Global interactions between bioenergy and climate policies

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Draft

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1. Introduction

Over the past few years, interest in bioenergy has boomed with higher oil prices and concerns about energy security, farm incomes, and mitigation of climate change. Large-scale commercial bioenergy production could have far reaching implications for regional and global input and output markets associated with food, forestry, chemical, and energy sectors, as well as affecting household welfare. As such, large-scale bioenergy programs are likely to have economy-wide and global effects on greenhouse gas emissions. Similarly, there is significant interest in international agricultural and forestry based greenhouse gas (GHG) mitigation, which could help reduce emissions abatement costs facing regulated sectors in developed countries and provide revenue to developing countries and farmers in exchange for modifying land management for mitigation. Changes in production practices in these sectors could reduce emissions and increase terrestrial carbon stocks, as well as provide fossil fuel energy feedstock substitutes to the power and transportation sectors. However, bioenergy and climate policies are being formulated largely independent of one another. Therefore, understanding the interaction between these potentially competing policy objectives is valuable for identifying possible constraints that one policy might

be placing on the other, as well as potential complementarities that could be exploited for developing mutually reinforcing policies.

This study develops and applies a new 19 region, 31 sector global computable general equilibrium (CGE) platform with explicit consideration of bioenergy flows through the economy, greenhouse gas emissions and forest carbon fluxes, as well as GHG mitigation and sequestration costs, and endogenous land reallocation responses across sectors and within and across regions. Recent data and model development has made it possible to explicitly model global land-use, net greenhouse gas effects, and agriculture and forestry mitigation technologies in CGE models (see Hertel *et al.*, 2009a). For this study, we integrate and expand upon four independent components: (1) the GTAP-E energy modeling framework (developed by Burniaux and Truong (2002), and modified by McDougall and Golub (2007)) as extended by Birur *et al.* (2008) with liquid biofuels and their by-products (Taheripour et al. 2010), (2) the GTAP-AEZ-GHG land-use modeling and greenhouse gas emissions mitigation (forest carbon sequestration and non-CO_2 greenhouse gas emissions) framework (Hertel *et al.*, 2009b; Golub et al., 2009), (3) new GTAP non-CO_2 emissions data for all sectors of the economy (Rose and Lee, 2009) and forest carbon stock data by species, vintage and AEZ (Sohngen *et al.*, 2009), and (4) the fossil fuel CO_2 emissions database developed by Lee (2007). The new CGE framework allows us to capture detailed GHG effects (CO_2 and non-CO_2) and control costs within and across a fairly disaggregated sector and regional structure; thereby estimating the reallocation implications of the policies.

With this framework, we assess the effects of US bioenergy expansion on sectoral, regional and global GHG emissions mitigation potential. Do bioenergy programs facilitate or constrain GHG mitigation opportunities? For instance, Golub *et al*. (2009) estimate substantial

GHG mitigation potential in non-US forests (8.9 $GtCO_2yr^{-1}$ at $27/$tCO_2$eq). Furthermore, Golub *et al.* (2009) find that a carbon tax could lead to input substitution in agricultural production away from land and fertilizer (e.g., in China, an approximate 20% reduction in paddy rice acreage and 10% reduction in crop production fertilizer use at the same GHG price). Both results run counter to the changes in land-use induced by biofuels, as estimated by Hertel *et al.* (2010) (e.g., 9% loss of Brazilian forest driven by US and EU biofuels policies). However, given the energy security benefits for bioenergy, we also evaluate whether a land GHG policy could manage international indirect land-use leakage concerns for bioenergy, and how might a GHG policy affect the cost of biofuels mandates?

In the next section we describe our modeling approach and scenarios for investigating this topic. We then discuss our results and conclude with by highlighting some of our insights for policy-makers.

2. Methodology

In this work we combine GTAP-AEZ-GHG model described in Hertel *et al.*, (2009b) and Golub et al. (2009) and GTAP-BIO of Birur *et al*. (2008).

2.1 GTAP-AEZ-GHG model

GTAP-AEZ-GHG model used in this work is an extension of GTAP-E model with 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. The explicit treatment of GHG mitigation options in the model is derived from detailed sector and technology specific studies of abatement options. For instance, in the agricultural sectors, the model is calibrated in a partial

equilibrium mode to non-CO_2 GHG mitigation possibilities derived from engineering and agronomic studies developed by the US Environmental Protection Agency (USEPA, 2006). The agricultural production structure in this CGE model then allows for general equilibrium abatement responses with more refined mitigation responses than currently available in the literature with similar models so that abatement can occur by (e.g.) reducing fertilizer use, changing the way in which existing fertilizer is applied, as well as changing total output.

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). The CGE model's regional responses are calibrated to the forest carbon sequestration supply curves. These responses include 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).

The CGE analysis is conducted using a 19 region aggregation of the GTAP data base (see Table A1 in Appendix for regional aggregation) and it utilizes version 6 of the GTAP data base representing the world economy in 2001. We use the v.6 data base, since GHG emissions and land use are only now being updated to the v.7, 2004 data base. 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, on the one hand, and from fossil fuels combustion and industrial activities, on the other.

2.2 Introduction of biofuels

We introduce several elements of GTAP-BIO model (Birur et al. 2008) into this modeling platform: the Leontief demand for ethanol as a fuel oxygenator, the potential for ethanol and other biofuels to

substitute for petroleum products as an energy source, and conventional ethanol production co-products that affect the net profitability of ethanol. We draw on the revised set of parameters proposed by Beckman, Hertel and Tyner (2010) who undertook a historical validation exercise and find that the energy demand elasticities in the standard GTAP-E model were far too elastic.

We use a modified GTAP v.6 data base that incorporates biofuels and their by-products (Taheripour et al. 2010). Ethanol from corn (in US), ethanol from wheat (in EU), sugar cane ethanol and oilseeds biodiesel are split out from the standard GTAP sectors. There are two types of by-products introduced into the GTAP data base and the model: (1) Dried distillers grains with soluble (DDGS), by-product of corn ethanol and wheat ethanol; and oilseeds meal, by-product of crude vegetable oil. DDGS in the data base refer to ethanol by-product. Other types of distillers grains are not included in DDGS and included in a separate "processed feed" sector. In contrast to DDGS, oilseeds meal in the data covers all types of meal produced across the world.

2.3 Heterogeneous land

When modeling competition for land, it is important to recognize that land is a 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^{o}C 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 enter as inputs into a 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 as would be expected if production of all homogeneous national commodities occurred directly at the AEZ level (Hertel et al., 2009).

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 crop and livestock uses. Therefore, we 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. The land owner then decides on the allocation of land between various crops, again based on relative returns in crop sectors.

2.4 GHG emissions

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. 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 13% of

global non-CO_2 emissions from agriculture, respectively. In China, paddy rice cultivation is an important source of methane emissions. Ruminant and non ruminant sectors and the "other agriculture" category that includes fruit and vegetables are other large sources of GHG emissions in China. The ruminant sector in Sub Saharan Africa is single largest agricultural source of non-CO_2 emissions globally.

To model and evaluate the general equilibrium input allocation responses to mitigation policies, we tied emissions to explicit input or output levels. Three types of agricultural production mitigation responses are captured: those associated with intermediate input use, primary factors, and those associated with sector outputs. More specifically, the methane emissions associated with paddy rice production are tied to acreage cultivated, as the emissions tend to be proportional to the amount of paddy rice land. Nitrous oxide emissions from crop production are tied to fertilizer use. Emissions associated with enteric fermentation, manure management in ruminants and non-ruminants are tied to output. Emissions from biomass burning, and stationary and mobile combustion are tied to sector output. 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 permitted to respond to a methane emissions tax not only by using less land, but also by changing the emissions intensity of paddy rice land.

Any given emissions entry in Figure 1 may be large because the economic activity in the sector is large (e.g., a large dairy sector), or it may be large due to a high level of base period emissions, per dollar of input (Avetisyan et al. 2010). The latter is termed the "emissions intensity" of a given activity, and this intensity is critical in determining the impact of a carbon-equivalent emissions tax on a given sector. Figure 2 shows emission intensities per dollar of

output (kgCO_2eq/$) when all non-$CO_2$ emissions in livestock sectors, including those related to output, factors and intermediate inputs use, are tied to output. Sub Saharan Africa (S_S_Afr), Malaysia and Indonesia, Rest of Southeast Asia (R_SE_Asia) and Brazil have highest emission intensities.

The U.S. Environmental Protection Agency (USEPA) has estimated the engineering mitigation costs and emissions implications of alternative management strategies for key non-CO_2 emissions sources—paddy rice, other croplands (wheat, maize, soybean), and livestock enteric and manure emissions (USEPA, 2006). Figure 3 summarizes the percentage abatement response for the livestock sectors in each region at a marginal cost of 27 $/tCO2-eq. The information was developed by the authors from the estimated USEPA (2006) abatement costs for 2010 and customized for our model's sector and regional aggregation. The CGE model used in this study is calibrated to these more disaggregated and consistent marginal abatement cost (MAC) curves. For livestock sectors we use new information on abatement opportunities summarized in Figure 3. In the crop sectors we apply parameters reported in Golub et al. (2009).[1] The calibration procedure is described in Golub et al. (2009) and operates by adjusting the elasticities of substitution between emissions and respective inputs/outputs in order to replicate the customized USEPA abatement possibility estimates at 27$/t$CO_2$eq.

3. Results

In this draft of the paper, we first look at the global abatement opportunities and then focus on the abatement in agriculture and forestry with and without US biofuel mandate. We summarize

[1] Because of more disaggregated data used in this project, we apply Rest of the World (ROW) parameters reported in the previous work to all regions other than China and USA. In future versions of this paper, we plan to calibrate each of 17 regions (currently all sharing the same ROW parameters), as well as several of the new sectors to more disaggregated marginal abatement curves when they become available.

the global market interactions between different abatement opportunities with general equilibrium GHG abatement supply schedules. The general equilibrium supply schedules are derived by varying the per unit carbon tax incrementally up to \$50/tCO_2eq in all sectors and regions of the global economy. Figure 4 portrays the global abatement supply, including all GHG emissions and sequestration -- non-CO_2 emissions from agriculture, forest carbon sequestration, industrial CO_2 and non-CO_2 GHG, and emissions from private consumption -- taking into account full general equilibrium adjustments. At 27\$/tCO_2eq, the model predicts that global emissions can be reduced by 12 GtCO_2eq (billion metric tonnes of carbon dioxide equivalent) with almost half of the reduction provided by sequestration in forests (5 GtCO_2eq) and 1.2 GtCO_2eq abatement provided by agricultural sectors. The magnitude of the potential abatement possibilities in land using sectors highlights the importance of devoting greater attention to these sources of future mitigation.

We now turn to the analysis of a range of mitigation policies with different regional and sectoral coverage to illustrate the mitigation potential of and interactions between regions and sectors. The experiments and respective results are summarized in Table 2. Global forest carbon sequestration price is applied in all scenarios. The scenarios vary by participation of agricultural sectors and non-Annex 1 countries in abatement policies. The experiment results in Table 2 are paired to compare global vs. Annex 1 only abatement. Scenario 2, where tax on emissions in agriculture is imposed in Annex 1 countries only, demonstrates that forest carbon sequestration subsidy introduced in both Annex 1 and non-Annex 1 manages agricultural sector emissions leakage to non-Annex 1 countries.[2] In Scenario 4, where all industries are subject to tax only in

[2] The leakage is defined as emission increase in regions not subject to carbon tax relative to emission reduction achieved in regions where the tax is imposed.

Annex 1 regions, there is a small (3%) leakage in non land using sectors and private consumption.[3] Similarly, in scenario 6 where carbon tax is imposed in non agricultural sectors of Annex 1, there is a small (about 4%) leakage in non land using sectors and private consumption. Interestingly, in this experiment, emissions from global agricultural production decline, but within Annex 1 they grow reflecting shift of agricultural production to Annex 1. Scenario 6 demonstrates that when only non-agriculture is subject to carbon tax in Annex 1 and forest carbon sequestration subsidy is introduced globally, emissions from agriculture are reduced globally because the forest carbon sequestration incentive bids land away from agriculture. However, there is 14 mill tCO2eq increase in emissions from Annex I agricultural sectors due to expanded agricultural production in this region.

Next, we focus on emissions from land using sectors and consider two experiments. In both experiments global emissions and sequestration in agriculture and forestry (both CO2 and non-CO2 emissions) are the only sources subject to a 27$/tCO2eq carbon tax. First experiment is based on initial data representing world economy in 2001. The second experiment consists of two steps. First, we introduce US corn ethanol mandate by modeling expansion of US corn ethanol from 2001 level to 15 billion gallons per year. In this exercise we follow Hertel et al. (2010b) by forcing additional ethanol production, with the higher costs passed forward to consumers in the form of higher fuel prices. Then, using updated data base with 15 bill gallons of US corn ethanol in place, we introduce the carbon tax in agriculture and forest carbon sequestration subsidy globally. Total changes in GHG emissions, changes in carbon sequestered in forests under subsidy and change in emissions from agricultural sectors in the two experiments, with expanded corn ethanol production and without, are shown in Table 3.

[3] This leakage is calculated as (2906-2808)/2906*100 = 3%.

The expanded ethanol production results in reduced abatement potential, especially from forests with a slight reduction in the potential from agricultural sectors. More specifically, for a modest increase in U.S. corn ethanol production, approximately 400 MtCO2eq of abatement is foregone at $27/tCO2eq. The corn ethanol policy has therefore increased the cost of abatement and reduced global abatement potential by 7%. USA abatement of course is directly affected as the mandate increases the value of cropland relative to afforestation potential. Other regions, especially those with direct agriculture and forestry trade ties to the US are disproportionate affected—such as Canada, Brazil, and the rest of South America. These results illustrate that in addition to the potential for a net increase in global emissions, corn ethanol mandates could impose an additional cost on society in the form of lost GHG abatement opportunities. Because the results are regionally disproportionate, the results raise questions about net regional consumption, production, and welfare implications.

4. **Summary and next steps**

Understanding interactions between potential bioenergy and climate policies is important. There are regional comparative advantages in biofuels production (as well as non-biofuels crops and timber production). There are also regional comparative advantages in land-based GHG mitigation, and economy-wide effects as policies affect energy and commodity markets, and trade patterns.

Our preliminary results indicate that expansion of US corn ethanol reduces the abatement potential for agriculture and forestry and thereby imposes an additional cost on society. This is

an intuitive result as the mandate increases the opportunity cost of abatement, especially for forest carbon sequestration. With this finding in hand, we will push forward into this topic, in particular, looking at whether there are non-linearities in the response with larger biofuel policies, cost implications of agriculture and forestry greenhouse gas incentives on biofuel production, and the potential for coordinated biofuel-greenhouse gas policies that are globally GHG neutral. By modeling bioenergy and climate policies independently and simultaneously, we assess the net comparative advantage regions have in meeting these two sets of goals, and the efficiency implications of bioenergy policies on GHG abatement, as well as the market implications for land-use, production, and global competitiveness, and the potential price and household ramifications that provide insights into sustainability.

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Table 1 CO_2 and Non-CO_2 GHG emissions by region ($MtCO_2eq$)

	Non-CO_2 GHGs			All	CO_2	All
	Nitrous oxide (N_2O)	Methane (CH_4)	F-Gas	non-CO_2	GHG	GHG
USA	402	554	139	1,095	5,985	7,080
EU27	412	457	57	926	3,888	4,814
BRAZIL	184	307	7	497	288	785
CAN	48	94	11	154	540	693
JAPAN	32	20	41	93	1,032	1,124
CHIHKG	641	753	60	1,455	2,918	4,373
INDIA	65	468	8	541	964	1,506
C_C_Amer	44	215	6	264	578	843
S_O_Amer	177	303	4	484	454	938
E_Asia	45	85	20	151	660	811
Mala_Indo	31	202	2	234	416	650
R_SE_Asia	62	260	4	326	363	689
R_S_Asia	84	172	1	256	153	409
Russia	58	297	15	369	1,493	1,862
Oth_CEE_CIS	114	435	5	555	1,001	1,556
Oth_Europe	8	10	4	22	107	128
MEAS_NAfr	117	319	8	443	1,533	1,976
S_S_AFR	315	590	8	913	468	1,381
Oceania	43	152	6	201	426	627
Total	2,881	5,691	405	8,977	23,270	32,247

Table 2 Global and Annex I emissions *reduction* under different policy assumptions, all at carbon price 27$/t$CO_2$eq, MtCO2eq

Scenario	All emissions reduction		Forest carbon sequestration		Agricultural sectors		Other sectors and private consumption	
	Global	Annex 1	Global	Annex 1	Global	Annex 1	Global	Annex 1
1. Global forest carbon sequestration subsidy, global carbon tax in agriculture	6,105	902	4,888	688	1,181	207	36	8
2. Global forest carbon sequestration subsidy, Annex 1 only tax in agriculture	5,201	973	4,818	703	359	259	24	10
3. Global forest carbon sequestration subsidy, carbon tax in all sectors	12,126	3,713	4,899	685	1,232	224	5,995	2,803
4. Global forest carbon sequestration subsidy, Annex 1 only tax in all sectors	7,959	3,871	4,790	699	362	266	2,808	2,906
5. Global forest carbon sequestration subsidy, global carbon tax in all non agricultural sectors	11,056	3,506	4,846	695	238	13	5,971	2,798
6. Global forest carbon sequestration subsidy, Annex 1 only tax in all non agricultural sectors	7,563	3,385	4,811	693	155	-14	2,597	2,707

Table 3 Changes in GHG emissions from land using sectors with and without US corn ethanol mandate under carbon tax in agriculture and forest carbon sequestration subsidy \$27/tCO_2eq, MtCO_2eq

Region	Total change in emissions		Change in forest carbon sequestration		Change in emissions from agriculture	
	Without corn ethanol mandate	With corn ethanol mandate	Without corn ethanol mandate	With corn ethanol mandate	Without corn ethanol mandate	With corn ethanol mandate
USA	-568	-540	452	419	-116	-117
EU27	-71	-70	9	7	-60	-60
BRAZIL	-839	-819	661	642	-180	-179
CAN	-78	-71	70	63	-8	-8
JAPAN	-39	-37	37	35	-2	-2
CHIHKG	-869	-844	660	636	-207	-205
INDIA	-392	-389	314	312	-76	-75
C_C_Amer	-216	-209	197	191	-17	-17
S_o_Amer	-1646	-1612	1565	1532	-80	-80
E_Asia	-168	-162	160	155	-6	-6
Mala_Indo	-58	-57	25	24	-33	-33
R_SE_Asia	-114	-112	13	13	-100	-99
R_S_Asia	-46	-45	18	17	-28	-28
Russia	-34	-34	5	4	-24	-24
Oth_CEE_CIS	-39	-39	2	2	-18	-18
Oth_Europe	-2	-2	0	0	-1	-1
MEAS_NAfr	-15	-14	4	4	-6	-6
S_S_AFR	-1174	-878	602	577	-327	-302
Oceania	-135	-136	116	117	-18	-18
Total	-6501	-6071	4910	4749	-1306	-1278

Figure 1 Non-CO_2 GHG emissions by agricultural sector and region (MMtCO_2eq)

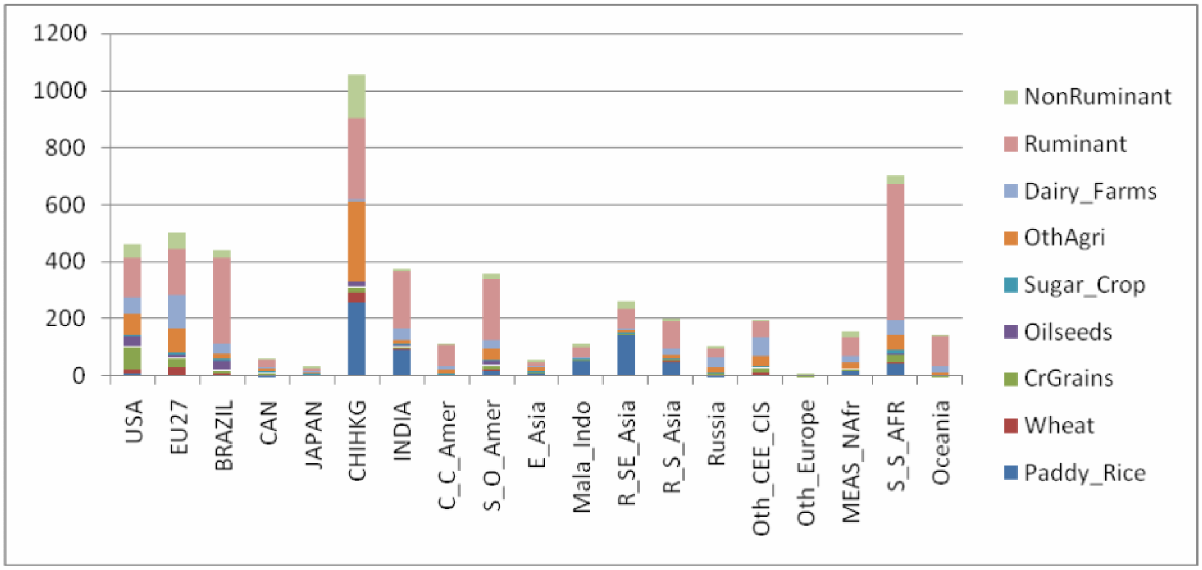


Figure 2 Emission intensity of output when all livestock sector non-CO_2 emissions, including emissions related to factors and intermediate input use, are tied to output (kgCO_2eq/$ of output)

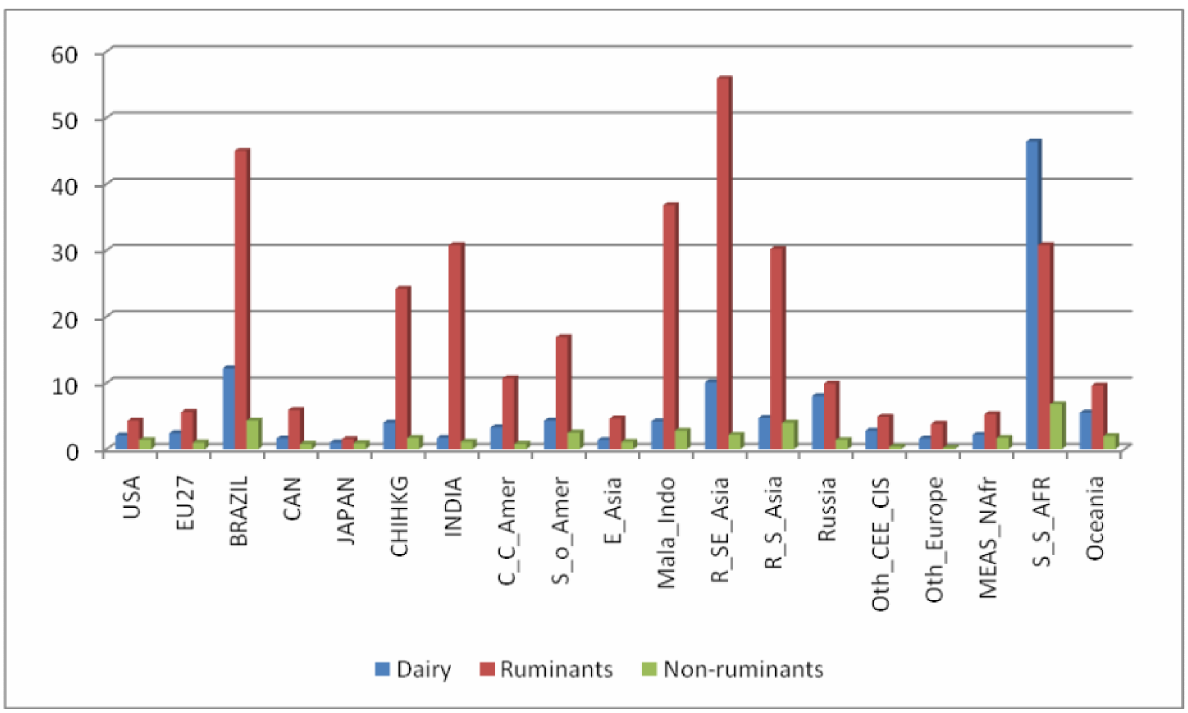
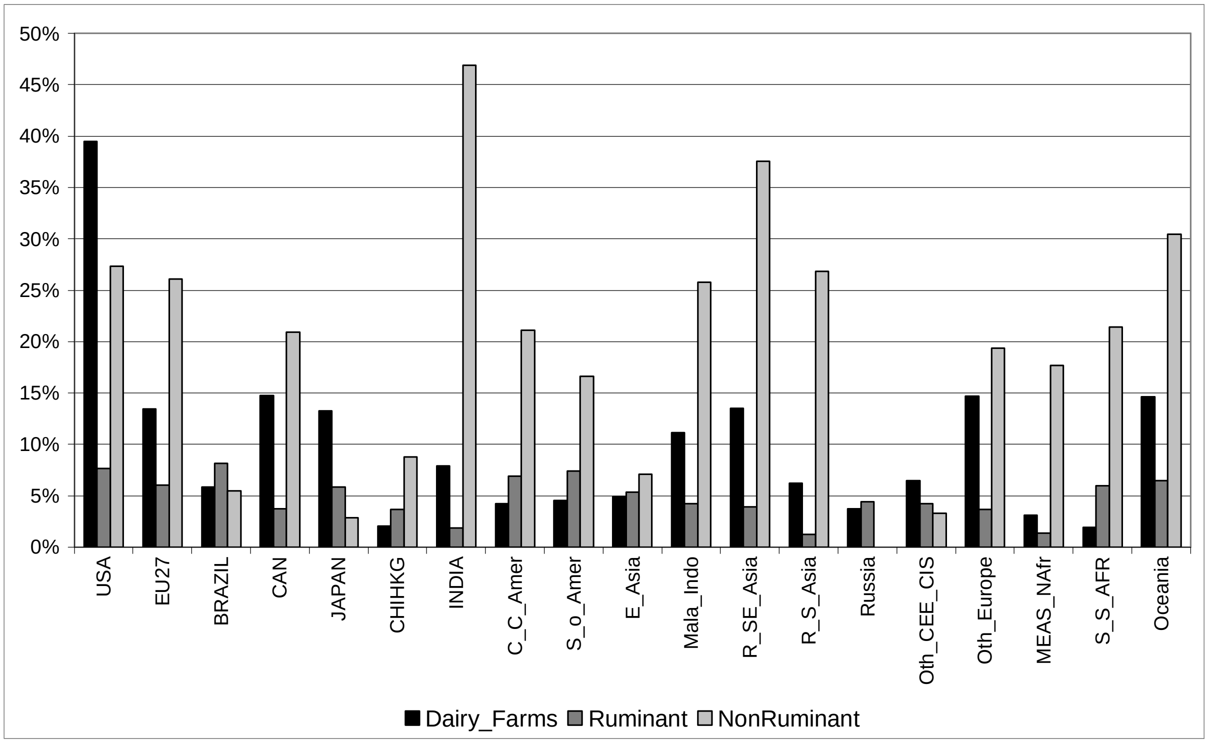
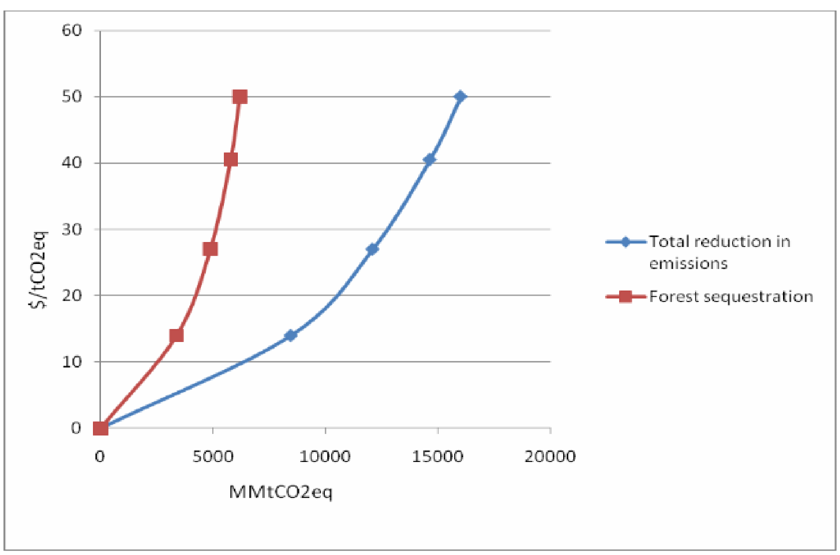


Figure 3: Partial equilibrium % abatement responses for the livestock sectors, at 27 $/tCO_2$-eq



Source: Derived from USEPA(2006) 2010 detailed abatement cost data.

Figure 4 Global general equilibrium GHG abatement supply schedule: global carbon tax in all sectors, private consumption, and sequestration subsidy in forestry



Appendix A

Table A1 Aggregation of GTAP regions

Region in the model	GTAP regions
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
Brazil	Brazil
Canada	Canada
Japan	Japan
China, Hong Kong	China, Hong Kong
India	India
Central and Caribbean Americas	Mexico, Rest of North America, Central America, Rest of Free Trade Area of the Americas, Rest of the Caribbean
South and Other Americas	Colombia, Peru, Venezuela, Rest of Andean Pact, Argentina, Chile, Uruguay, Rest of South America
East Asia	Korea, Taiwan, Rest of East Asia
Malaysia and Indonesia	Indonesia, Malaysia
Rest of South East Asia	Philippines, Singapore, Thailand, Viet Nam, Rest of Southeast Asia
Rest of South Asia	Bangladesh, Sri Lanka, Rest of South Asia
Russia	Russian Federation
Other East Europe and Rest of Former Soviet Union	Rest of Former Soviet Union, Turkey, Albania, Croatia, Rest of Europe
Rest of European Countries	Switzerland, Rest of EFTA
Middle East and North Africa	Rest of Middle East, Morocco, Tunisia, Rest of North Africa
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
Oceania	Australia, New Zealand, Rest of Oceania