Effects of the GHG Mitigation Policies on Livestock Sectors

by

Alla Golub*
Benjamin Henderson
Thomas Hertel
Steven Rose
Misak Avetisyan
Brent Sohngen**

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*Corresponding author: 403 W. State St., West Lafayette, IN 47907, email: golub@purdue.edu

**Golub, Hertel and Avetisyan are with the Center for Global Trade Analysis, Purdue University. Henderson is Livestock Policy Officer at the Livestock Information, Sector Analysis and Policy Branch, Food and Agriculture Organization (FAO) of the United Nations. Rose is a senior economist in the Global Climate Change Research Group of the Electric Power Research Institute. Brent Sohngen is Professor at the Department of Environmental and Natural Resource Economics, Ohio State University.

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Abstract

In this paper we have investigated effects of GHG mitigation policies on livestock sectors. We used a global computable general equilibrium GTAP-AEZ-GHG model with explicit unique regional land types, land uses and related GHG emissions. The model is then augmented with cost and GHG response information from partial equilibrium approaches to abatement of land-based greenhouse gas emissions. With this framework we analyze changes in regional livestock output, sector competitiveness and regional food consumption under different climate change mitigation policy regimes. Scenarios we have considered differ by participation/exclusion of agricultural sectors and non-Annex I countries, as well as policy instruments. The imposition of carbon tax in agriculture has adverse affects on food consumption, especially in developing countries. The reductions in food consumption are smaller if the agricultural producer subsidy is introduced to compensate for carbon tax the producers pay. The global forest carbon sequestration subsidy effectively controls emission leakage when carbon tax is imposed only in Annex I regions. The sequestration subsidy bids land away from agriculture in non-Annex 1 regions and prevents expansion of agricultural sectors. Though the sequestration subsidy allows reduction of GHG emissions, if implemented, the policy may adversely affect food security and agricultural development in developing countries.

Key words: climate change, livestock, greenhouse gas emissions, computable general equilibrium model, emission tax.

JEL: C68, Q15, Q54

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1. Introduction

Taking into account the entire livestock commodity chain – from land use and feed production, to livestock farming and waste management, to products processing and transportation – about 18 percent of global anthropogenic greenhouse gas (GHG) emissions can be attributed to the livestock sector (Steinfeld *et al*., 2006). Furthermore, global CH_4 emissions from livestock production alone are expected to increase by around 30% between 2000 and 2020, in response to strong growth in demand for meat and dairy products (USEPA, 2006a). Developing countries, which contribute more than two thirds of current emissions, are expected to account for most of this increase. This suggests that any strategy for reducing global GHG emissions should consider the livestock sector, and should not exclude developing countries. This report focuses attention on this under-investigated aspect of global climate change, namely GHG emissions from livestock production in developing, as well as developed countries.

Large differences in GHG emissions per unit of output (emission intensity) and mitigation potentials between regions, commodities, and production technologies mean that global mitigation policies could generate significant changes in the global distribution of livestock production, trade and consumption (Avetisyan et al., 2010), with attendant impacts on the well-being of farm households as well as consumers of livestock products. While mitigation policies should improve societal welfare, by internalizing some of the costs of climate change, the ensuing distributional consequences will strongly influence the various countries' and livestock sectors' willingness to take part in global mitigation solutions. An understanding of these distributional effects will therefore assist in designing mechanisms to encourage participation and address equity concerns. The goal of this project is to assess such impacts via a global economic analysis undertaken with a modified version of the GTAP computable general equilibrium (CGE) model of global trade, production, consumption and GHG emissions.

Further, mitigation policies in the livestock sector are unlikely to be implemented in isolation from climate policies in other agricultural sectors, as well as non-agricultural sectors such as forestry, energy and transport sectors. Interactions between these sectors under various climate policy regimes could have important consequences for sectors that share scarce resources. For example, competition for land resources between livestock sectors and other land using sectors will be critical in shaping the post-mitigation global geography of livestock production. Taxes on fossil fuel emissions will also affect the costs of production and transportation of livestock inputs and outputs.

The project builds on a global general equilibrium (GE) model (GTAP-AEZ-GHG) documented in Golub *et al*. (2009). This is a unified modeling framework that links the agricultural, forestry, food processing, manufacturing and services sectors through land, labor and capital markets, consumers' budget constraints, as well as through international trade. The model also incorporates different land-types, land uses and related GHG emissions and sequestration, and mitigation options as identified by the US-EPA(2006).

For the present paper, we extend the 3 region model of Golub *et al*. (2009) to 19 regions, and generate estimates of global livestock GHG abatement potential over the medium term (for a representative year with a 20-year time horizon). We focus particular attention on the ensuing reorganization of global livestock production, trade and consumption following the introduction of a carbon price in agriculture, forestry and other sectors. We consider a variety of mitigation policies, which reflect global initiatives being considered under the United Nations Framework Convention on Climate Change (UNFCCC). Given the recent commitment of funds to reduce deforestation and the conspicuous absence of agriculture in the Copenhagen Accord, the indirect impacts on agriculture stemming from the implementation of climate policies in other sectors will be examined. Further, given that Non-Annex I countries are not subject to emission targets under the Kyoto Protocol, we model the impacts of mitigation policies that apply to Annex I countries only, as well as those that apply to both Annex I and Non-Annex I countries. We also extend the modeling framework to accommodate an abatement subsidy, given that payment for mitigation activities in developing countries is a more likely option than carbon taxes for achieving mitigation – and such payments are also likely to be the preferred mechanism for achieving abatement in industrialized country agriculture.

2. Methodology

2.1. Modeling approach

We build on the GTAP-AEZ-GHG model described in Golub et al. (2009). Those authors start from the basic GTAP-E CGE model (developed by Burniaux and Truong (2002), as modified by McDougall and Golub (2007)) and as validated by Beckman et al. (2010), 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.

The explicit treatment of GHG mitigation options is based on a series of partial equilibrium studies of specific sectors' abatement options. 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). The agricultural production structure in this model allows for more refined mitigation responses than currently available in the CGE literature. For example, in the model abatement can occur by reducing overall fertilizer use, as well as by changing the way in which fertilizer is applied.

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 (GTM) of Sohngen and Mendelsohn (2007)[1]. Then, the CGE model's regional responses are calibrated to the forest carbon 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) of forest carbon sequestration (GTM's extensive and intensive forest carbon sequestration margins are presented

[1] See Table A1 in Appendix for mapping between 19 GTAP and 18 GTM regions.

in the Tables A5 and A6 in Appendix).

The 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 version 6, since land use data are only now being updated to the version 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. 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^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 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. The CET parameter among three land cover types is set to -0.5. The absolute value of this parameter represents the *upper bound* (the case of an infinitesimal share for that use) on the elasticity of supply to a given use of land in response to a change in its rental rate. The more dominant a given use in total land revenue, the smaller its own-price elasticity of acreage supply. The lower bound on this supply elasticity is zero (whereby all land is already devoted to that activity). Therefore, the actual supply elasticity is dependent on the relative importance (measured by land rents share) of a given land use in the overall market for land and is therefore endogenous. 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).

2.3. GHG emissions

Data on anthropogenic fossil fuel combustion CO_2 and all non-CO_2 GHG emissions for the 19 regions of the model 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. Figure 1a shows global CO2 and non-CO_2 GHG emissions by sector. The electricity sector is the largest single contributor (29%). Within agriculture, crops and meat ruminant sectors emit 7% each. Figure 1b shows sectoral breakdown of global non-CO_2 emissions. More than half of all non-CO_2 emissions are related to agricultural activity. A detailed breakdown of non-CO_2 emissions from the agricultural sectors by region is provided in Figure 1c. Livestock production makes a significant contribution to agricultural emissions in all regions (63% of the agricultural non-CO_2 emissions in total), and China[2] and Sub Saharan Africa are the largest contributors with 20% and 13% of global non-CO_2 emissions from agriculture, respectively. These two regions are also the largest contributors of global non-CO_2 emissions from the livestock sectors, and the ruminant sector in Sub Saharan Africa is single largest agricultural source of non-CO_2 emissions globally. In China and Rest of South East Asia (R_SE_Asia) paddy rice cultivation is an important source of methane emissions.

To model and evaluate the general equilibrium input allocation responses to mitigation policies, we tied emissions to explicit input or output flows. Three types of agricultural production mitigation responses are captured: those associated with intermediate input use (e.g. fertilizer), primary factors (e.g., land in paddy rice production), and those associated with sector outputs (e.g., emissions from biomass burning, and stationary and mobile combustion). Emissions associated with enteric fermentation, manure management in ruminants and non-ruminants are tied to livestock output in order to better facilitate calibration to EPA's abatement cost estimates (see below for a discussion of this point).

Input related emissions are not always restricted to be released in fixed proportion to the amount of input used. We introduce an additional layer of substitution possibilities in the production structure to reflect changes in production practices which reduce the intensity of input-related emissions. 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, and similarly for fertilizer use in coarse grains production, whereby producers can increase the frequency of application (while keeping total use fixed) to mitigate nitrous oxide emissions.

Any given emissions entry in Figure 1c may be large because the economic activity in the sector is large (e.g., a large dairy sector), and/or there is a high level of emissions per dollar of activity. The latter is termed the "emissions intensity" of a given activity, and this intensity is

[2] China region in the model is denoted by CHIHKG and includes China and Hong Kong.

critical in determining the impact of a carbon-equivalent emissions tax on a given sector. As shown in figure 2a, 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) of the ruminant sector are significantly higher than the emission intensities of non-ruminant production in all regions and of the dairy production in all regions except Sub Saharan Africa. There is great variation in emissions intensities within a given sector, across countries. Ruminant meat production intensities vary by more than an order of magnitude, with the lowest intensities in Japan, USA, East Asia and Oth_Europe. Rest of Southeast Asia (R_SE_Asia), Brazil, Malaysia and Indonesia, Sub Saharan Africa (S_S_Afr), India and Rest of South Asia (R_S_Asia), have highest ruminant sector emission intensities.

Avetisyan et al. (2010) investigate this phenomenon in detail. They decompose emissions per dollar of output into emissions per animal and value of output per animal and show that most of the variation in emissions intensities may be attributed to differences in the value of annual output per animal (Figure 2b). Countries with highly productive livestock industries, while generally having higher physical emissions intensities (emissions/animal), have much lower economic emissions intensities (emissions/dollar of output).

Further, Avetisyan et al. (2010) decompose the value of output per animal into differences in physical yield (output per head) and price per unit of output and compute coefficients of variation of each factor to the variation in the value of output across regions. They find that in case of cow milk most of the variation in the value of output per animal is due to variation in livestock yield per animal, while for cattle meat, prices per unit of output are responsible for the dominating portion of variation. If price reflects quality of a product, then their finding reflects the fact that milk is more homogenous product in terms of quality, and price do not vary that much across countries. Meat, on the other hand, may have very different quality attributes reflected in its prices.

In addition to the emissions intensities, the economic impacts of climate policy on each sector also depend on their marginal costs of abating emissions. As discussed, the model used in this study relies on marginal costs associated with abatement strategies for key non-CO_2 emissions including livestock enteric and manure emissions, as well as methane emissions from paddy rice, and nitrous oxide emissions, primarily from grains (wheat, maize, soybean) — estimated by the U.S. Environmental Protection Agency (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 derived from estimated US-EPA(2006) abatement cost schedules for 2010 and customized for our model's sector and regional aggregation.[3] This figure demonstrates that, while the emissions contribution of the non-ruminant sector is small relative to other livestock sectors (Figure 1c), the capacity for abatement, in percentage terms, is higher for this sector than for dairy farms and ruminant meat production in most regions (Figure 3). By comparison, the ruminant sector has much less *relative* abatement potential, in percentage terms, in most regions, but larger *absolute* potential due to the higher level of base emissions from this sector. Combining the emissions intensities and abatement possibilities summarized in Figures

[3] We are thankful to Steven Rose for constructing the abatement cost curves for the sector and region aggregation used in this work.

2a and 3, we would expect to see the outputs from the ruminant sectors of Rest of South East Asia, Brazil and Sub Saharan Africa most negatively affected (in percentage terms) by the imposition of a global emissions tax, and the non-ruminant sectors of regions such as the Other Europe, EU and India least affected.

The CGE model used in this study is calibrated to the US-EPA (2006) marginal abatement cost (MAC) curves corresponding to each individual model region and sector. 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 US-EPA abatement possibility estimates at 27\$/tCO_2eq. More specifically, the calibration process for input-related agricultural emissions begins from introduction of the elasticities of substitution in production, both amongst intermediate inputs and value-added and between elements of value-added. The elasticities are calibrated using econometric estimates reported in a survey of the econometric literature by the OECD (2001) and the approach suggested by Keeney and Hertel (2005). We then fix output levels in the sectors, as well as input prices to match the partial equilibrium assumptions of the engineering cost estimates, and proceed to vary the carbon equivalent price to map out a partial equilibrium abatement response for the relevant sector in each region.

In the crop sectors we apply parameters reported in Golub et al. (2009).[4] For livestock sectors we use new information on abatement opportunities as summarized in Figure 3. In the case of non-CO_2 emissions from the livestock sectors, the econometrically estimated production function gives an overly large abatement response in some regions. Rather than altering the entire production function to reproduce this one fact – a measure which would have far-reaching implications for many other issues – we choose instead to simply link emissions to output. At this point we can simply alter the substitution elasticity between emissions and the input aggregate in order to replicate the US-EPA abatement estimate at 27\$/tCO_2eq, without destroying the integrity of the underlying production function for the sector.

3. Results

Having calibrated the GTAP-AEZ-GHG model to a suite of partial equilibrium GHG abatement cost schedules, we now deploy our CGE model to investigate the market interactions between these different abatement opportunities. This is the focal point of our paper. We summarize the

[4] 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 the future, 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 costs curves when they become available. In Golub et al. (2009) the emissions from crop response was compared to that of the US-EPA prediction at 13.5\$/tCO_2eq. In the process of calibration in Golub et al. (2009), for the N_2O emissions from fertilizer use in the crops sectors, the two abatement cost estimates were in good agreement, so no further adjustment was required. However, in the case of methane emissions from paddy rice production, the level of abatement predicted by the CGE model is too low – the econometrically estimated production function parameters suggest less scope for abatement than the US-EPA estimates. In this case, the possibility of changes in input emissions intensity was added via introduced substitution between land and methane emissions in paddy rice production.

aggregate implications of these interactions with the general equilibrium GHG abatement supply schedules reported in figures 4a and 4b. The general equilibrium supply schedules are derived by varying the per unit carbon tax incrementally up to \$35/tCO_2eq in all sectors and regions of the global economy. Figure 4a portrays the global abatement supply, including all GHG emissions and sequestration –non-CO_2 emissions from agriculture, forest carbon sequestration, energy 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 GHG emissions can be reduced by 12 GtCO_2eq with almost half of the reduction provided by sequestration in forests (5 GtCO_2eq) and 1.2 GtCO_2eq abatement provided by agricultural sectors. In Figure 4a, carbon sequestered in forests is decomposed into intensive and extensive margins. The extensive margin can be seen as the difference between the forestry total abatement curve in Figure 4a and the intensification curve. Figure 4b offers a closer look at the abatement supply schedule within agriculture. The *direct emission reduction* from livestock is 0.8 GtCO_2eq, or about 62% of abatement in agriculture and 6% of global emissions reduction (Figure 4a). The large magnitude of the potential forest and agriculture abatement possibilities highlights the importance of devoting greater attention to these sources of future mitigation. To date, most studies have focused heavily on the industrial, residential, commercial and transport abatement of fossil fuel-based emissions. However, in our analysis, these account for only half of the total economic abatement potential in the near term, at modest carbon prices. Mitigation in the land-based activities related to forestry and agriculture account for the other half of abatement possibilities.

Having this abatement overview firmly in mind, we now turn to the analysis of five alternative mitigation policy scenarios. Table 2a describes each scenario and Table 2b shows the results. In all of these scenarios, we put a price on global forest carbon emissions and sequestration, taxing emissions and providing payments for sequestration. The scenarios are differentiated according to participation of the agriculture sectors as well as the participation of non-Annex I countries. In scenario 1, a carbon price policy of 27\$/tCO_2eq is applied to all sectors. In this setting, the world is able to take advantage of all mitigation possibilities. Indeed, the greater the number of sectors and regions that the abatement policies cover, the lower the average cost of CO_2eq tonnes abated will be for a given mitigation quantity (e.g., de la Chesnaye and Weyant, 2006).[5]

However, the global application of an emission tax is unlikely to be politically acceptable, particularly among developing countries, where near term food security and development concerns justifiably take priority over the economically efficient management of long run environmental issues. Consequently, the mitigation responsibilities of countries under the United Nations Framework Convention on Climate Change (UNFCCC) vary according to their economic development status: Annex I countries (industrialized countries and countries in transition) are subjected to mitigation targets which are to be met at their own cost; whereas non-Annex I countries (developing countries) are not subject to mitigation targets, but could potentially receive assistance from industrialized countries to implement abatement measures.

[5] Put another way, for a given abatement quantity, the total cost of a policy scenario that targets all regions and sectors will be lower than any policy that targets any subset of these regions and sectors.

Scenarios 2 - 5 fall within the realm of the policy approaches considered under the UNFCCC, as they only levy emission taxes in agriculture of Annex I regions or provide abatement subsidy to agriculture in non-Annex I. In scenario 2, a forest carbon sequestration subsidy is provided globally, but the carbon tax is only applied to Annex I countries, and agriculture is included in this policy. Scenario 3, where both the forest carbon sequestration subsidy and carbon tax are implemented in Annex I only, is included to examine the importance of forest carbon sequestration subsidy to control leakage in non-Annex 1 countries. In scenario 4, the agriculture sectors in Annex I countries are left out of the mitigation possibilities, so that the carbon tax applies only to the non-agricultural sectors (and to fossil fuels emissions in agriculture) in Annex I. In scenario 5 the carbon tax is applied to all sectors and regions as in scenario 1, however, the cost of the tax is returned to agricultural producers of non-Annex I regions in the form of an output subsidy in order to offset the price-increasing aspect of the mitigation effort.

Implementation of scenario 5 deserves some additional discussion. Without first applying the carbon tax, it is difficult to specify the subsidy in a way that equates its marginal value with marginal cost of abatement. To overcome this problem, we explicitly impose a carbon tax on input and output related emissions in agriculture in non-Annex I countries, but require that these agricultural producers are reimbursed for the amount of tax they pay.[6] This mixed instrument approach is designed to offset the costs of the carbon tax for farmers in non-Annex I regions, without directly reducing their marginal abatement incentives. Annex II countries foot the bill for abatement by non-Annex I agricultural producers (see Table A1 in Appendix for definitions of Annex I, Annex II and non-Annex I regions).[7] The relative contribution of each region within the Annex II group is proportional to its regional income. Payments made by Annex II regions and transfers received by non-Annex I regions are reported in Table A2 of the Appendix.

The results reported in Table 2b provide some important insights. Firstly, note the critical role played by forest carbon sequestration. In scenario 1, this accounts for 40% of global abatement at 27 \$/tCO_2eq. And the relative contribution of forest carbon sequestration rises as other abatement options are removed from the policy coverage. When non-Annex I countries are removed from the carbon tax (scenario 2), global forest sequestration's share of the total rises to 60%. Omitting agriculture from the Annex I mitigation effort (scenario 4) further reduces global abatement and forest sequestration's share of the total rises to 64% -- nearly two-thirds the world total. This includes significant gains in forest carbon from all types of activities—avoided deforestation, afforestation, and forest management.

A second insight from Table 2b relates to the interplay between agricultural abatement and forest carbon sequestration. When agriculture is exempted from carbon taxation in non-Annex I countries, there is a dramatic reduction in global abatement from agriculture, which drops from 1,204 to just 381 MMtCO2eq – a decline of more than two-thirds. More interestingly,

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[6] In the scenario 5, when carbon tax is imposed, the sum of carbon tax paid by the sector and the net output subsidy revenue does not change relative to market value of output.

[7] Given our regional aggregation, it is quite difficult to define regions that are Annex I, but not Annex II. We can't do it perfectly, because 11 out the EU27 are Annex I, but not Annex II (Bulgaria, Cyprus, Czech Republic, Hungary, Poland, Romania, Slovakia, Slovenia, Estonia, Latvia, Lithuania). We use imperfect Annex II definition that includes all Annex I except Russia.

the cost of forest carbon sequestration rises so that the 27$/tCO2eq forest carbon sequestration subsidy buys less abatement due to higher returns to land employed in agriculture. As a result, forests' global contribution to emissions reduction falls from 4,902 to 4,790 MtCO2eq.

The forest carbon sequestration subsidy contributes to the moderation of emissions leakage in agriculture, when carbon sequestration is given globally but tax is imposed only in Annex 1 and there is no tax in any of the non-Annex 1 sectors (scenario 2). To confirm this point, we run scenario 3 where non-Annex 1 regions are exempt from any climate mitigation policy, and the forest carbon sequestration subsidy and carbon tax in all sectors are introduced in Annex 1 only. Without the sequestration subsidy and carbon tax in non-Annex 1, there are important emission leakages. Globally, there is 7% ((3911-3633)/3911*100) leakage in non-Annex 1 when this region is omitted from the mitigation policy. The leakage effect is observed in all sectors presented in Table 2b (leakage rates are 25% in agriculture, 35% in livestock within agriculture; and 4% in other sectors). The results indicate deforestation in non-Annex 1 as 722 - 632 = 90 $MtCO_2eq$ emitted into atmosphere due to an expansion in non-Annex 1 agriculture sectors.

When agriculture is exempted from abatement in Annex I countries (contrast scenarios 4 and 2), Annex I emissions reduction in agriculture is reduced by 272 MMtCO2eq (1 – 273), while emissions in non-Annex I countries fall more in scenario 4 vs. scenario 2 as agricultural activities shift back towards Annex I regions.[8] The global rise in agriculture emissions in scenario 4 compared to scenario 2 (381 – 169 = 212 $MtCO_2eq$) is less than the Annex I change. The reduced pressure on land use in non-Annex I countries means that the same forest carbon sequestration subsidies in the tropics have a greater impact, and total sequestration in non-Annex I countries rises by 25 MtCO2eq ((4,810–695) – (4,790 –699)).

As with scenario 1, a carbon policy is applied to all sectors and regions in scenario 5, but in contrast to scenario 1, there is an output subsidy to agricultural producers in non-Annex I regions which offsets the cost of the mitigation actions in this sector. This subsidy means that overall agricultural output in developing countries falls by less – or may increase in some cases – and therefore agriculture's contribution to global mitigation is reduced from 1,204 to 801. The more robust agriculture sector also competes more effectively with forest carbon sequestration, so that measure also yields less mitigation in forests at a given carbon price.[9] The contribution of Annex I regions relative to non-Annex I regions is larger in scenario 5 than in scenario 1, and global abatement is reduced from 12 $GtCO_2eq$ to 11.5 $GtCO_2eq$.

[8] Non-Annex 1 emission reduction in agriculture in scenario 4 is 169-1 = 168 MMtCO2eq and in scenario 2 is 381-273 = 108.

[9] The carbon tax paid by agriculture producers and the subsidy they receive are determined by the remaining after tax emissions multiplied by the carbon price. It may be the case that producers would have some incentive to keep emissions higher to increase the subsidy payment despite the carbon tax imposed. However, it is not the case. In this scenario emissions in all non-Annex I regions and all sectors are reduced, except oilseeds in Mala_Indo and R_SE_Asia and dairy in S_S_Afr where slight increases in emissions are observed.

3.1 Impact of forest extensification on agricultural emissions

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. We considered additional simulations where we provided global forest carbon sequestration subsidy and imposed a global carbon tax in all sectors except for agriculture (see Table A3 in the Appendix). We found that of the two forest extensification effects on emissions – forests bidding land away from agriculture production and intensification of the remaining agricultural land – former effect dominates at the global scale. However, there is considerable variation in regional responses. When agriculture is exempt from carbon tax and carbon sequestration subsidy is provided in all regions, the effect of intensification of agriculture dominates and GHG emissions from agriculture increase in USA, EU27, Canada and Other Europe – regions with very intensive agriculture.

3.2. Changes in output, emissions and emission intensities

Next, we take a detailed look at the changes in emissions and output by agricultural sector and region in selected scenarios, paying particular attention to the interaction between competing land uses. Tables 3a and 3b summarize the changes in output value and emissions for agricultural sectors according to their location in either Annex I or non-Annex I regions for scenarios 1 and 2. In scenario 1 (Table 3a), which assumes mitigation policies are applied in all sectors, emission intensities are reduced as emissions fall by more than output in all sectors and regions. This is the purpose of the carbon tax. However, all agricultural sectors in non-Annex I regions suffer larger falls in output compared with Annex I regions. This is mainly due to the fact that they have higher emissions intensities (recall Figure 2a).[10] In both dairy and non ruminant sectors output falls by more and emissions by less (in percentage terms) in non-Annex I compared to Annex I regions. In the ruminant sector there are larger emission reductions in non-Annex I regions, however, ruminant output in these regions falls more heavily (in percentage terms) than output of any other sector in both Annex I and non-Annex I regions. Focusing on livestock at the global level, there are larger percentage declines in ruminant sector output compared with non-ruminant output, while percentage changes in emissions between the sectors are similar. This reflects the combination of higher emission intensities in ruminants, but greater scope for abatement in the non-ruminant sector.

Table 3b summarizes these results for scenario 2, which assumes a global sequestration subsidy for forestry and an emissions tax on all sectors in Annex I only. This time the improvement in environmental efficiencies are largely limited to Annex I regions. In this scenario the agricultural sectors in non-Annex I regions experience very little change in environmental efficiency, as they are not subject to an emissions tax. By comparing the results in

[10] In dairy sectors of non-Annex I, in additional to higher emission intensities, the capacity for abatement in percentage terms is smaller than the capacity for abatement in Annex I (see Figure 3). This also contributes to larger falls in dairy output in non-Annex I under the carbon tax.

tables 3a and 3b, one can see both the foregone improvement in emission intensities in non-Annex I regions in scenario 2, as well as the significant difference in output reductions in non-Annex 1 regions between the two scenarios.

Changes in emissions and output in the abatement subsidy experiment (scenario 5) are presented in Table 3c. Now non-Annex 1 agriculture producers are supported by the abatement subsidy and agriculture sector output does not fall as much as in scenario 1 and the changes in output are close to those observed in the case when non-Annex 1 agriculture is completely exempt from the carbon tax (scenario 2, Table 3b). Moreover, non-Annex 1 ruminant sector output expands. Looking at the emission results, we find reduction in emissions in all agricultural sectors in non-Annex 1. To summarize, the mixed policy instrument applied in scenario 5 results in reduced emission intensities in both Annex I and non-Annex I regions with relatively minor overall reduction in output in non-Annex I agriculture sectors. This point is illustrated in Figures 5a and 5b which compare composition of percent changes in emissions in ruminant meats sector in each region in scenarios 1 and 5. With the global carbon tax (scenario 1, Figure 5a) most of the emission reduction in non-Annex 1 regions is achieved via reduction in output. When the tax paid by agriculture producers is returned in the form of an output subsidy (scenario 5, Figure 5b), less emissions reduction is achieved. However, within these emissions reductions, the changes in emissions intensities play much larger role.

Figures 6a-6c provide a more detailed regional breakdown of changes in output at constant (2001) world prices for the livestock sectors. In scenario 1 (Figure 6a), when the global tax is applied in all sectors, most of the regions experience large reductions in livestock sector output. Dairy output shrinks in all regions (except very small increases in Mala_Indo and Other_Europe regions) and most significantly in Oth_CEE_CIS and India. The ruminant meats sector experiences the largest declines in output value, particularly in Sub Saharan Africa, Brazil and S_O_Amer, whereas ruminant meat production expands in the EU27 and Japan. Globally, the fall in the value of non ruminant production is smaller than in ruminant meats sector. However, due to its very large non-ruminant meat sector, China experiences a steep decline in output value. Non-ruminant output rises in a few Annex I regions. In scenario 2 (Figure 6b), where non-Annex 1 regions are exempt from carbon tax, but offered forest carbon sequestration subsidy, the output consequences improve markedly for most non-Annex I countries, whereas livestock sectors in the USA, EU and Oceania suffer heavy losses in output value. Figure 6c portrays changes in regional livestock sectors output in scenario 5 where non-Annex I producers receive abatement subsidy. The changes are similar to those observed in Figure 6b for scenario 2. In terms of livestock output, the main beneficiaries of the abatement subsidy are Rest of South Asia (R_S_Asia) and Sub Saharan Africa (S_S_Africa) where output is expanding relative to scenario 2. In USA and EU27, livestock output falls more when the abatement subsidy is provided to non-Annex I. Finally, Figure 6d shows how each region contributes to the global change in livestock production in each scenario.

3.3 Changes in global competitiveness

A natural way of evaluating changes in global competitiveness in the wake of these alternative climate policy scenarios is to examine the changes in net trade flows. Accordingly, figures 7a-c report changes in trade balances for agriculture and food sectors by region for scenarios 1, 2 and 5, respectively. The carbon tax in scenario 1 sharply changes the pattern of global competitiveness, with the US and EU benefiting from their low emission intensities in livestock production (Figure 2a). They expand net exports of processed meat (livestock is traded mostly in processed form), while high emission intensity regions such as Brazil and Sub Saharan Africa show a deterioration in their trade balance for this and other food categories. Though similar in direction, the changes in sector trade balances are much less dramatic in scenario 2, when the carbon tax is imposed in Annex I regions only. Figure 7b demonstrates that the forest carbon sequestration subsidy bids land away from agriculture in non-Annex 1 and prevents expansion of livestock exports from these countries. As an extreme case, changes in sector trade balances of South and Other Americas region (S_O_Amer) are almost identical between scenarios 1 and 2. Changes in trade balances in scenario 5 where the global tax is imposed in all sectors, but agriculture producers in non-Annex I receive the abatement subsidy, are very similar to changes in trade balances observed in scenario 2 where non-Annex I regions are exempt from the carbon tax.

3.4 Impacts on food consumption

We explore the food security consequences of GHG mitigation policies under different policy scenarios. Figures 8a-c report changes in annual consumption per capita measured in 2001 prices and population for scenarios 1, 2 and 5. For presentation purposes, in the tables and figures below the 16 food commodities of the model are aggregated into 7 groups ("dairy_farms", "ruminants", and "nonruminants" represent single food commodities). Figure 8a shows that in scenario 1 the largest, about 30 US$, reduction in per capita annual consumption is observed in Other South America region (S_O_Amer). Figure 8b demonstrates that even when agricultural sectors are not directly targeted in non-Annex I regions, these regions experience declines in food consumption because forest carbon sequestration subsidy bids land away from agriculture. When a subsidy is given to agricultural producers in non-Annex 1 regions (Figure 8c), consumption improvements are observed in many developing counties. However, there are large declines in consumption of Annex 1 regions. Table 4 contrasts food consumption outcomes in tax and subsidy experiments (scenarios 1 and 5, respectively). In comparison to scenario 1, the subsidy improves the consumption outcome in all non-Annex 1 regions, especially in Sub Saharan Africa.

It is also useful to know how structure of the food consumption bundle changes under the carbon tax and subsidy. Figures 9a and 9b for scenarios 1 and 5, respectively, show changes in the expenditure shares of 5 food categories, representing aggregation of 16 food commodities in the model.[11] In these figures livestock products represent aggregation of raw and processed products, e.g. "dairy products" in figures 9a and 9b combine raw and processed dairy. Similar definitions apply to ruminant products and non-ruminant products in figures 9a and 9b. Under the carbon tax (scenario 1), in Brazil the expenditure share of ruminant products falls by 1.5% while share of other food is expanding, with quantity of aggregated across different categories food consumption falling by 6% (Table 5). In Sub Saharan Africa large changes are observed in shares of ruminant and non-ruminant products that fall by 1.4% and 0.3% respectively. In the

[11] The problem with expenditure shares is that they hide the price and quantity changes. With rising prices, quantity can fall, but the budget share still rises. For this we have computed the value of food consumption at initial period prices and focused on relative changes in that in Figures 8a-c discussed above.

abatement subsidy scenario (Figure 9b), changes in the relative contribution of various foods are negligible, especially in the regions receiving subsidy. Figures 9a and 9b illustrate the overall tendency to move away from livestock based products toward crops and other foods. These changes in the composition of food consumption are conditional on the abatement responses our CGE model is calibrated to, as well as the structure of the demand system. As it is mentioned earlier, for the crops sectors in our 19 regions we borrowed abatement parameters from 3 region model. The food bundle response will need to be reevaluated as new information on abatement options in crop sectors for the 19 regions become available.

The results presented above illustrate that reductions in food consumption are an important response to GHG mitigation policies in both Annex 1 and non-Annex 1 regions. In developed countries, however, lower food consumption may not translate into nutritional deficits, and even may have some health benefits if it is reduction in red meat consumption. In contrast, the reductions in food consumption in many developing countries will have adverse effects on nutrition. In the analysis of the emissions triggered by US maize ethanol expansion, Hertel et al. (2010) look at the "nutritional cost" of the market-mediated response to maize ethanol. We take a similar approach, and in order to isolate the size of the nutritional costs of the global carbon tax, we ran scenario 1 (global carbon tax and sequestration subsidy) but holding food consumption fixed with a series of country-by-commodity subsidies. Comparison of scenario 1 without and with food consumption fixed is reported in Appendix in Table A4. When food consumption is not allowed to adjust, the global GHG mitigation potential is reduced by 370 MtCO_2eq (or 3% relative to 12 GtCO_2eq achieved in scenario 1), where about one third of the decline comes from reduced carbon sequestration in non-Annex I forests and two thirds from less abatement in agriculture. This fixed food consumption scenario and the scenario with an offsetting output subsidy in non-Annex I countries' agricultural sectors both help to reduce adverse impact on food consumption. It should be noted, however, that in the fixed food consumption scenario food production shifts to low emissions intensities regions and non-Annex I production declines, though less than in scenario 1. In contrast, subsidy supports producers in non-Annex I countries providing much less reduction and in some cases expansion of output at now reduced emission intensities.

3.5 Tax versus mixed policy instrument

Table 5 compares the results of the output subsidy experiment (scenario 5) and outcomes of the global tax (scenario 1). Compared to the global tax-only scenario, the output subsidy is only 53% as effective in controlling livestock emissions. This is not surprising, because the introduction of the subsidies improves the profitability of livestock producers in non-Annex I regions, resulting in a lower contraction of output (and in some cases an increase in output), compared with the tax-only scenario. The non-dairy ruminant sectors in non-Annex I regions, experience the largest improvements in output following the introduction of the abatement subsidies. Perhaps most importantly, reductions in food consumption are less severe in all non-Annex I regions, following the introduction of the subsidies, particularly in Brazil and Sub Saharan Africa. Much of the improvement in production experienced by non-Annex I countries is matched by a deterioration in production among the livestock sectors in Annex I countries, following the introduction of abatement subsidies for non-Annex I countries. This is particularly true in the non-dairy ruminant sectors of Canada and Oceania.

3.6 Changes in land use

Imposition of carbon taxes in agriculture and forestry has a tremendous impact on land rents and land use. For illustrative purposes we focus here on scenario 5. Table 6 lists percent changes in land rents by region and by land use category (cropland, pasture and forests). Extreme increases in land rents in forestry are observed in South America and Brazil – regions with large forest carbon sequestration potential. These changes in land rents result in land use changes, as reported in Figure 10 for agro-ecological zone 10[12]. In this particular AEZ, we see the primary shift in land use patterns being one of expanding forest cover, primarily at the expense of crop land cover, which declines in most regions. In AEZs with shorter growing periods, the forest cover is drawn more heavily from pasture lands.

The large changes in land rents, accompanied by relatively modest changes in land supplies is indicative of relatively small price elasticities of land supply to forestry. Our land supply elasticities are drawn from recent cross-section econometric studies (Ahmed et al. 2008); they are significantly larger than those used in many global models (e.g., IFPRI's IMPACT model and IIASA's BLS model). However, one could argue that, in the very long run, an important consequence of ambitious carbon sequestration programs would be to increase use of lands which are currently unmanaged. If this were to occur, we would expect somewhat more modest changes in land rents and larger changes in forest land cover.

3.7 Changes in welfare, utility and terms of trade

Changes in regional welfare, per capita utility from aggregated household expenditures and terms of trade for all five scenarios are included in the Appendix (Figures A1-A3). There are two main factors driving these welfare changes: changes in efficiency associated with the taxes, and changes in the terms of trade associated with changing world prices. Since we have not explicitly incorporated the negative externality associated with the GHG emissions, the efficiency component is misleading.

3.8 Emissions from livestock supply chain

In this part of the report we estimate emissions from livestock while taking into account the entire livestock commodity chain, including emissions from feed production, livestock farming, waste management, products processing and transportation.[13] This model framework is well suited to this task, because it links detailed non-CO_2 and CO_2 GHG emissions to economic sectors and emissions drivers in all regions of the World.

We estimate GHG emissions from three livestock supply chains (meat ruminants, dairy ruminants and non ruminants) separately and then add them up to assess emissions from global livestock supply chain. For each livestock sector we break analysis into two parts. The first part

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[12] This agro-ecological zone is chosen as an example because it is present in almost all 19 regions of the model.
[13] We have not included emissions associated with domestic wholesale-retail trade and transport required to get the product to consumers.

estimates emissions from livestock products as they leave the "farm gate", while the second part estimates emissions due to processing. The first part includes emissions from livestock farming, waste management, emissions from producing feed for animals, emissions from growing crops to produce the feed and so on. A convenient way to estimate these emissions is to run our global model as a quantity-based, global input-output model in which all prices are fixed at their baseline level and output is simply doubled. With fixed prices no substitution will occur, and to double the production of livestock we must double input use in the sector. This will trigger increases in the production of those inputs, and associated emissions. Of course this rise will not be by the full 100% unless the expanding sector is the only user of these inputs. Furthermore, the input supply sectors must also expand their purchases, thereby leading to further rounds of emissions, and so on. By solving the entire model at once we are able to capture all of these direct and indirect changes in emissions. The sum of all changes in the emissions of this simulation represents global emissions from livestock production up to the farm gate. To take into account emissions from processing, we use a similar, fixed price closure and run a separate experiment for each of the three processed livestock sectors (processed ruminants, processed dairy and processed non ruminants), where we double production of the processed livestock sector output. The obtained changes in global emissions are then reduced to avoid double counting of direct emissions from livestock farming and all other emissions already counted in the first set of experiments.

Results of the supply chain analysis for each type of livestock are presented in Table 7. Let us focus on meat ruminant supply chain emissions, keeping in mind that similar discussion applies to non ruminant and dairy ruminant supply chains. In our framework, the meat ruminant sector (before processing into processed ruminants) is responsible for 2,532 $MtCO_2eq$. 94% of these emissions are direct emissions from livestock farming (enteric fermentation and manure management). Emissions from growing crops for feed, from production of other feed, and from energy inputs and other inputs required to produce meat ruminant output are responsible for the remaining 6%. Converting farm meat ruminant output into processed ruminant products generates additional 143 $MtCO_2eq$. Total emissions from meat ruminant supply chain are 2,675 $MtCO_2eq$. Adding 1,213 from non ruminants supply chain and 852 from dairy supply chain results in total 4,741 $MtCO_2eq$ emissions from the global livestock supply chain, which represent 15% of global anthropogenic GHG emissions reported in Table 1 (note, Table 1 does not include terrestrial carbon fluxes). This figure is relatively close to 18% of anthropogenic emissions attributed to the livestock sector in Steinfeld *et al*. (2006). There are few categories of emissions that were omitted from our calculation, that may explain differences between our and Steinfeld *et al*. result. We have not taken into account emissions from land use change. These are the primary omission, and when they are excluded from the FAO study, that estimate is reduced to about 15% of global emissions as well. We have also omitted emissions from wholesale and retail trade (though these are small in the GTAP emissions data and the entire wholesale/retail trade sector represents only about 1% of the global emissions), emissions from further processing of processed ruminants, processed non ruminants and processed dairy (these products enter as inputs into production of other foods), emissions from uses of livestock agricultural sectors output by sectors other than three processing sectors we have considered, and emissions from processing meat products by households.

4. Conclusion

In this study we have investigated effects of GHG mitigation policies on livestock sectors. We use a global computable general equilibrium GTAP-AEZ-GHG model with explicit unique regional land types, land uses and related GHG emissions. The model is augmented with cost and GHG response information from two partial equilibrium approaches to abatement of land-based greenhouse gas emissions. For agricultural mitigation of GHGs, we calibrate our model to mitigation possibilities derived from detailed engineering and agronomic studies developed by the U.S. Environmental Protection Agency (USEPA, 2006). In the case of forest carbon sequestration, we draw on estimates of optimal sequestration responses to global forest carbon subsidies, derived from the modified Global Timber Model of Sohngen and Mendelsohn (2007), following the approach outlined in Golub et al. (2009).

With this framework we analyze changes in the regional livestock output, competitiveness, and food consumption under different climate change mitigation policy regimes. Scenarios we have considered differ by participation/exclusion of agricultural sectors and non-Annex I countries, as well as policy instrument – carbon tax or mixed instrument. Analysis of the initial data reveals that emission intensities, measured in emissions per dollar of output, differ across livestock sectors and regions. These emission intensities determine the economic cost of a carbon tax to each regional sector. High intensity regions suffer a greater cost increase and therefore lose competitiveness relative to the low intensity regions. With the carbon subsidy, the link between emission intensity and reduction in output is less apparent in the non-Annex 1 regions which are compensated for the added cost incurred as a result of the carbon tax.

In the absence of such a subsidy, the imposition of a carbon tax in agriculture anywhere in the world raises the cost of food and therefore has adverse affects on food consumption, especially in developing countries. The reductions in food consumption are smaller if the agricultural producer subsidy is introduced to compensate for carbon tax the producers pay. Finally, our results highlight importance of forest carbon sequestration. The global forest carbon sequestration subsidy effectively controls emission leakage when carbon tax is imposed only in Annex I regions. The sequestration subsidy bids land away from agriculture in non-Annex 1 regions and prevents expansion of livestock and other agricultural sectors. Though the forest sequestration subsidy allows reduction of GHG emissions, if implemented, the policy may adversely affect food security and agricultural development in developing countries.

Our findings have significant implications for the structuring of policies to achieve cost effective mitigation. In the non-Annex I countries, where agricultural production is land and emissions intensive and avoided deforestation and afforestation are low cost abatement strategies, agricultural sectors are more heavily penalized by the introduction of a forest carbon sequestration subsidy than in Annex I countries. Adding a pecuniary penalty on agricultural emissions could result in production and food consumption decreases precisely in those regions which are most vulnerable. In such cases mixed instrument strategy which compensates farmers in non-Annex I regions for the higher costs associated with abatement is essential.

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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

Note: These emissions do not include land use change related emissions.

Table 2a Description of the scenarios

Scenario	Carbon tax in non-agriculture		Carbon tax in agriculture		Carbon sequestration subsidy		Agricultural abatement subsidy
	Annex 1	Non-Annex 1	Annex 1	Non-Annex 1	Annex 1	Non-Annex 1	Non-Annex 1
1	√	√	√	√	√	√	-
2	√	-	√	-	√	√	-
3	√	-	√	-	√	-	-
4	√	-	-	-	√	√	-
5	√	√	√	√	√	√	√

Table 2b Global and Annex I emissions *reduction* under different policy assumptions at 27 $/t$CO_2eq, MtCO_2$eq

Scenario	All emissions reduction		Forest carbon sequestration		Agricultural sectors		Livestock sectors (within agriculture)		Other sectors and private consumption	
	Global	Annex I	Global	Annex I	Global	Annex I	Global	Annex I	Global	Annex I
1. Global forest carbon sequestration subsidy, carbon tax in all sectors, all regions	12,105	3,720	4,902	686	1,204	230	745	119	5,999	2,804
2. Global forest carbon sequestration subsidy, Annex I only tax in all sectors	7,970	3,879	4,790	699	381	273	229	155	2,798	2,907
3. Annex 1 forest carbon sequestration subsidy, Annex I only tax in all sectors	3633	3911	632	722	224	298	106	163	2777	2891
4. Global forest carbon sequestration subsidy, Annex I only tax in all non agricultural sectors and tax on emissions from fossil fuels combustion in agriculture	7,763	3595	4,810	695	169	1	131	8	2,784	2,899
5. Global forest carbon sequestration subsidy, carbon tax in all sectors, all regions; subsidy in non-Annex 1 agricultural sectors	11,549	3,795	4,788	696	801	276	395	158	5,960	2,822

Table 3a Changes in output (by value at constant world prices) and emissions by agricultural sector, under policy scenario 1

	Dairy	Ruminant	Non ruminant	Paddy rice	Other crops	Total agric.
Annex I						
Δ output (mill. USD)	-$1,827	$474	-$302	$800	-$57	-$911
Δ output %	-2%	1%	0%	4%	-0.02%	-0.1%
Δ emissions %	-21%	-7%	-23%	-22%	-23%	-17%
Non Annex I						
Δ output (mill. USD)	-$4,394	-$12,162	-$10,214	-$4,556	-$23,522	-$54,847
Δ output %	-6%	-14%	-5%	-5%	-4%	-5%
Δ emissions %	-14%	-27%	-21%	-27%	-18%	-24%
Global						
Δ output (mill. USD)	-$6,221	-$11,688	-$10,515	-$3,756	-$23,579	-$55,759
Δ output %	-4%	-7%	-3%	-4%	-2%	-3%
Δ emissions %	-17%	-23%	-22%	-27%	-20%	-22%

Table 3b Changes in output (by value at constant world prices) and emissions by agricultural sector, under policy scenario 2

	Dairy	Ruminant	Non ruminant	Paddy rice	Other crops	Total agric.
Annex I						
Δ output (mill. USD)	-$2,110	-$4,396	-$1,417	$150	-$690	-$8,462
Δ output %	-2%	-5%	-1%	1%	-0.2%	-1%
Δ emissions %	-21%	-15%	-24%	-27%	-23%	-20%
Non Annex I						
Δ output (mill. USD)	-$639	$213	-$1,178	-$1,008	-$8,845	-$11,457
Δ output %	-1%	0%	-1%	-1%	-1%	-1%
Δ emissions %	-1%	-4%	-1%	-6%	1%	-3%
Global						
Δ output (mill. USD)	-$2,749	-$4,182	-$2,595	-$858	-$9,534	-$19,919
Δ output %	-2%	-2%	-1%	-1%	-1%	-1%
Δ emissions %	-10%	-6%	-8%	-7%	-8%	-7%

Table 3c Changes in output (by value at constant world prices) and emissions by agricultural sector, under policy scenario 5

	Dairy	Ruminant	Non Ruminant	Paddy Rice	Other Crops	Total Agriculture
Annex I						
Δ output (mill. USD)	-$2,314	-$4,687	-$1,881	$12	-$1,740	-$10,610
Δ output , %	-3	-6	-2	0.1	-0.5	-2
Δ emissions, %	-21	-15	-24	-28	-24	-20
Non Annex I						
Δ output (mill. USD)	-$1,464	$604	-$1,605	-$21	-$9,245	-$11,731
Δ output , %	-2	1	-1	-0.03	-1	-1
Δ emissions , %	-6	-9	-16	-23	-15	-13
Global						
Δ output (mill. USD)	-$3,778	-$4,083	-$3,486	-$8	-$10,985	-$22,340
Δ output , %	-2	-2	-1	0	-1	-1
Δ emissions , %	-13	-10	-18	-23	-18	-15

Table 4 Percent change in food consumption by category and region in scenarios 1 and 5

	USA	EU27	BRAZIL	CAN	JAPAN	CHIHKG	INDIA	C_C_Amer	S_o_Amer	E_Asia	Mala_Indo	R_SE_Asia	R_S_Asia	Russia	Oth_CEE_CIS	Oth_Europe	MEAS_NAfr	S_S_AFR	Oceania
Scenario 1																			
Crops	-1	-1	-5	-1	0	-2	-2	-3	-6	-2	-2	-1	-1	-6	-1	0	-3	-3	-2
Dairy_Farms	-4	-3	-11	-3	-2	-9	-5	-5	-10	-4	-3	-4	-3	-14	-4	-3	-5	-23	-6
Ruminant	-7	-5	-23	-6	-4	-18	-13	-10	-16	-7	-17	-21	-12	-14	-5	-6	-8	-21	-10
NonRuminant	-2	-1	-6	-2	-1	-7	-4	-2	-5	-3	-4	-2	-3	-8	-3	-2	-4	-11	-3
Processed dairy	-1	-1	-5	-1	-1	-3	-4	-2	-6	-2	-3	-2	-2	-8	-1	-1	-4	-10	-3
Processed meat	-3	-1	-13	-3	-1	-6	-5	-2	-8	-3	-4	-3	-2	-8	-2	-2	-5	-14	-5
Other food	-1	0	-3	-1	0	-4	-2	-1	-4	-2	-2	-1	-1	-7	-1	-1	-4	-5	-1
Scenario 5																			
Crops	-1	-1	-2	-1	0	-1	0	-2	-4	-2	0	0	2	-6	1	0	-2	1	-2
Dairy_Farms	-4	-3	-2	-3	-3	-3	-1	-3	-7	-2	-1	1	4	-13	1	-3	-3	2	-6
Ruminant	-7	-5	-3	-6	-4	-3	-1	-3	-7	-3	-2	1	4	-14	1	-5	-3	1	-10
NonRuminant	-3	-2	1	-2	-2	-1	0	-1	-2	-1	0	2	5	-8	1	-2	-3	2	-3
Processed dairy	-2	-1	0	-1	-1	0	-1	-1	-4	-1	-1	1	5	-8	2	-1	-3	2	-4
Processed meat	-3	-2	0	-3	-2	-1	0	-1	-3	-1	-1	2	5	-8	1	-2	-3	2	-5
Other food	-1	-1	0	-1	-1	-1	0	-1	-2	-1	0	1	2	-7	1	-1	-3	1	-2

Table 5 Changes in food consumption, livestock emissions and output with two alternative instruments (scenarios 1 and 5)

Region	Emissions reduction in agriculture, MtCO2eq		Emissions reduction in livestock, MtCO2eq		Change in dairy production, %		Change in non-dairy ruminant production, %		Change in non-ruminant production, %		Change in food consumption, %	
	Tax	Output subsidy	Tax	Output subsidy	Tax	Output subsidy	Tax	Output subsidy	Tax	Output subsidy	Tax	Output subsidy
1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*
USA	111	119	48	52	-1	-2	0	-3	-1	-2	-1	-1
EU27	62	76	38	49	-1	-2	3	-3	0	-2	-1	-1
BRAZIL	154	75	131	57	-9	-1	-30	-5	-27	-6	-6	0
CAN	8	11	3	5	-1	-1	-3	-11	2	0	-1	-1
JAPAN	2	2	1	1	0	0	5	2	2	1	0	-1
CHIHKG	208	128	79	27	-3	-2	-15	1	-6	-1	-4	-1
INDIA	84	35	58	10	-5	-1	-23	1	-3	0	-3	0
C_C_Amer	16	7	14	5	-3	-1	-10	4	-1	0	-2	-1
S_o_Amer	77	58	50	33	-9	-5	-13	-5	-7	-3	-5	-3
E_Asia	6	5	2	1	-2	-1	-2	2	-3	-1	-2	-2
Mala_Indo	27	15	14	4	3	3	-27	5	-2	2	-2	0
R_SE_Asia	82	35	42	5	-3	4	-43	12	-2	2	-2	1
R_S_Asia	35	12	22	1	-3	3	-17	4	-3	3	-2	2
Russia	29	29	14	14	-14	-14	-14	-15	-1	-2	-8	-8
Oth_CEE_CIS	31	23	17	11	-7	-3	-8	-2	-4	0	-2	1
Oth_Europe	2	2	1	1	1	0	6	1	0	-1	-1	-1
MEAS_NAfr	15	8	8	2	-2	0	-3	5	-2	-1	-4	-3
S_S_AFR	239	123	191	81	-22	3	-22	2	-14	1	-7	1
Oceania	17	38	15	36	-10	-9	0	-23	-4	-7	-2	-3
Total	1204	801	745	395								

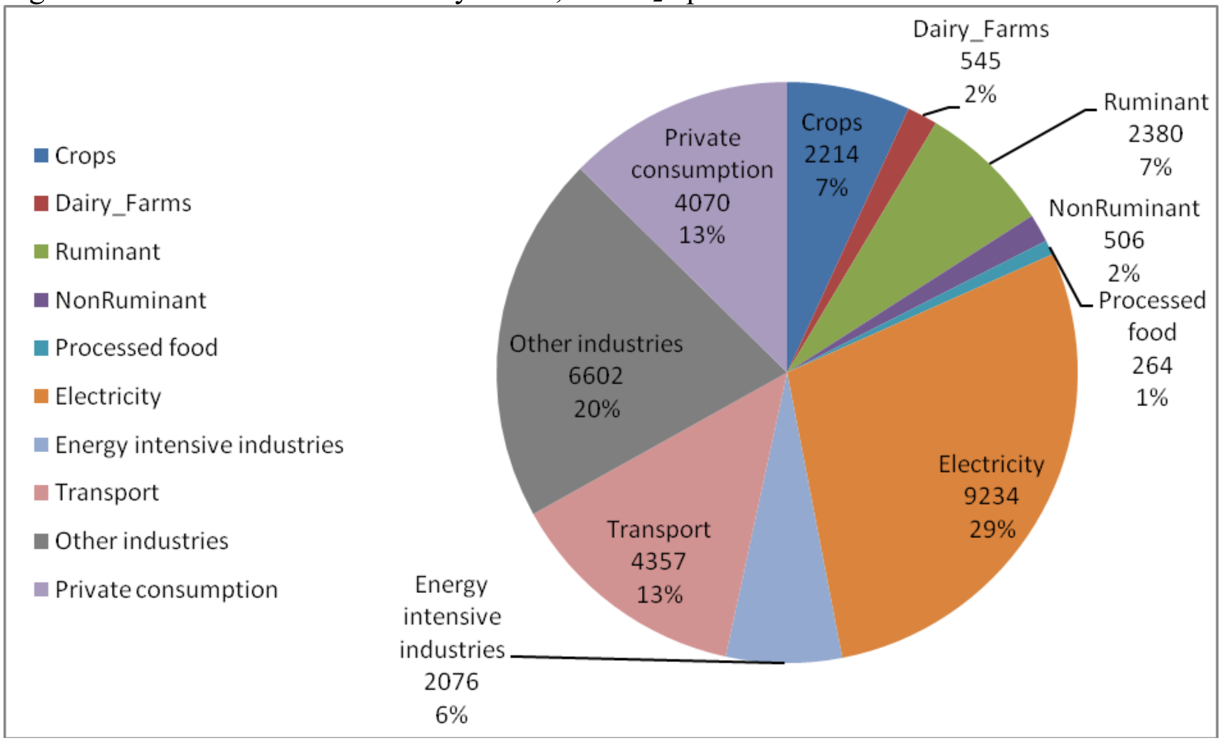
Table 6 Changes in land rents in three broad land use categories by region in scenario 5, %

Region	Cropland	Pasture	Forests
USA	29	16	364
EU27	7	5	18
BRAZIL	143	119	2,804
CAN	31	18	127
JAPAN	23	23	71
CHIHKG	21	35	196
INDIA	27	21	356
C_C_Amer	43	42	293
S_o_Amer	116	134	3,042
E_Asia	29	31	462
Mala_Indo	14	3	65
R_SE_Asia	5	-13	63
R_S_Asia	15	17	86
Russia	0	-8	35
Oth_CEE_CIS	2	-3	-3
Oth_Europe	5	3	3
MEAS_NAfr	7	8	30
S_S_AFR	101	-4	550
Oceania	46	-4	1,346

Table 7 Supply chain approach to emissions from livestock, $MtCO_2eq$

	Ruminant meats	Non ruminants	Ruminant dairy
Direct from livestock farming	2380	506	545
Crops	74	234	68
Other crops- or livestock-based inputs	17	45	20
Energy inputs	40	86	48
Other inputs	21	40	26
Total before the "farm gate"	2532	911	707
Between farm gate and output of processed livestock product	143	302	145
Total	2675	1213	852
Global livestock supply chain	4741		

Figure 1a Global GHG emissions by sector, $MtCO_2eq$



Note: The emissions include both CO_2 and non-CO_2 GHG emissions, but do not include emissions from land use change.

Figure 1b Global non-CO_2 GHG emissions by sector, $MtCO_2eq$

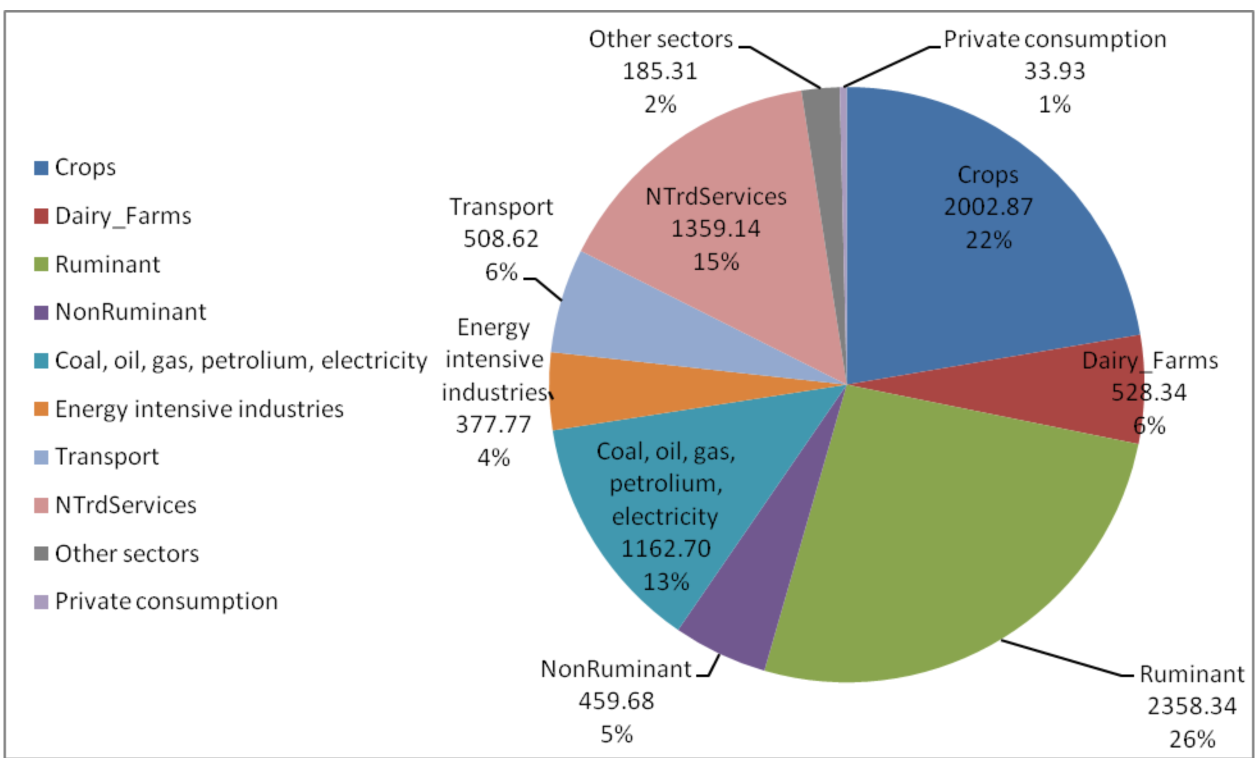


Figure 1c Non-CO_2 GHG emissions by agricultural sector and region, $MtCO_2eq$

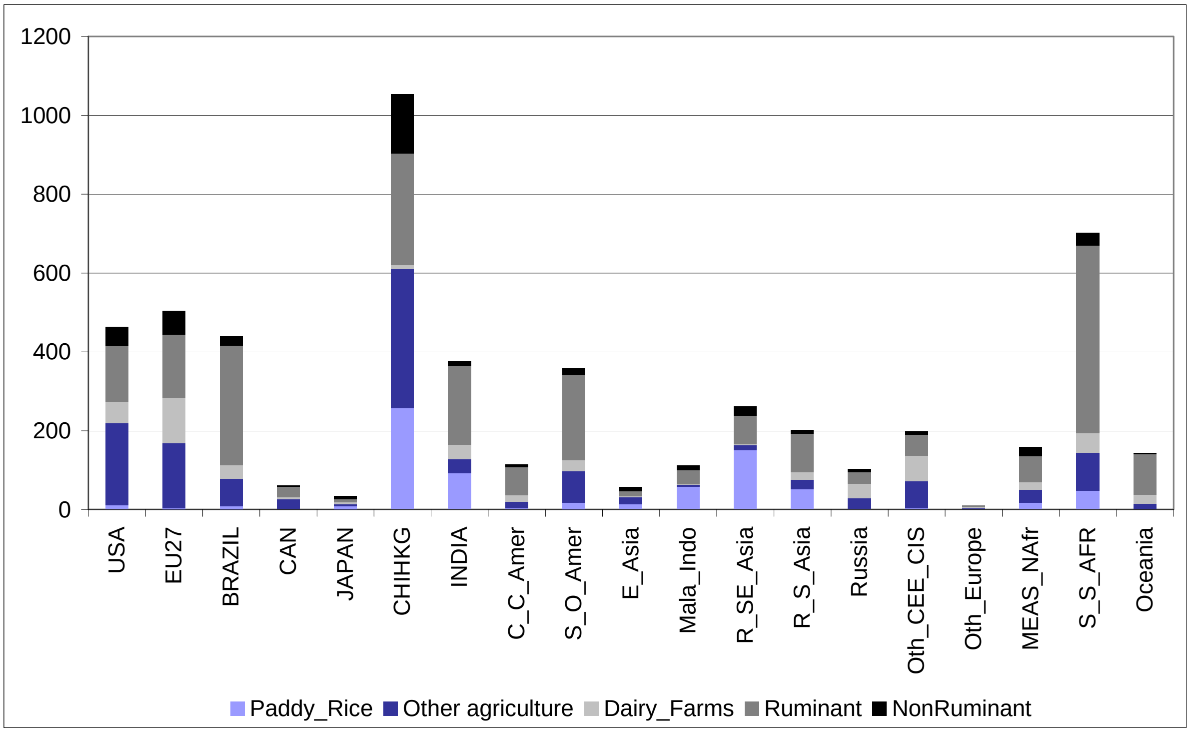


Figure 2a Emission intensity of output when all livestock sector non-CO_2 emissions, including emissions related to factors and intermediate input use, are tied to output ($kgCO_2eq$/$ of output)

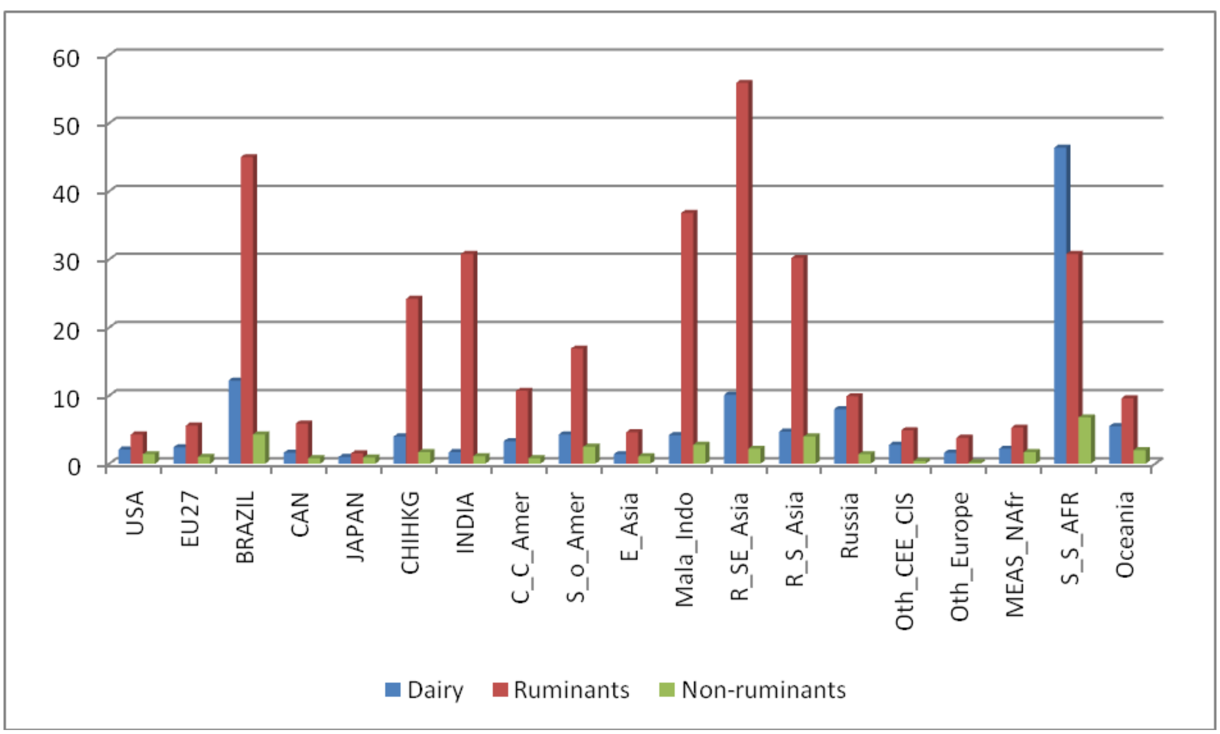
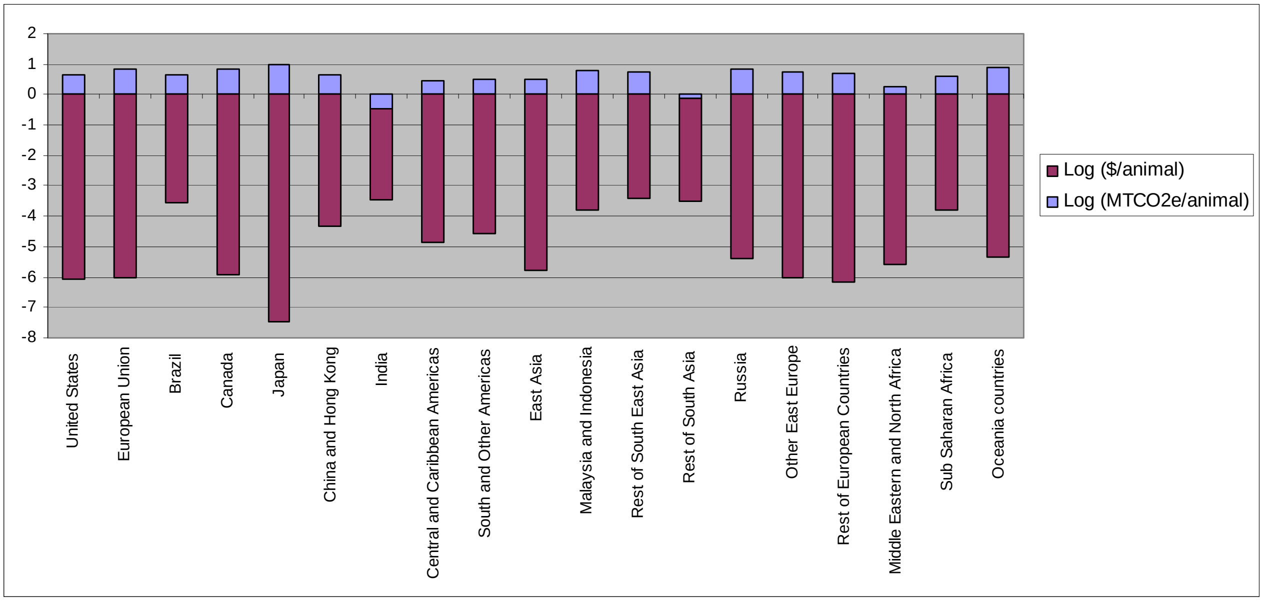
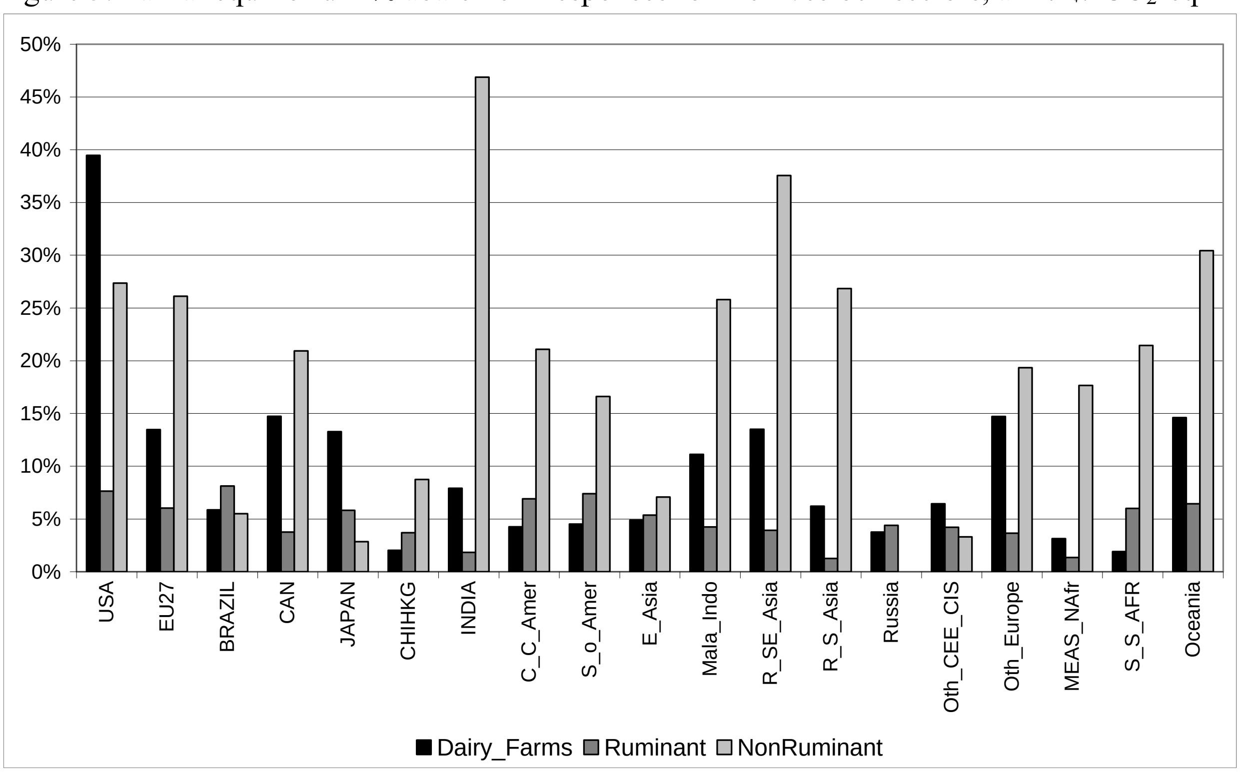


Figure 2b Disaggregation of emissions intensities per dollar of output in ruminant sector



Source: Avetisyan et al. 2010.

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

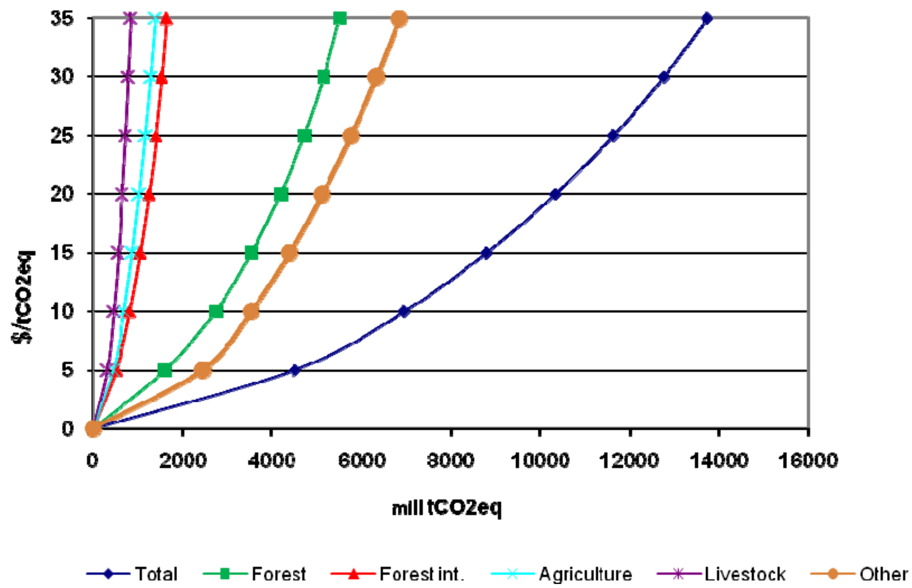


Figure 4b Global crops and livestock general equilibrium GHG abatement supply schedule

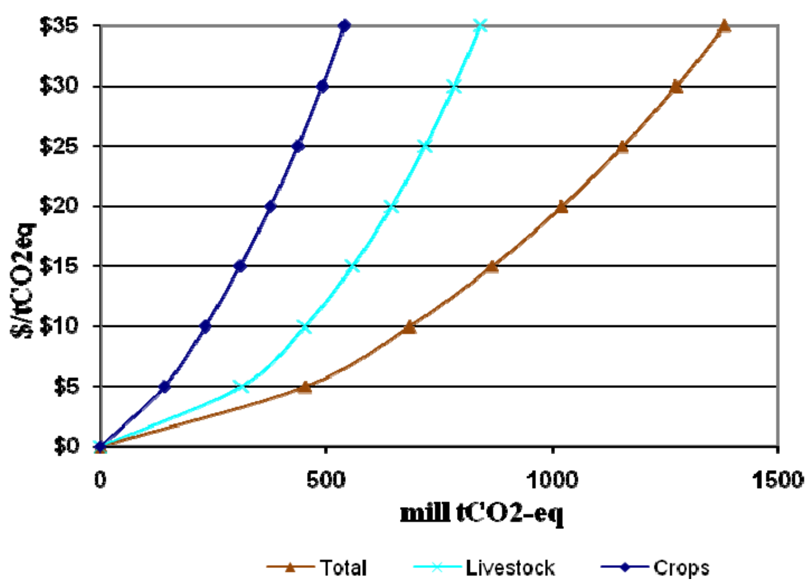


Figure 5a Decomposition of changes in GHG emissions from ruminant sectors under 27$/t$CO_2$eq global carbon tax and forest carbon sequestration subsidy (scenario 1), %

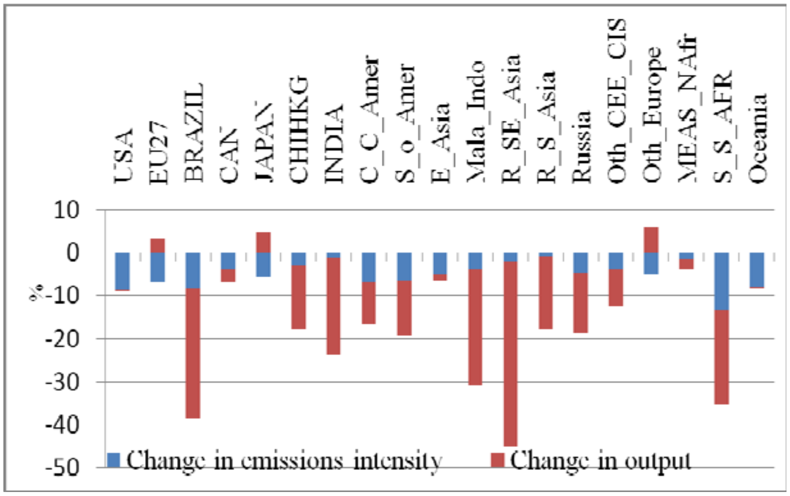


Figure 5b Decomposition of changes in GHG emissions from ruminants under 27$/t$CO_2$eq global carbon tax and forest carbon sequestration subsidy with carbon tax returned to non-Annex 1 agricultural producers in the form of output subsidy (scenario 5), %

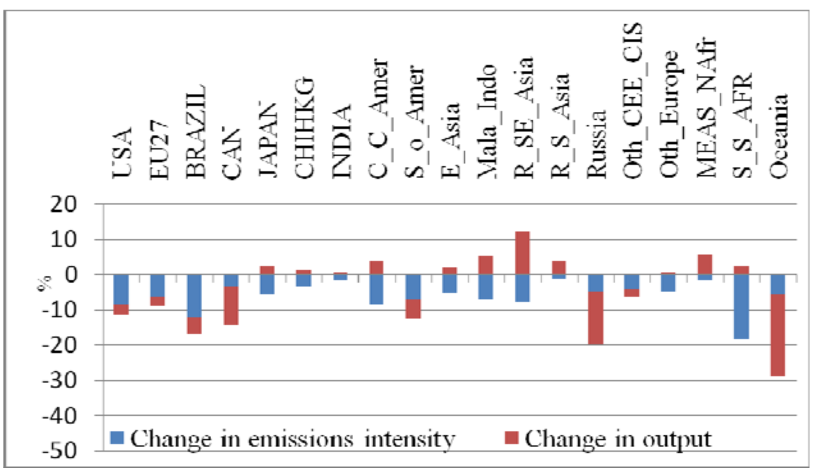


Figure 6a Changes in value of output in livestock sectors at constant world prices when global 27 \$/tCO_2eq tax is imposed in all sectors (scenario 1), mill 2001 US\$

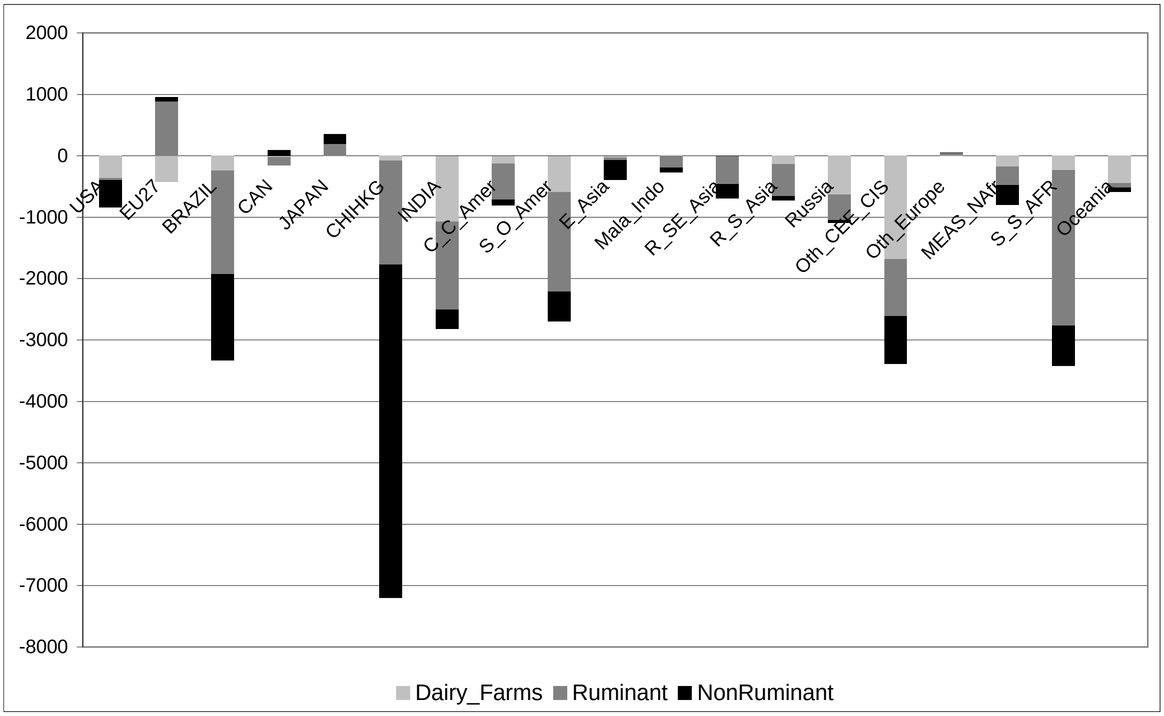


Figure 6b Changes in value of output in livestock sectors at constant world prices when an Annex I-only 27 \$/tCO_2eq tax is imposed in all sectors (scenario 2), mill 2001 US\$

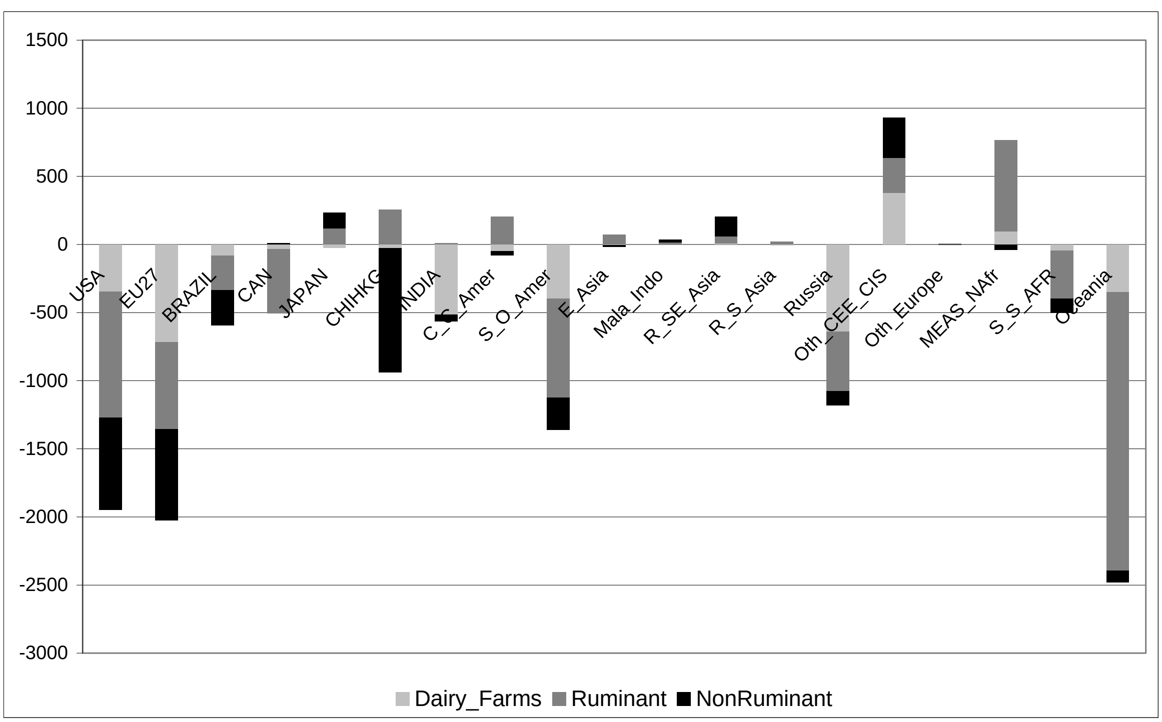


Figure 6c Changes in value of output in livestock sectors at constant world prices when global 27 $/tCO_2eq tax is imposed and non-Annex I agriculture producers are given abatement subsidy (scenario 5), mill 2001 US$

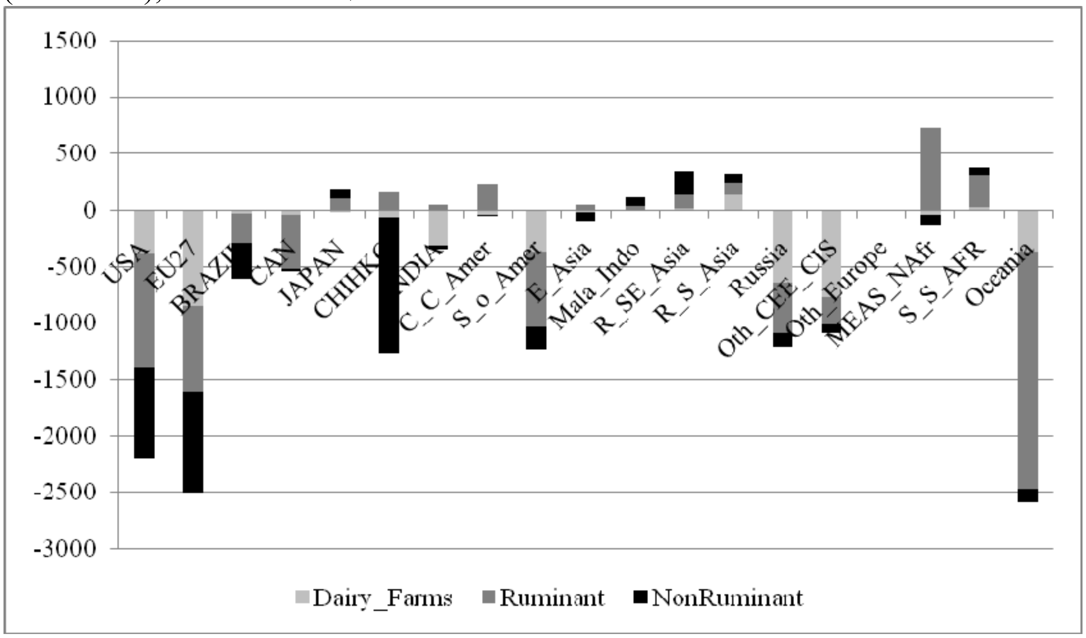


Figure 6d Regional changes in value of output in aggregated livestock sectors under different scenarios at 27$/tCO_2eq tax, mill 2001 US$

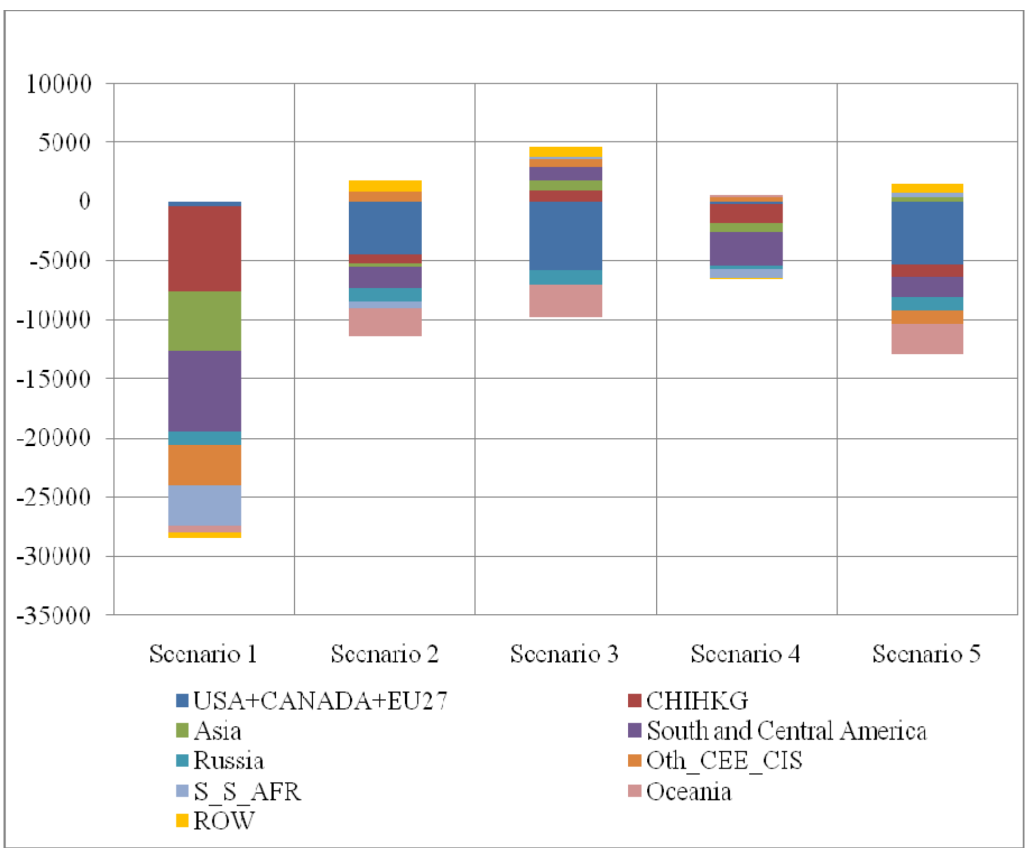


Figure 7a Changes in trade balances in agriculture and food sectors in scenario 1, by sector and region, mill 2001 US$

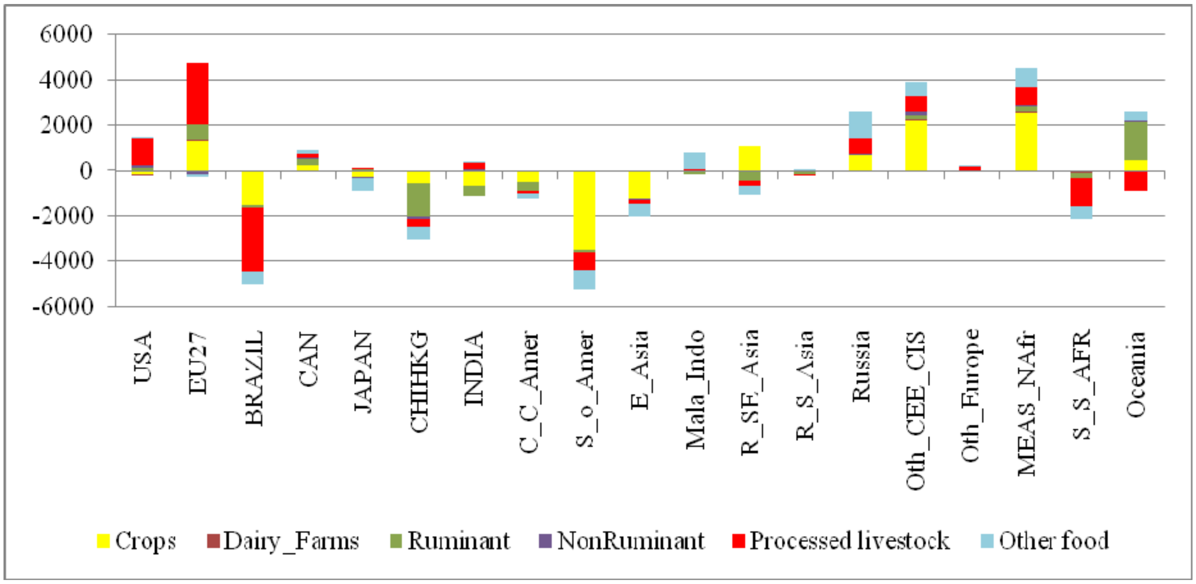


Figure 7b Changes in trade balances in agriculture and food sectors in scenario 2, by sector and region, mill 2001 US$

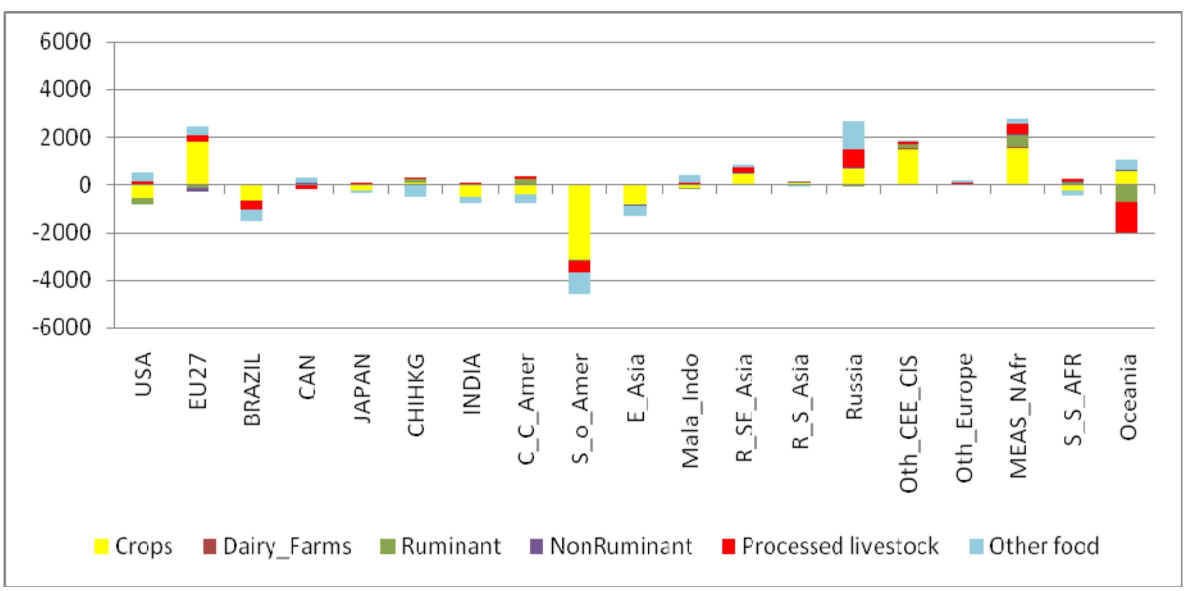


Figure 7c Changes in trade balances in agriculture and food sectors in scenario 5, by sector and region, mill 2001 US$

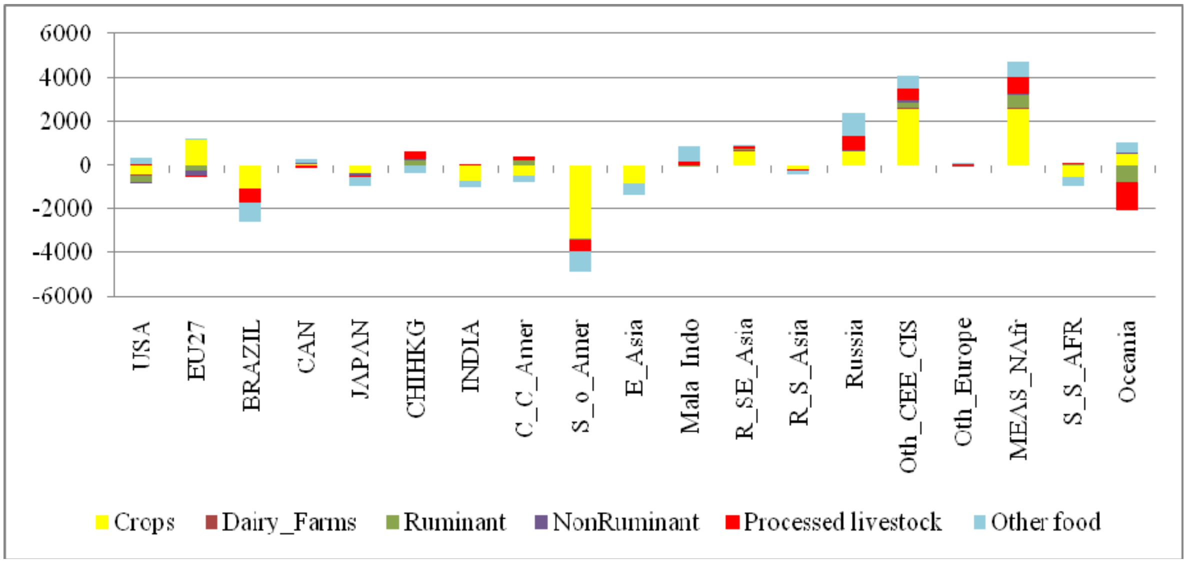


Figure 8a Changes in per capita annual consumption at 2001 prices and population by food category and region in scenario 1 (2001 US$)

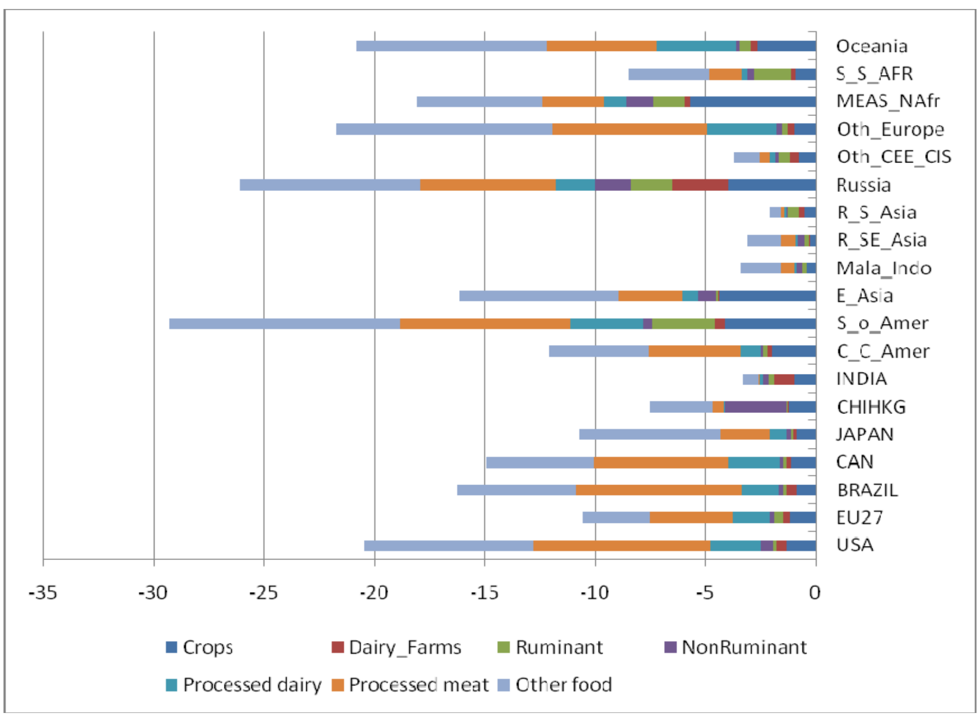


Figure 8b Changes in per capita annual consumption at 2001 prices and population by food category and region in scenario 2 (2001 US$)

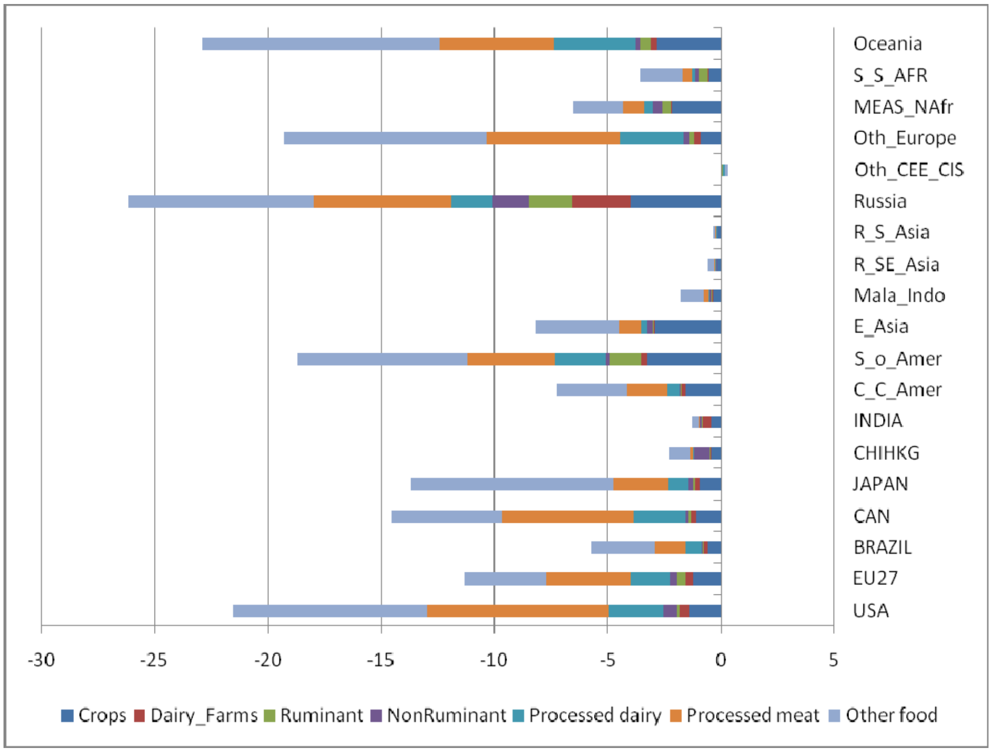


Figure 8c Changes in per capita annual consumption at 2001 prices and population by food category and region in scenario 5 (2001 US$)

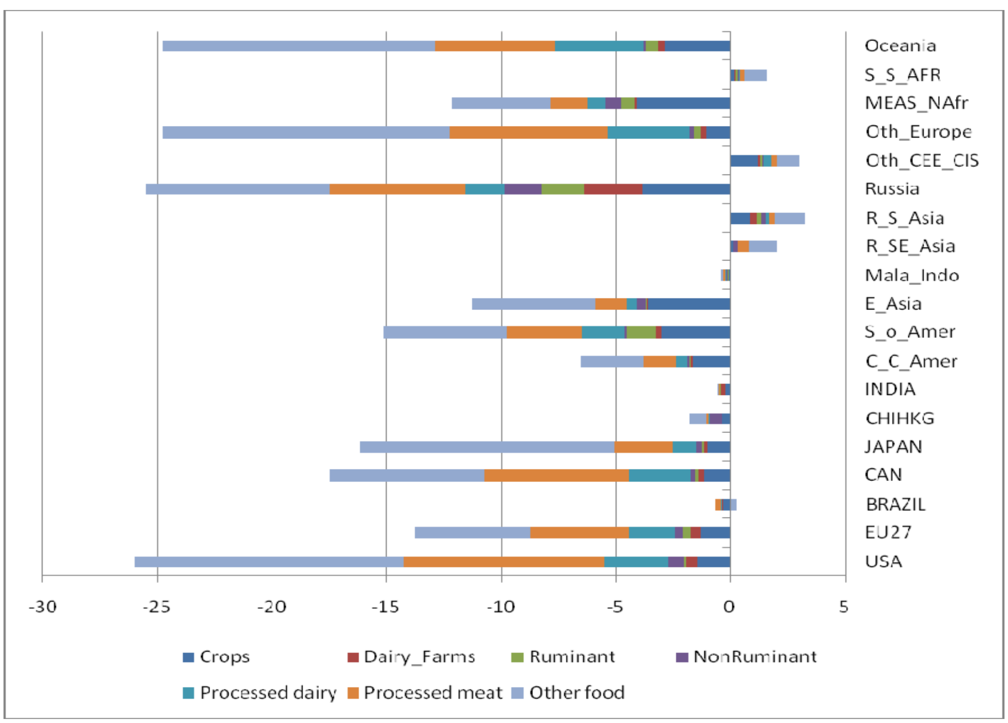


Figure 9a Changes in the structure of food consumption bundle under the carbon tax (scenario 1), %

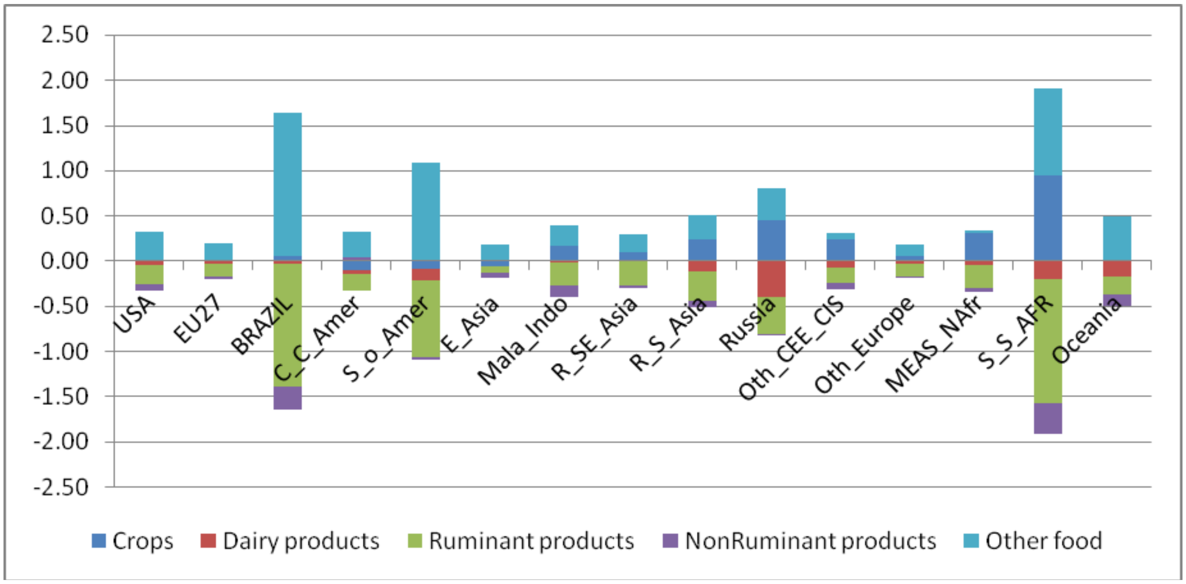


Figure 9b Changes in the structure of food consumption bundle under the abatement subsidy in non-Annex I (scenario 5), %

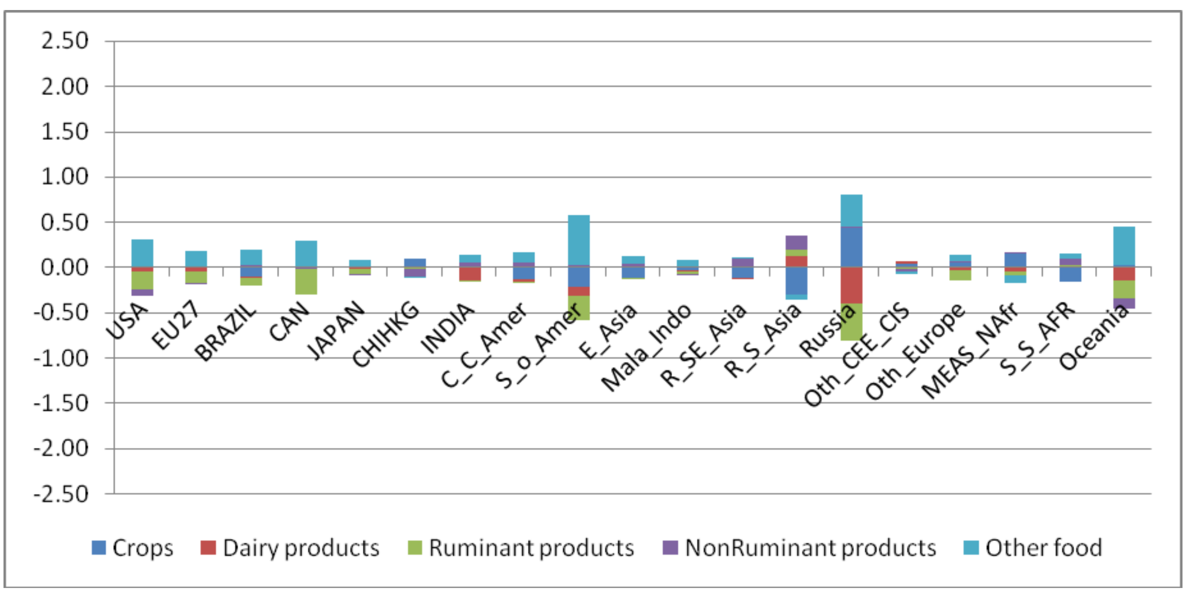
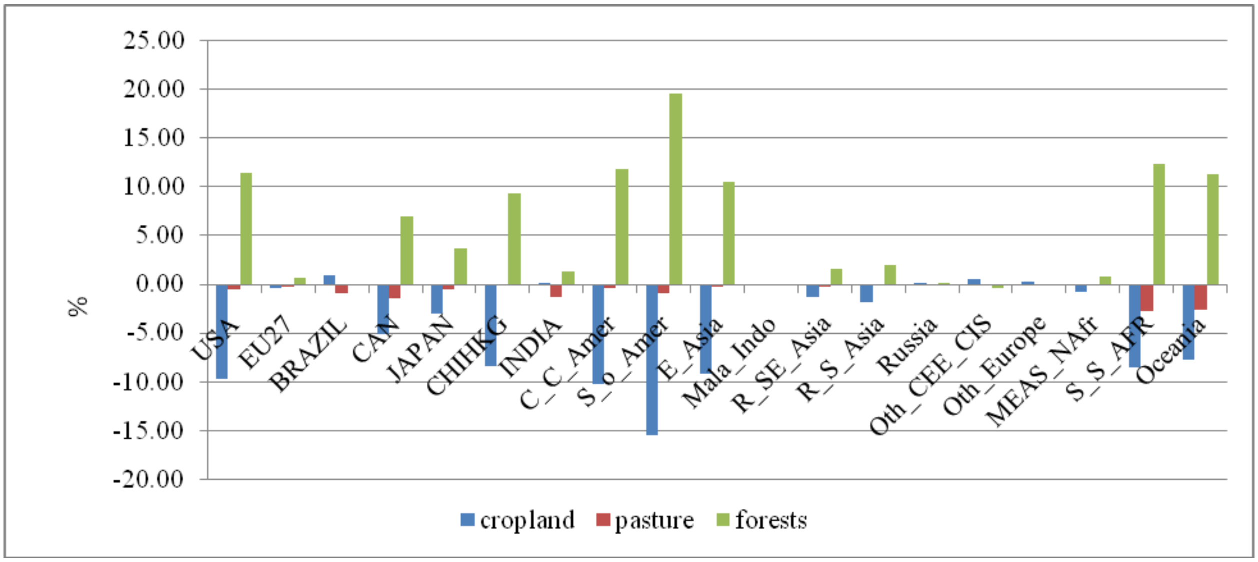


Figure 10 Changes in land use represented by land rents share weighted percent changes in effective hectares (scenario 5), %



Appendix

Table A1 Aggregation of GTAP regions

Code	Region in the model	GTAP regions	Group	GTM region
USA	United States	United States	Annex I and II	USA
EU27	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	Annex I and II	EU25
BRAZIL	Brazil	Brazil	Non-Annex I	Brazil
CAN	Canada	Canada	Annex I and II	Canada
JAPAN	Japan	Japan	Annex I and II	Japan
CHIHKG	China, Hong Kong	China, Hong Kong	Non-Annex I	China, Hong Kong
INDIA	India	India	Non-Annex I	India
C_C_Amer	Central and Caribbean Americas	Mexico, Rest of North America, Central America, Rest of Free Trade Area of the Americas, Rest of the Caribbean	Non-Annex I	Central America
S_O_Amer	South and Other Americas	Colombia, Peru, Venezuela, Rest of Andean Pact, Argentina, Chile, Uruguay, Rest of South America	Non-Annex I	Rest of South America
E_Asia	East Asia	Korea, Taiwan, Rest of East Asia	Non-Annex I	
Mala_Indo	Malaysia and Indonesia	Indonesia, Malaysia	Non-Annex I	Southeast Asia
R_SE_Asia	Rest of South East Asia	Philippines, Singapore, Thailand, Viet Nam, Rest of Southeast Asia	Non-Annex I	Southeast Asia
R_S_Asia	Rest of South Asia	Bangladesh, Sri Lanka, Rest of South Asia	Non-Annex I	East Asia
RUSSIA	Russia	Russian Federation	Annex I	Russia
Oth_CEE_CIS	Other East Europe and Rest of Former Soviet Union	Rest of Former Soviet Union, Turkey, Albania, Croatia, Rest of Europe	Non-Annex I	Other CEE
Oth_Europe	Rest of European Countries	Switzerland, Rest of EFTA	Annex I and II	Other Europe
MEAS_NAfr	Middle East and North Africa	Rest of Middle East, Morocco, Tunisia, Rest of North Africa	Non-Annex I	Middle East and North Africa
S_S_AFR	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	Non-Annex I	Sub Saharan Africa
Oceania	Oceania	Australia, New Zealand, Rest of Oceania	Annex I and II	Oceania

Table A2 Carbon tax revenue, forest carbon sequestration (f.c.s.) subsidy, and payments made by Annex II regions and transfers received by non-Annex 1 regions when emissions are priced at 27 $/tCO_2eq$, mill 2001 US$

Region	Global carbon tax and f.c.s. subsidy (scenario 1)				Global carbon tax, f.c.s. subsidy and abatement subsidy to agriculture producers in non-Annex I (scenario 5)				
	Carbon` tax revenue	F.c.s. subsidy received	Net carbon tax revenue	Net carbon tax revenue as % of 2001 income	Carbon` tax revenue	F.c.s. subsidy received	Abatement subsidy to agriculture producers in non-Annex I paid by Annex II	Net carbon tax revenue	Net carbon tax revenue as % of 2001 income
USA	127,874	12,190	115,684	1.3	127,479	12,319	-42,066	73,094	0.8
EU27	105,774	218	105,556	1.4	105,169	250	-33,837	71,082	1.0
BRAZIL	8,058	17,811	-9,753	-2.2	9,880	17,480	10,234	2,634	0.6
CAN	9,680	1,866	7,814	1.2	9,615	1,919	-2,944	4,752	0.7
JAPAN	24,601	979	23,622	0.7	24,525	1,011	-16,451	7,063	0.2
CHIHKG	61,761	17,765	43,995	3.7	64,296	16,804	26,696	74,188	6.2
INDIA	15,304	8,536	6,768	1.6	16,932	8,248	9,204	17,887	4.1
C_C_Amer	10,187	5,294	4,893	0.6	10,482	5,170	3,096	8,408	1.1
S_o_Amer	4,868	42,146	-37,278	-6.3	5,417	41,705	8,391	-27,896	-4.7
E_Asia	16,168	4,322	11,846	1.8	16,196	4,269	1,584	13,511	2.0
Mala_Indo	9,936	652	9,284	4.4	10,296	608	2,632	12,320	5.8
R_SE_Asia	13,598	356	13,242	3.9	14,951	310	6,231	20,872	6.2
R_S_Asia	6,744	471	6,272	4.7	7,460	431	5,157	12,187	9.1
Russia	36,094	131	35,963	13.5	36,066	133	0	35,934	13.5
Oth_CEE_CIS	29,570	27	29,543	11.1	30,123	28	5,411	35,506	13.4
Oth_Europe	2,832	-1	2,833	0.8	2,824	0	-1,693	1,131	0.3
MEAS_NAfr	44,357	113	44,244	5.6	44,594	105	4,271	48,760	6.2
S_S_AFR	1,322	16,354	-15,033	-5.3	4,533	15,326	15,791	4,998	1.8
Oceania	3,349	3,132	216	0.1	2,787	3,164	-1,706	-2,084	-0.6
Global	532,077	132,363	399,714	1.4	543,627	129,280	0	414,347	1.5
Non-Annex I							98,698		1.55
Annex II							-98,698		-0.46

Table A3 Change in GHG emissions when agriculture sectors are exempt from 27$/t$CO_2$eq carbon tax, Mt$CO_2$eq

	USA	EU27	BRAZIL	CAN	JAPAN	CHIHKG	INDIA	C_C_Amer	S_o_Amer	E_Asia	Mala_Indo	R_SE_Asia	R_S_Asia	Russia	Oth_CEE_CIS	Oth_Europe	MEAS_NAfr	S_S_AFR	Oceania	Total
Land using agricultural sectors are excluded from carbon tax globally (non ruminants are under carbon tax)																				
Livestock	-15	-15	-48	-1	0	-33	-11	-5	-22	-1	-4	-9	-3	-4	-7	0	-5	-63	-4	-251
Ruminant dairy and ruminant meat	-1	1	-43	0	0	-7	-6	-4	-18	0	-1	0	-1	-4	-6	0	0	-55	-3	-148
Non ruminants	-15	-16	-5	-1	0	-25	-5	-1	-4	-1	-3	-9	-3	-1	-1	0	-4	-9	-1	-103
Crops	3	5	-5	2	0	-23	-8	-1	-11	-1	-2	-3	-1	-2	-3	0	-1	-15	0	-66
Total agriculture	-13	-10	-53	1	0	-56	-19	-6	-33	-2	-7	-12	-4	-6	-10	0	-5	-78	-5	-317
All agricultural sectors are excluded from carbon tax globally																				
Livestock	-1	1	-38	0	0	-13	-6	-4	-18	0	-1	0	-1	-4	-7	0	-1	-55	-4	-152
Ruminant dairy and ruminant meat	-1	1	-36	0	0	-8	-6	-4	-18	0	-1	0	-1	-4	-6	0	0	-53	-4	-141
Non ruminants	0	0	-2	0	0	-5	0	0	-1	0	0	0	0	0	0	0	0	-1	0	-11
Crops	3	5	-5	2	0	-22	-8	-1	-11	-1	-2	-2	-1	-2	-3	0	-1	-15	0	-65
Total agriculture	1	5	-43	1	0	-35	-14	-5	-30	-1	-3	-3	-2	-6	-10	0	-2	-69	-4	-217

Note: The two simulations presented in the table A3 differ in our treatment of non ruminant sector. The issue is that agricultural land using sectors of the model include all agricultural sectors except non ruminants. The non ruminant livestock sector does not compete directly for land with other land using sectors in the model (ruminant sectors, crops and forestry). Of course, there is indirect competition as increased production of poultry, for example, will boost the feed requirements and hence increase the demand for land in feed grains. To isolate the effect of indirect competition for land from non ruminant sector, in our first simulation we treat non ruminants in the same way as other non-land using sectors and impose carbon tax in this sector. In the second simulation we include non ruminant sector with other agricultural land using sectors that are exempted from carbon tax. In the first simulation (first panel of table A3), global emissions from agriculture decline by 317 MtCO2eq with about half of the decline coming from land using livestock sectors and one fifth coming from crop sectors. These reductions are driven by the competition for land between subsidized forestry sector and the (tax free) agriculture sectors. One third of the emissions reduction comes from the non ruminant sector where carbon tax is imposed. While global emissions from crop sectors decline by 66 $MtCO_2eq$, US, EU27, Canada and Japan - regions with intensive crop production systems - are increasing their emissions. Emissions from agriculture (all agricultural sectors together) fall in all regions except Canada, where increase in emissions from crops dominates emissions reduction achieved in livestock sectors. Now compare these results with second panel of Table A3 where non ruminants are also exempt from carbon tax. Again, global emissions from agriculture decline, but the reduction is now smaller (217 $MtCO_2eq$) because non ruminant sector is not subject to carbon tax. However, changes in emissions in crop sectors are very similar to those reported in first panel of the table: global emissions are reduced because land is moving to forestry. Regions with intensive crop production systems (USA, EU27, Canada and Japan) increase their emissions in crop sectors and total emissions from agriculture. Overall, we concluded that of the two forest extensification effects on emissions – forests bidding land away from agriculture production and intensification of the remaining agricultural land – former effect dominates. Global emissions reduction in agriculture masks variation in regional responses. GHG emissions do increase in the crop sectors of USA, EU27, Canada and Other Europe -- regions with very intensive agriculture.

Table A4 GHG emissions *reduction* under (1) scenario 1 and (2) scenario 1 with food consumption fixed at the baseline levels, at carbon price 27$/t$CO_2eq, MtCO_2$eq

Scenario	All emissions reduction		Forest carbon sequestration		Agricultural sectors		Livestock sectors (within agriculture)		Other sectors and private consumption	
	Global	Annex I	Global	Annex I	Global	Annex I	Global	Annex I	Global	Annex I
1. Global forest carbon sequestration subsidy, carbon tax in all sectors, all regions	12,105	3,720	4,902	686	1,204	230	745	119	5,999	2,804
2. As above, but food consumption is fixed in all regions	11,735	3,682	4,789	675	931	202	525	102	6015	2805

Table A5 Global Timber Model changes in forest carbon sequestration under different carbon price assumptions; present value over 20 years; milltCO$_2$eq

Intensive Margin

Carbon price	US	CHINA	BRAZIL	CANADA	RUSSIA	EU 25	OTHER EUROPE	OTHER CEE	CENT AMERICA	REST SOUTH AM	SUB SAHARAN AF
10	57	83	248	455	137	1	0	11	1	100	38
50	178	1,055	253	410	5,946	7	0	22	166	2,156	2,433
100	698	3,505	2,884	467	5,949	51	1	35	368	4,541	3,728
200	1,232	4,728	6,915	2,596	6,000	51	1	83	398	4,566	3,992
400	1,712	6,121	7,789	3,182	5,811	146	1	228	400	4,599	4,020
800	3,042	6,423	9,564	5,773	5,899	925	103	403	401	4,602	4,025

Extensive Margin

Carbon price	US	CHINA	BRAZIL	CANADA	RUSSIA	EU 25	OTHER EUROPE	OTHER CEE	CENT AMERICA	REST SOUTH AM	SUB SAHARAN AF
10	686	24	139	-124	-10	-1	0	3	16	540	158
50	3,492	668	1,260	291	-320	-5	0	-4	1,878	2,997	656
100	5,378	1,885	2,819	439	14	38	-1	7	1,889	8,717	2,378
200	6,761	3,516	6,916	551	-204	70	-1	179	2,010	10,547	2,460
400	7,825	3,506	6,560	2,310	464	36	0	138	1,894	11,078	2,713
800	7,259	3,580	5,073	553	1,257	1,140	-101	-150	2,019	11,419	2,917

Table A5 (cont.)

Intensive Margin

Carbon price	SOUTHEAST ASIA	OCEANIA	JAPAN	AF MIDDLE E	EAST ASIA	SOUTH ASIA	INDIA	TOTAL
10	1,511	27	188	3	16	5	140	3,022
50	6,409	27	288	4	118	280	6,132	25,885
100	6,411	25	233	9	510	420	6,153	35,988
200	6,417	29	871	17	653	778	6,183	45,511
400	6,418	40	1,149	28	785	833	6,186	49,447
800	6,418	62	1,500	43	786	1,079	6,187	57,235

Extensive Margin

Carbon price	SOUTHEAST ASIA	OCEANIA	JAPAN	AF MIDDLE E	EAST ASIA	SOUTH ASIA	INDIA	TOTAL
10	2,015	386	26	1	16	34	1,083	4,994
50	331	1,811	-7	53	864	129	2,378	16,471
100	336	1,818	295	42	538	229	4,355	31,176
200	350	1,789	-101	93	536	317	5,426	41,215
400	394	1,874	889	129	426	576	6,361	47,173
800	404	1,882	1,569	125	438	461	6,921	46,766

Table A6 Global Timber Model changes in forest carbon sequestration under different carbon price assumptions; annual equivalent amount; milltCO$_2$eq

Total Carbon (sum of extensive and intensive margins)

Carbon price	US	CHINA	BRAZIL	CANADA	RUSSIA	EU 25	OTHER EUROPE	OTHER CEE	CENT AMERICA	REST SOUTH AM	SUB SAHARAN AF	SOUTHEAST ASIA	OCEANIA	JAPAN	AF MIDDLE E	EAST ASIA	SOUTH ASIA	INDIA	TOTAL
10	60	9	31	27	10	0	0	1	1	51	16	283	33	17	0	3	3	98	643
50	295	138	121	56	451	0	0	1	164	413	248	541	147	23	5	79	33	683	3399
100	488	433	458	73	478	7	0	3	181	1064	490	541	148	42	4	84	52	843	5389
200	641	662	1110	253	465	10	0	21	193	1213	518	543	146	62	9	95	88	932	6959
400	765	772	1151	441	504	15	0	29	184	1258	540	547	154	164	13	97	113	1007	7753
800	827	803	1175	508	574	166	0	20	194	1286	557	547	156	246	14	98	124	1052	8345

Intensive margin

Carbon price	US	CHINA	BRAZIL	CANADA	RUSSIA	EU 25	OTHER EUROPE	OTHER CEE	CENT AMERICA	REST SOUTH AM	N AFSUB SAHARA	SOUTHEAST ASIA	OCEANIA	JAPAN	AF MIDDLE E	EAST ASIA	SOUTH ASIA	INDIA	TOTAL
10	5	7	20	36	11	0	0	1	0	8	3	121	2	15	0	1	0	11	242
50	14	85	20	33	477	1	0	2	13	173	195	514	2	23	0	9	22	492	2077
100	56	281	231	37	477	4	0	3	29	364	299	514	2	19	1	41	34	494	2888
200	99	379	555	208	481	4	0	7	32	366	320	515	2	70	1	52	62	496	3652
400	137	491	625	255	466	12	0	18	32	369	323	515	3	92	2	63	67	496	3968
800	244	515	767	463	473	74	8	32	32	369	323	515	5	120	3	63	87	496	4593

Extensive margin

n priceCarbo	US	CHINA	BRAZIL	CANADA	RUSSIA	EU 25	OTHER EUROPE	OTHER CEE	CENT AMERICA	REST SOUTH AM	SUB SAHARAN AF	SOUTHEAST ASIA	OCEANIA	JAPAN	AF MIDDLE E	EAST ASIA	SOUTH ASIA	INDIA	TOTAL
10	55	2	11	-10	-1	0	0	0	1	43	13	162	31	2	0	1	3	87	401
50	280	54	101	23	-26	0	0	0	151	240	53	27	145	-1	4	69	10	191	1322
100	432	151	226	35	1	3	0	1	152	699	191	27	146	24	3	43	18	349	2502
200	542	282	555	44	-16	6	0	14	161	846	197	28	144	-8	7	43	25	435	3307
400	628	281	526	185	37	3	0	11	152	889	218	32	150	71	10	34	46	510	3785
800	582	287	407	44	101	91	-8	-12	162	916	234	32	151	126	10	35	37	555	3753

Figure A1 Changes in regional and global welfare in five scenarios reported in Table 2b, %

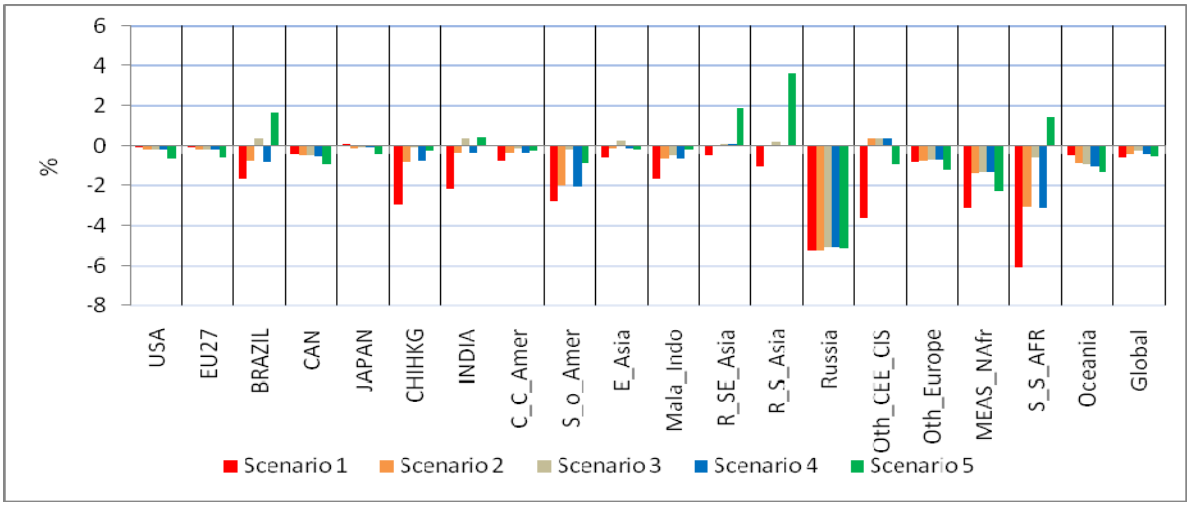


Figure A2 Changes in per capita utility from aggregate household expenditure by region in five scenarios reported in Table 2b, %

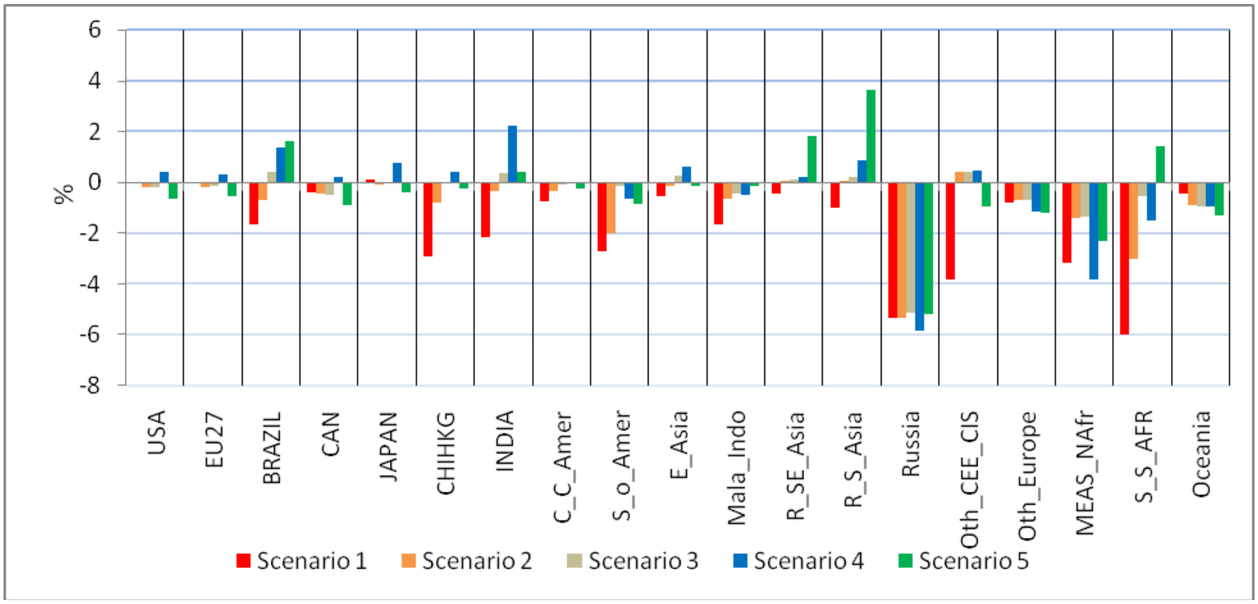


Figure A3 Changes in terms of trade in five scenarios reported in Table 2b, %