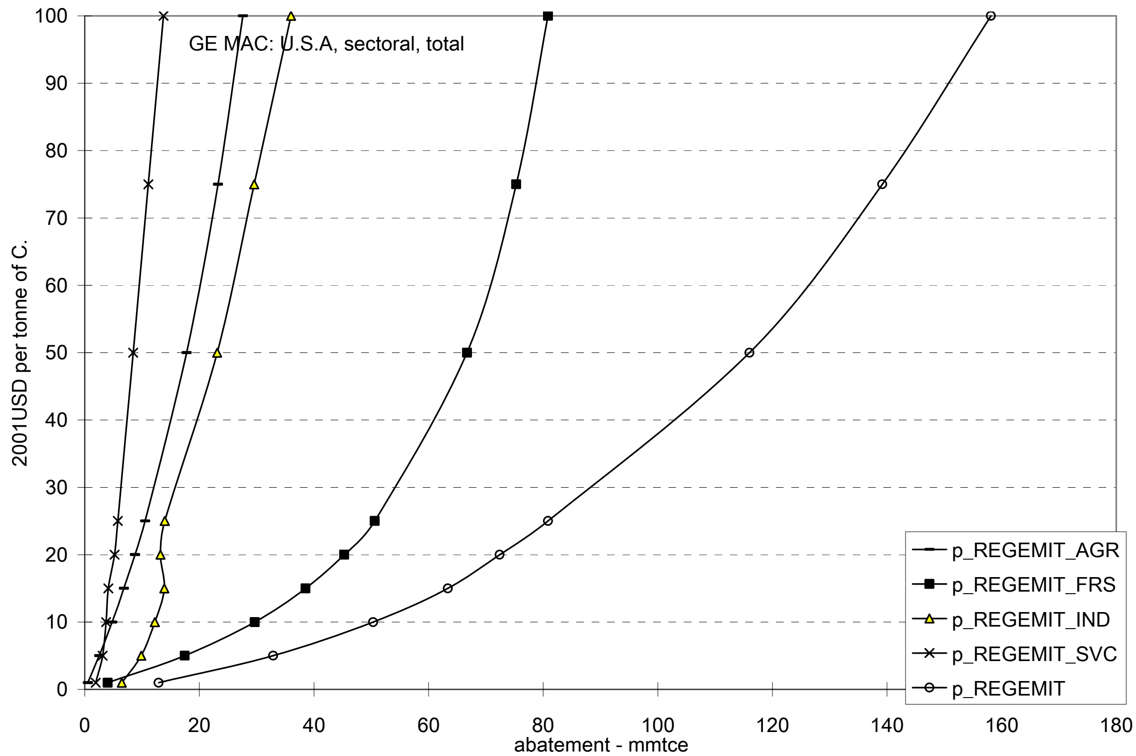


Figure 8: Regional general equilibrium GHG abatement supply schedules for USA only carbon tax

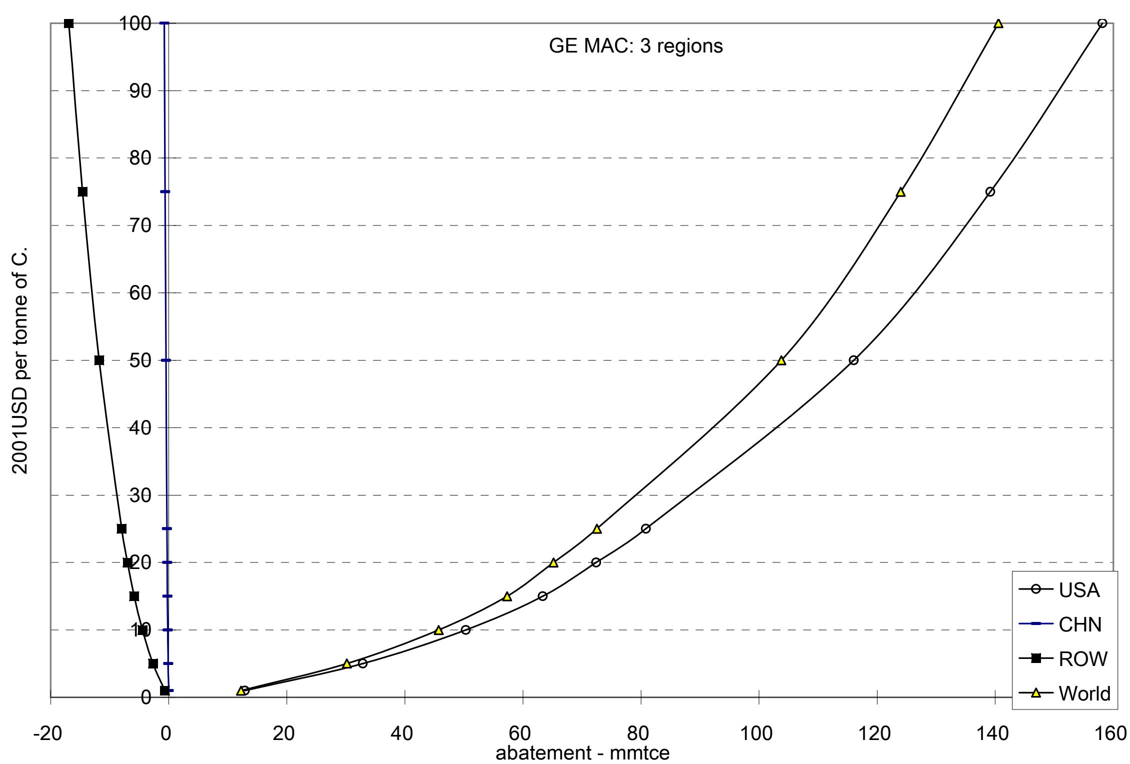


Figure 9: Regional general equilibrium GHG abatement supply schedules for global carbon tax

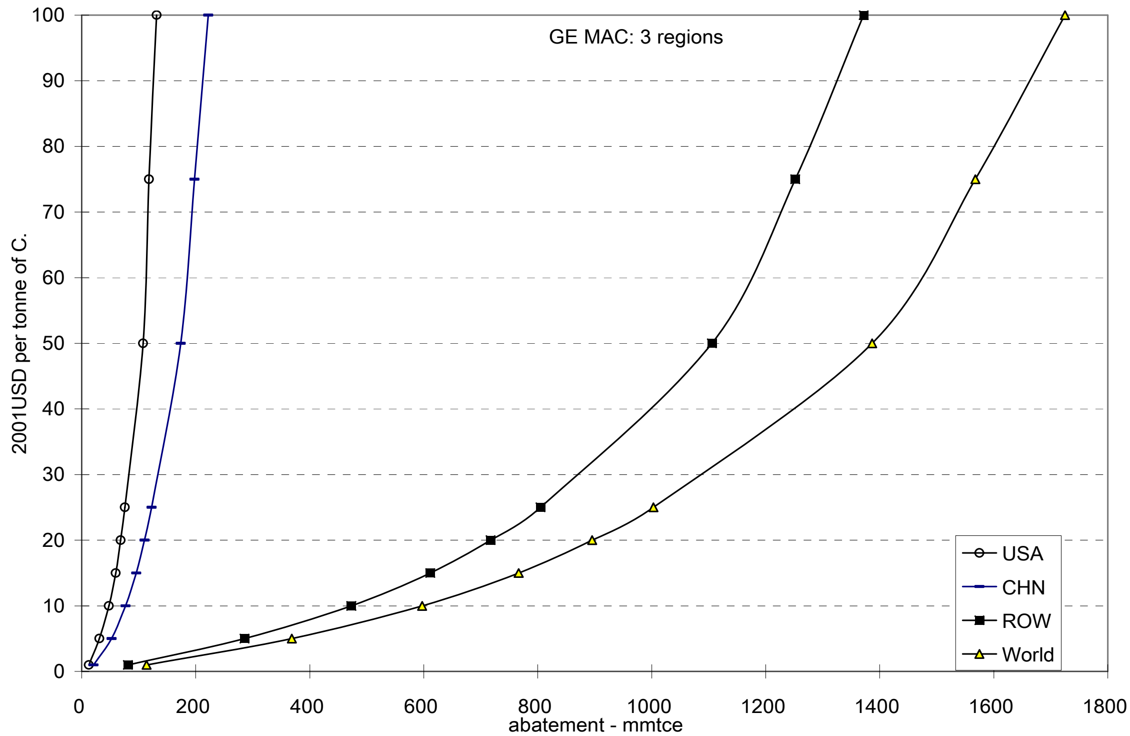


Figure 10: USA sector general equilibrium GHG abatement supply schedules for global carbon tax