The Relative Role of Land in Climate Policy

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Abstract

Land-based activities are responsible for a large part of global greenhouse gas (GHG) emissions, yet the economics of land-use decisions have rarely been explicitly modeled in global mitigation studies. This paper integrates the analysis of land use related non-CO_2 emissions and forest carbon sequestration with more conventional analyses of CO_2 emissions from fossil fuel combustion to provide a comprehensive assessment of the relative role of land in global GHG emissions and mitigation. For this paper, we utilize a new general equilibrium framework which effectively captures the opportunity costs of land-use decisions in agriculture and forestry, the implications of these decisions for GHG emissions, as well as mitigation options in agriculture and forestry. By combining this with a more conventional analysis of fossil fuel-based CO_2 emissions mitigation, we are able to analyze trade-offs and feedbacks between GHG emissions reductions in land-based and fossil fuel combustion intensive sectors. We explore the general equilibrium effects when land rents are endogenous and large-scale adoption of mitigation technologies produces feedbacks across sectors and regions.

Motivation

This paper integrates the analysis of land use related non-CO_2 emissions and forest carbon sequestration with more conventional analyses of CO_2 emissions from fossil fuel combustion to provide a comprehensive assessment of the relative role of land in global GHG emissions and mitigation. For this paper, we utilize a new, general equilibrium framework which effectively captures the opportunity costs of land-use decisions in agriculture and forestry, the implications of these decisions for GHG emissions, as well as mitigation options in agriculture and forestry. By combining this with a more conventional analysis of fossil fuel-based CO_2 emissions mitigation, we are able to analyze trade-offs and feedbacks between GHG emissions reductions in land-based and fossil fuel combustion intensive sectors. We explore the general equilibrium effects when land rents are endogenous and large-scale adoption of mitigation technologies produces feedbacks across sectors and regions. Computable general equilibrium (CGE) economic models are well suited to evaluate these kinds of tradeoffs, and have been extensively used in the climate change policy debate. Existing CGE frameworks, however, are not well structured to model land use alternatives and the associated emissions sources and mitigation opportunities. This work has been hindered by a lack of data, such as consistent and disaggregated global land resources and non-CO_2 GHG emissions databases linked to underlying economic activity and GHG emissions and sequestration drivers.

Methodology

Modeling approach

For this paper we build on GTAP-AEZ-GHG model developed by Golub, Hertel, Lee, Rose and Sohngen (2008), henceforth referred to as GHLRS. They started from GTAP-E CGE model (developed by Burniaux and Truong (2002) and modified by McDougal and Golub (2007)) and added unique regional land types -- Agro-Ecological Zones (AEZs) (Lee et al., 2009) and detailed non-CO_2 GHG emissions for all sectors of the economy (Rose and Lee, 2009), with emphasis placed on land-based GHG emissions and forest carbon sequestration.

Following GHLRS, in this work the explicit treatment of GHG mitigation options is based on a variety of partial equilibrium approaches. In the agricultural sectors, the model is calibrated based on non-CO_2 GHG mitigation possibilities derived from detailed engineering and agronomic studies developed by the US Environmental Protection Agency (USEPA, 2006). In the case of forest carbon sequestration, the estimates of optimal sequestration responses to global forest carbon subsidies are derived from the modified Global Timber Model of Sohngen and Mendelsohn (2007). Then, CGE model's regional responses are calibrated to the forest carbon supply curves. This includes both the extensive margin (increased forest land cover) and intensive margin (increased carbon stocks on existing forest lands due to modifications of rotation ages of harvesting trees and management).

In addition to explicitly modeled heterogeneous land inputs (AEZs), a more disaggregated emissions and forest sequestration modeling structure (than currently modeled in the climate economics literature) is developed. The structure allows for more refined mitigation responses (e.g., input substitution, forest intensification and extensification). Special attention is paid to the land-using activities at the disaggregated level, including forestry, paddy rice, wheat, coarse grains, oilseeds and livestock subsectors. Three types of agricultural production mitigation responses are captured: those associated with intermediate input use (e.g., nitrous oxide emissions from fertilizer use in crops), those associated with primary factors (e.g., methane emissions paddy rice), and those associated with sector outputs (e.g., methane emissions from agricultural residue burning). Furthermore, an additional layer of substitution elasticities is introduced into the production structure to allow for substitution between input-related emissions and specific inputs. Thus, for example, paddy rice producers are allowed to respond to a methane emissions tax not only by using less land, but also by changing the emissions intensity of land.

The purpose of GHLRS analysis is methodological. For simplicity of representation, it utilizes only 3 region aggregation of the GTAP data base. To provide a comprehensive assessment of the relative role of land in global GHG emissions and mitigation, we work with much more disaggregated data. The analysis is conducted using 19 region/31 production sector aggregation of the version 6 of GTAP data base representing world economy in 2001 (see Table A1 in Appendix for regional aggregation). (Version 6 of GTAP data base is used due to the fact that the global land use data are circa 2000.) We also include CO_2 emissions from fossil fuel combustion (Lee, 2007) linked to underlying economic activity to allow for rigorous consideration of the trade-offs between emissions reduction in land using sectors and from fossil fuels combustion and industrial activities.

Heterogeneous land

When modeling competition for land it is important to recognize that land is heterogeneous endowment. To reflect this, we bring in climatic and agronomic information by introducing AEZs (Lee *et al*., 2009). We distinguish 18 AEZs, which differ along two dimensions: growing period (6 categories of 60 day growing period intervals), and climatic zones (3 categories: 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 concept "length of growing period" refers to the number of days within a year of temperatures above 5^oC when moisture conditions are considered adequate for crop production. This approach evaluates the suitability of each AEZ for production of crops, livestock and forestry 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 historically observed to take place in that AEZ. Indeed, if two uses (e.g., citrus groves and wheat) do not presently appear in the same AEZ, then they will not compete in the land market. The different AEZs then enter as inputs into national production function for each land using sector. With a sufficiently high elasticity of substitution in use, the returns to land across AEZs, but within a given use, will move closely together.

Even after disaggregating land use by AEZ, there remains substantial heterogeneity within AEZs. In addition, there are numerous barriers to land conversion between agriculture and forestry, as well as within agriculture -- say between crops and livestock uses. Therefore, we further limit the potential for movement of land from one use to another within an AEZ. In the model, the allocation of land is determined through a nested constant elasticity of transformation (CET), multi-stage optimization structure (Ahammad and Mi, 2005). The rent-maximizing land owner first decides on the allocation of land among three land cover types, i.e. forest, cropland and grazing land, based on relative returns to land (here we depart from GHLRS who employ slightly different nested structure). The land owner then decides on the allocation of land between various crops, again based on relative returns in crop sectors. To set the CET parameter among three land cover types, we follow the recommendations in Ahmed *et al*. (2009) and to reflect long run nature of the issue we model we choose CET parameter -0.9. The CET parameter governing the ease of land mobility across crops is set twice larger. As with the land cover elasticity, this represents the upper bound on crop acreage response to an increase in the rental rate on a specific crop type. The lower bound is zero (when all crop land in an AEZ is devoted to a single crop).

GHG emissions data

Data on CO_2 and non-CO_2 GHG emissions are provided in Table 1. Globally non-CO_2 emissions represent about one third of CO_2 GHG emissions with China and USA as leading contributors. More than half of these non-CO_2 emissions are related to agricultural activities (1437 MMTCE). A detailed breakdown of non-CO_2 emissions from the agricultural sectors by region is provided in Figure 1. China plus Hong Kong and Sub Saharan Africa are the largest contributors with 20% and 14% of global non-CO_2 emissions from agriculture, respectively. In China, paddy rice cultivation is important source of methane emissions, as well as ruminant and non ruminant production. Ruminant sector in Sub Saharan Africa is single largest agricultural source of non-CO_2 emissions globally. In USA, methane emissions from enteric fermentation, as well as nitrous oxide emissions from crop production are large sources of emissions.

Forest carbon sequestration

Forest carbon stocks can be increased by increasing the biomass on existing forest acreage (the intensive margin) or by expanding forest land (the extensive margin). The former increases carbon storage per hectare with modifications of rotation ages of harvesting trees and management. The later afforests non-forested lands and prevents conversion of forests. First, we develop regional forest carbon supply curves using the partial equilibrium, dynamic optimization model of global timber markets and carbon stocks. Then, we calibrate the CGE model's regional responses to the curves.

We map out the carbon supply curves by introducing a range of carbon prices to the global timber model. The endogenous variables (e.g., harvest age, harvest area, land use change, and timberland management) adjust 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 in the baseline case where there is no carbon tax.

The global timber model can simulate long-run carbon sequestration potential by decade for 100 years. In this work, we consider the potential for sequestration in a single "representative" year within the first 50 years. Specifically, we calculate the present value of cumulative sequestration over the first 50 years, and then calculate the annual equivalent amount. We use a 5% discount rate, the rate assumed by the global timber model. The results for 16 regions in global timber model are reported in Table 2. Compared to 20 years time horizon used in GHLRS work, the long run would increase the potential for sequestration as longer term adjustments would be taken into account.

Carbon sequestration in each region is 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 third panel of Table 2. These entries are determined by assessing the annual change in forestland area, tracking new hectares in forests compared to the baseline due to afforestation and avoided deforestation, and tracking the carbon on those hectares. For regions that undergo afforestation in response to carbon policies (typically temperate regions), carbon on new hectares are tracked by age class so that the accumulation of carbon on new hectares occurs only as fast as the forests grow. Benefits from afforestation and reductions in deforestation are expected in Rest of South America, US, Brazil, and Russia. Smaller sequestration potential is observed in Sub Saharan Africa, Oceania and China. In the Rest of South America, sequestration potential on extensive margin is very responsive to carbon price.

The combined effect of management and aging represent the "intensive" margin for sequestration, as they reflect the stock of carbon per unit of forestland.[1] The forestry model's projections for annualized sequestration at the intensive margin at each carbon price in the first 50 years are reported in the second panel of Table 2. Overall, there is a large potential for increasing the forest carbon stock at the intensive margin, providing between 58% and 63% of total forest carbon sequestration for considered price range. According to Table 2, at carbon prices in the range between $10 and $100 the largest sequestration potential is in Russia and South East Asia. As carbon prices rise, the largest potential is shifted to Brazil and Rest of South America.

We calibrate the GTAP-AEZ-GHG model to Table 2 carbon sequestration margins by implementing a forest sequestration subsidy with the model running in a partial equilibrium mode to mimic the assumptions made in the carbon price simulation with the Global Timber Model (labor and capital prices are fixed, as well as land rents in all sectors except forestry; household utility is fixed as well to reflect fixed between baseline and carbon price scenarios income in the global timber model). The subsidy is applied to an augmented regional land input that includes two components: composite forest land (aggregated land from all AEZs used in the country's forestry production) and the own-use of forestry products in the forestry sector, which can be thought of as representing the volume of forest

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[1] The aging component is estimated by comparing the carbon that accrues in forests under the particular carbon price scenario examined versus the carbon that would have accrued in the carbon price scenario timberland area (and management intensity) if managed with the baseline age classes. The management component is estimated by comparing the carbon sequestered under the carbon price scenario to the carbon sequestered assuming the carbon price scenario forest area and age classes are managed with the baseline management intensities.

biomass on a given amount of forest land. Forest land area and forest biomass volume are allowed to substitute in production with an elasticity of substitution denoted by 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—the intensive margin (modified management and aging) and the extensive margin (more land in forests).

We perform two calibrations. First, we assume that $\sigma_{carbon} = 0$. In this case, the effect of the sequestration subsidy will be to increase the profitability of forestry with current management practices, thereby leading to an expansion of forest land with constant carbon intensity. *This is the extensive margin* and we calibrate to it by adjusting the incremental annual carbon intensity of forests.

Next, we calibrate the intensive margin. To do so, we fix the total land in forestry, thereby eliminating the extensive margin altogether, and introduce $\sigma_{carbon} > 0$ (once again running the model in partial equilibrium mode to mimic the assumptions made in carbon price simulation with the global timber model). In this case, the subsidy encourages an increase in the carbon intensity of forestry. In our model, this is reflected as a substitution of own-use of forest products, in the forestry sector, for forest land. This *reduces net forestry output* (net output is gross output produced *less* own-use). In effect, the forestry sector would choose to sacrifice some sales of commercial timber by adopting production practices that increase the carbon content on existing forest land. This intensive margin is calibrated by adjusting σ_{carbon} until the GTAP-AEZ-GHG model replicates the carbon sequestration response from the global timber model. GHLRS showed this formulation of the GTAP-AEZ-GHG model permits to replicate abatement costs from the dynamic timber model quite well for subsidies up to $100/TCE.

Preliminary Results

Having calibrated the GTAP-AEZ-GHG model to a suite of partial equilibrium GHG abatement costs, we now deploy our CGE model to investigate the market interactions between these different abatement opportunities. We summarize these interactions with general equilibrium GHG abatement supply schedules. We also briefly consider regional versus global carbon policies. The general equilibrium supply schedules are derived by varying the per unit carbon tax incrementally from $1/TCE to $100/TCE.

Figure 2 portrays the global abatement supply, including both non- CO_2 emissions from agriculture and forest carbon sequestration, taking into account full general equilibrium adjustments. Here, we see that forestry and agriculture could provide emission reductions of up to 3.0 BTCE per year in the near term. The largest share of global abatement is from the extensive margin of forestry, which may be seen as the difference between the forestry total abatement curve in Figure 2 and the intensification curve. Most of this abatement is due to reduced emissions through avoided deforestation in tropical regions. Avoiding deforestation has a relatively large immediate impact on carbon emissions as large quantities of *in situ* carbon are preserved.

For ease of exposition, we focus our discussion on the highest tax level shown in Figure 2: $100/TCE. Table 3 decomposes the global abatement at this price by region (columns) and type – fertilizer, paddy rice, ruminant livestock, miscellaneous agriculture and forest sequestration (rows). In all regions, forest sequestration provides the largest proportion of the total emissions reductions. Reductions in emissions from fertilizer use in US and from paddy rice in China are the second largest abatement activities, whereas ruminant livestock related emissions are the second largest individual source of abatement in ROW.

Carbon sequestration through forest extensification has two different effects on emissions from agriculture. On the one hand, forest extensification 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, which can drive up GHG emissions from any particular hectare. In a separate simulation of the forest sequestration subsidy alone, we have ascertained that the former effect dominates, so that sequestration-driven forest extensification reduces overall agriculture emissions.

An important aspect of climate policy relates to how well countries coordinate their actions. Carbon price differences across regions could distort markets. It is therefore useful to assess how the general equilibrium supply of abatement changes depends on assumptions regarding regional carbon policies. Analysis is frequently conducted on a country-by-country basis, implicitly assuming that other countries do not have carbon policies (e.g, Murray et al. (2005) for the USA). To explore these issues, we construct a simple example, beginning with the global carbon tax policy described above. The general equilibrium abatement supply for the two forestry options (intensification and extensification) and the agricultural sector, resulting from a global carbon tax reveals that, at $100/TCE, US abatement reaches a maximum of 210 MMTCE, with a 27 MMTCE reduction derived from the agricultural sector and 183 MMTCE through forest sequestration. Now contrast this with the case where abatement is implemented in USA alone. In this case, at $100/TCE, US abatement reaches a maximum of 217 MMTCE – about 5 percent more abatement for the same carbon price, with around 180 MMTCE obtained from forest sequestration and 38 MMTCE from agriculture emissions. In agriculture, USA abatement is diminished by 29% under the global tax compared to the USA only tax. The domestic carbon tax increases the cost of USA agricultural products relative to overseas production. As a result, non-USA production increases, as do GHG emissions. On the other hand, when the tax is applied globally, USA agriculture is able to exploit its comparative production advantage; thus USA-based GHG abatement in agriculture becomes more expensive as the opportunity cost of mitigation increases. In short, differential regional carbon prices can affect the marginal abatement of each region. Studies that only examine national carbon policies, and do not consider the relative effects of regional carbon policies, could significantly mis-estimate the extent of abatement in agriculture and forestry. Finally, we integrate the analysis of land use related non-CO_2 emissions and forest carbon sequestration with more conventional analyses of CO_2 emissions from fossil fuel combustion in all sectors. With an economy-wide global emissions tax of $100 per tonne of carbon equivalent, the reduction in emissions from agricultural sectors and increase in forest carbon sequestration would amount to about one half of the overall global abatement (Table 4) with the contribution varying across regions.

Conclusions

In our analysis of carbon taxation, we find that forest carbon sequestration is the dominant strategy for GHG emissions mitigation globally in the land using sectors. However, when compared to the rest of the world, in the US and China land-use emissions abatement comes disproportionately from agriculture, and within USA agriculture, disproportionately from reductions in fertilizer-related emissions. In the world as a whole, agriculture-related mitigation comes predominantly from reduced methane emissions in the ruminant livestock sector, followed by fertilizer and methane emissions from paddy rice.

Using this model, we will also analyze the effect of emissions quantity constraints. Of particular interest here is the relative role of land-based mitigation in satisfying a domestic or international emissions quantity constraint. We will be evaluating the general equilibrium responses, as rising energy and other intermediate input prices affect land using sector production and mitigation costs, while rising food and timber costs affect household expenditure shares, and regional variations in both effects redefine trade flows.

References

Ahammad, H., and R. Mi. 2005. “Land Use Change Modeling in GTEM: Accounting for forest sinks”. Australian Bureau of Agricultural and Resource Economics. Presented at EMF 22: Climate Change Control Scenarios, Stanford University, California, 25-27 May, 2005.

Ahmed, A. S., T. W. Hertel, and R. Lubowski. 2009. “Calibration of a Land Cover Supply Function Using Transition Probabilities” , GTAP Research Memorandum No. 14, Center for Global Trade Analysis. Purdue University, West Lafayette, IN, USA.

Burniaux, J. and T. Truong. 2002. "GTAP-E: An Energy-Environmental Version of the GTAP Model", GTAP Technical Paper No. 16, Center for Global Trade Analysis. Purdue University, West Lafayette, IN.

FAO and IIASA. 2000. Global Agro-Ecological Zones - 2000. Food and Agriculture Organization (FAO) of the United Nations, Rome, Italy, and International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria.

Golub, A., T.W. Hertel, H.-L. Lee, S. Rose and B. Sohngen. 2008. “The opportunity Cost of Land Use and the Global Potential for Greenhouse Gas Mitigation in Agriculture and Forestry”. GTAP Working Paper No. 36, Center for Global Trade Analysis. Purdue University, West Lafayette, IN, USA.

Lee, H.-L.. 2007. “An Emissions Data Base for Integrated Assessment of Climate Change Policy Using GTAP”. GTAP Resource #1143, Center for Global Trade Analysis, Purdue University, https://www.gtap.agecon.purdue.edu/resources/res_display.asp?RecordID=1143

Lee, H.-L., T. W. Hertel, S. Rose and M. Avetisyan. 2009. “An *Integrated Global Land Use Data Base for CGE Analysis of Climate Change Policy Options*,” in Thomas Hertel, Steven Rose, Richard Tol (eds.), *Economic Analysis of Land Use in Global Climate Change Policy*, Routledge Publishing.

McDougall, R. and A. Golub. 2007. “GTAP-E Release 6: A Revised Energy-Environmental Version of the GTAP Model", GTAP Research Memorandum No. 15, Center for Global Trade Analysis. Purdue University, West Lafayette, IN, USA.

Murray, B.C., B.L. Sohngen, A.J. Sommer, B.M. Depro, K.M. Jones, B.A. McCarl, D. Gillig, B. DeAngelo, and K. Andrasko. 2005. EPA-R-05-006. "Greenhouse Gas Mitigation Potential in U.S. Forestry and Agriculture." Washington, D.C: U.S. Environmental Protection Agency, Office of Atmospheric Programs.

Rose, S. and H.-L. Lee. 2009. “Non-CO_2 Greenhouse Gas Emissions Data for Climate Change Economic Analysis” in Thomas Hertel, Steven Rose, Richard Tol (eds.), *Economic Analysis of Land Use in Global Climate Change Policy*, Routledge Publishing.

Sohngen, B. and R. Mendelsohn. 2007. "A Sensitivity Analysis of Carbon Sequestration." In *Human-Induced Climate Change: An Interdisciplinary Assessment*. Edited by M. Schlesinger. Cambridge University Press.

USEPA. 2006. *Global Mitigation of Non-* CO_2 *Greenhouse Gases*. United States Environmental Protection Agency, Washington, DC, 430-R-06-005, http://www.epa.gov/nonco2/econ-inv/international.html

Table 1 CO_2 and Non-CO_2 GHG emissions by region (MMTCE)

	Non-CO2 GHGs				
	Nitrous oxide (N2O)	Methane (CH4)	F-Gas	All non-CO2	CO2 GHG
USA	110	151	38	299	1562
EU27	112	125	15	252	1042
China, Hong Kong	175	205	16	396	764
India	18	128	2	148	259
Russia	16	81	4	101	397
Other East Europe and Rest of Former Soviet Union	28	118	1	147	265
Middle East and North Africa	18	87	2	107	335
Other regions	287	656	31	974	1394
Total	764	1551	109	2424	6019

Table 2 Carbon sequestration supply schedule: by category, annual equivalent abatement over 50 years (MMTCE)

Total Carbon

Pc	US	China	Brazil	Canada	Russia	EU ANNEX I	EU NON-ANNEX I	South Asia	Central America	Rest South America	Sub Saharan AF	South East Asia	Oceania	Japan	AF Middle East	East Asia	Total
10	10	1	6	2	43	1	0	6	1	11	9	44	7	0	0	2	144
50	53	30	48	15	132	10	0	58	9	86	31	146	23	5	0	7	655
100	78	67	102	26	180	10	1	88	13	132	64	167	24	7	0	21	981
200	101	129	194	49	201	16	2	106	15	213	102	195	24	9	1	29	1385
400	119	185	254	89	226	31	8	124	17	238	107	210	24	23	1	33	1690
800	135	216	262	123	258	62	14	129	18	251	127	212	28	35	1	34	1905

Intensive

Pc	US	China	Brazil	Canada	Russia	EU ANNEX I	EU NON-ANNEX I	South Asia	Central America	Rest South America	Sub Saharan AF	South East Asia	Oceania	Japan	AF Middle East	East Asia	Total
10	0	1	5	2	42	2	0	1	0	2	2	32	0	0	0	0	90
50	4	22	8	7	103	6	0	60	4	31	42	155	0	3	0	4	450
100	9	53	43	15	129	5	1	65	7	69	74	157	0	5	0	7	638
200	13	95	135	30	147	17	3	70	8	74	74	162	0	6	0	16	850
400	29	140	172	47	162	21	4	72	9	78	80	161	1	12	0	19	1008
800	41	157	172	73	167	44	6	75	9	79	80	164	4	19	0	19	1110

Extensive

Pc	US	China	Brazil	Canada	Russia	EU ANNEX I	EU NON-ANNEX I	South Asia	Central America	Rest South America	Sub Saharan AF	South East Asia	Oceania	Japan	AF Middle East	East Asia	Total
10	10	0	1	0	1	0	0.0	5	0	10	7	12	7	0	0.1	1	54
50	49	9	40	8	29	4	0.0	-2	5	55	-10	-9	23	1	0.2	3	205
100	70	14	59	11	52	5	0.3	23	6	63	-10	10	23	2	0.4	14	343
200	88	35	59	18	54	-1	-1.2	36	7	139	28	33	23	4	0.4	13	535
400	90	45	82	42	64	10	3.6	52	8	161	27	48	23	11	0.4	15	682
800	94	59	90	51	90	18	7.6	55	8	172	47	48	24	17	0.5	15	795

Table 3 General equilibrium impact of emissions taxes on net emissions in each region following a global tax of $100/TCE in agricultural sectors and forestry

Type/region of taxation	Global	Emissions change from region (MMTCE)		
		USA	CHN	ROW
Fertilizer	-81	-16	-14	-50
Land use related emissions in paddy rice (methane)	-53	0	-17	-36
Land and capital use related emissions in ruminant livestock	-111	-6	-11	-93
Miscellaneous	-52	-4	-16	-32
Forest sequestration	-2624	-183	-169	-2272
Total Impact	-2920	-210	-228	-2483

Table 4 Emissions reduction followed by global carbon tax of $100/TCE

Type/region of taxation	Global	Emissions change from region (MMTCE)		
		USA	CHN	ROW
Agricultural sectors emissions, CO2 and non-CO2, and carbon sequestration	-2920	-210	-228	-2483
All other emissions	-2265	-553	-555	-1157
Total Impact	-5185	-763	-783	-3640

Figure 1 Non-CO_2 GHG emissions by agricultural sector and region (MMTCE)

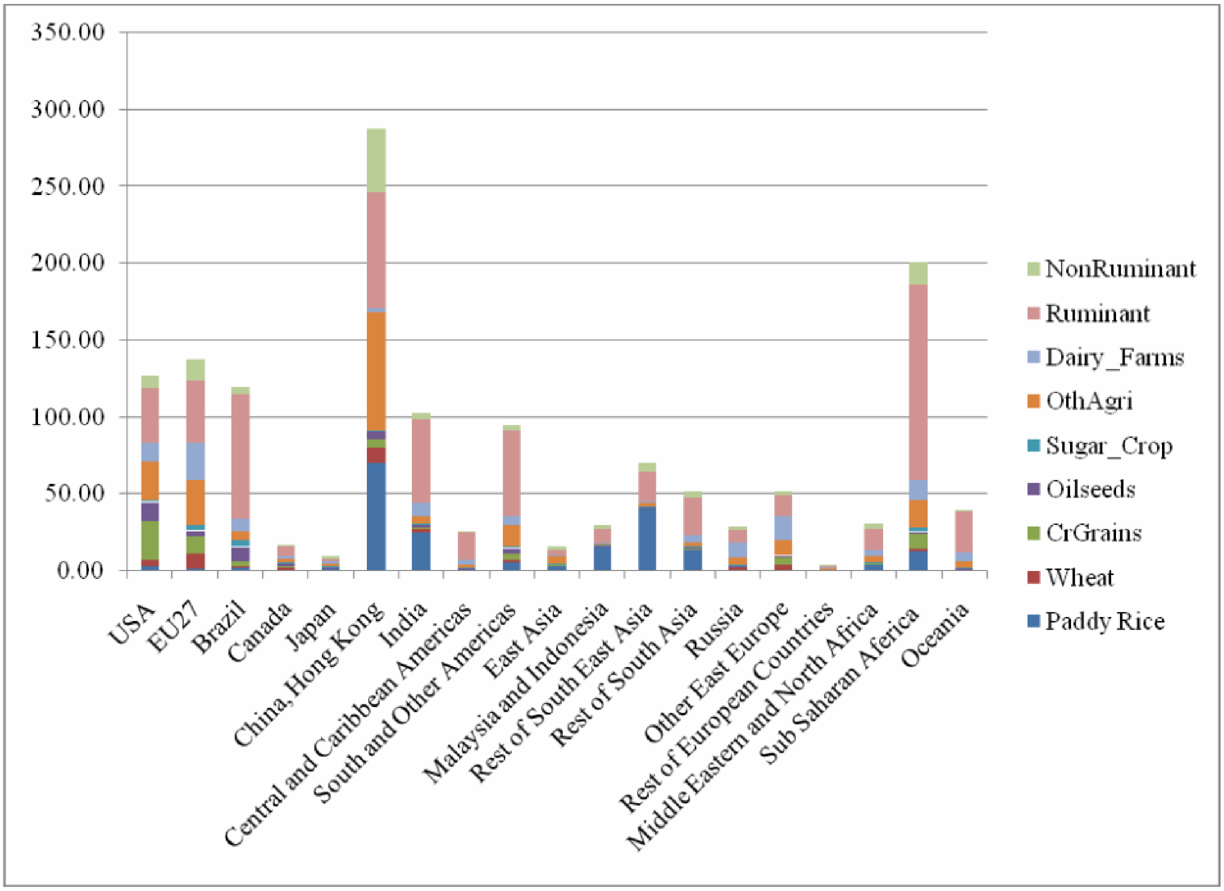
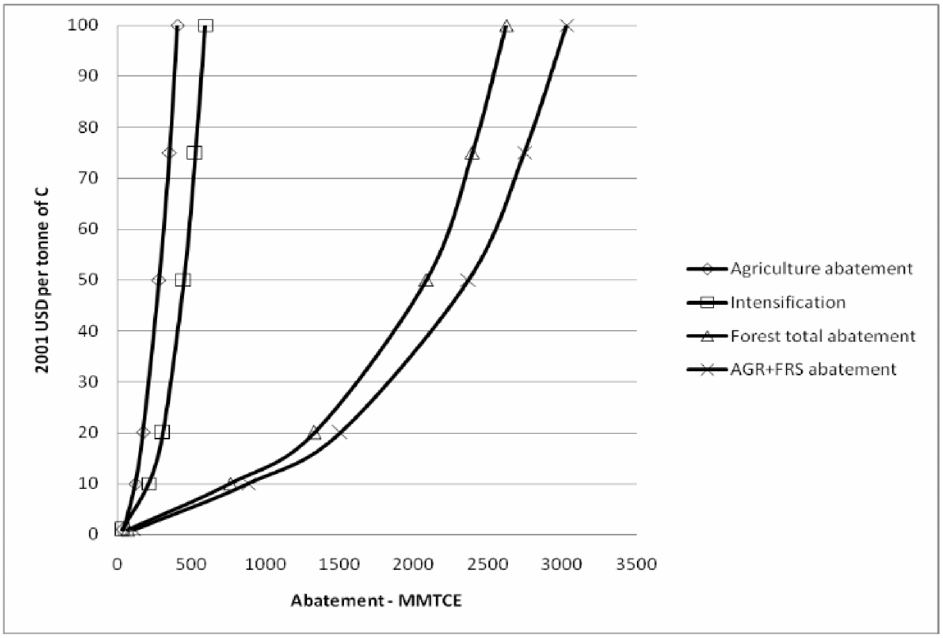


Figure 2 Global general equilibrium GHG abatement supply schedules: global carbon tax in agricultural sectors and forestry



Appendix

Table A1 Aggregation of GTAP regions and correspondence with regions in the dynamic forestry model

Region in the model	**GTAP regions**	**Region in forestry model**
United States	United States	United States
European Union 27	Austria, Belgium, Denmark, Finland, France, Germany, United Kingdom, Greece, Ireland, Italy, Luxemburg, Netherlands, Portugal, Spain, Sweden, Cyprus, Czech Republic, Hungary, Malta, Poland, Romania, Slovakia, Slovenia, Estonia, Latvia, Lithuania, Bulgaria	EU Annex I
Brazil	Brazil	Brazil
Canada	Canada	Canada
Japan	Japan	Japan
China, Hong Kong	China, Hong Kong	China
India	India	South Asia
Central and Caribbean Americas	Mexico, Rest of North America, Central America, Rest of Free Trade Area of the Americas, Rest of the Caribbean	Central America
South and Other Americas	Colombia, Peru, Venezuela, Rest of Andean Pact, Argentina, Chile, Uruguay, Rest of South America	Rest of South America
East Asia	Korea, Taiwan, Rest of East Asia	East Asia
Malaysia and Indonesia	Indonesia, Malaysia	South East Asia
Rest of South East Asia	Philippines, Singapore, Thailand, Viet Nam, Rest of Southeast Asia	South East Asia
Rest of South Asia	Bangladesh, Sri Lanka, Rest of South Asia	South Asia
Russia	Russian Federation	Russia
Other East Europe and Rest of Former Soviet Union	Rest of Former Soviet Union, Turkey, Albania, Croatia, Rest of Europe	EU Non-Annex I
Rest of European Countries	Switzerland, Rest of EFTA	EU Annex I
Middle East and North Africa	Rest of Middle East, Morocco, Tunisia, Rest of North Africa	Africa, Middle East
Sub Saharan Africa	Botswana, South Africa, Rest of South African Customs Union, Malawi, Mozambique, Tanzania, Zambia, Zimbabwe, Rest of Southern African Development Community, Madagascar, Uganda, Rest of Sub-Saharan Africa	Sub Saharan Africa
Oceania	Australia, New Zealand, Rest of Oceania	Oceania