GHG Mitigation Policies in Livestock Sectors: Competitiveness, Emission Leakage and Food Security

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By

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Introduction

Recent research on livestock's role in climate change has raised awareness about the contribution that livestock can make to global mitigation efforts, and has increased the likelihood that mitigation policies will eventually be imposed on the sector (Steinfeld et al. 2006, 2007; Smith et al. 2008; Rose et al. 2007; Bellarby et al. 2008; CAST 2004; McKinsey & Co 2009). The overriding challenge for the sector is to adjust to these emerging carbon constraints without compromising food security and livelihood improvement priorities in developing countries.

Livestock production is the world's largest source of methane (CH_4) emissions, most of which is derived from fermentative digestion by ruminant animals (Smith et al. 2007). Manure handling and storage is a significant source of both CH_4 and N_2O emissions. The greenhouse gas (GHG) contributions vary considerably between livestock systems and regions according to animal physiology, agro-climatic conditions, quality of feed resources, manure management practices, and degree of intensification (figure 1). Taking into account emissions along its entire commodity chain, livestock sectors are estimated to contribute 7.1 $GtCO_2eq$ emissions each year, which is approximately 18% of total annual global anthropogenic emissions (Steinfeld et al. 2006). If only direct on-farm emissions are considered, this share falls to around 11%. Livestock's share of total regional GHG emissions also differs greatly between regions (figure 2), accounting for nearly half of all emissions (45%) in Brazil and only a very small share of emissions in Japan.

Driven by rapid population growth, urbanization and rising per capita income growth in developing countries, the livestock sector is presently in the midst of a prolonged surge in demand, growing faster than the rest of agriculture in almost all countries (Steinfeld and Wassenaar 2007). This rapid demand-driven growth in livestock production has important implications for the growth of livestock emissions. Indeed, global CH_4 emissions from livestock production alone are expected to increase by around 30% between 2000 and 2020, and almost all of this growth is expected to arise in developing countries.

This study investigates effects of GHG mitigation policies on livestock sectors. Changes in livestock emissions and production by regional sector, and in food consumption are analyzed under a range of global mitigation polices that are broadly aligned with the different responsibilities of developed and developing countries under the UNFCCC. Food security impacts and the implications of emissions leakage and informal livestock sectors in developing regions, for climate policy effectiveness, are also examined.

Earlier work

In contrast to the relative abundance of global economic modeling studies on the mitigation of energy-related CO_2 emissions, there are far fewer studies assessing impacts of mitigation in livestock and other land using sectors. Of these, there are a number that provide “bottom-up” engineering-type mitigation cost estimates; these incorporate substantial detail on specific mitigation technologies in land using sectors (USEPA 2006a; McKinsey&Co 2009; IPCC 2008), but ignore market interactions, including competition for land and international commodity trade. These interactions are important and can alter the spatial allocation of cost efficient mitigation and can lead to emissions leakage through changing trade patterns. Global partial equilibrium models of land use address these shortcomings, but they do not capture linkages between land using sectors and the rest of the economy. These linkages are particularly important in developing countries where the agricultural and forestry sectors often account for a sizeable share of GDP, and when climate policy-related transfer payments are large. Such inter-sectoral linkages also matter when mitigation policies are imposed on closely related sectors. In this regard, computable general equilibrium (CGE) models are particularly useful, given their economy-wide scope. However, very few CGE models incorporate spatially explicit land use data, either in a unified model framework or by linking with a detailed geographical/biophysical model (van der Werf and Peterson 2009).

Hertel, Rose and Tol (2009) offer an overview of most of these approaches, including the GTAP-AEZ-GHG model (Hertel et al. 2009, Golub et al. 2009), which incorporates detailed spatial land use data for both agriculture and forestry in a unified CGE model framework. In addition to this, the revised GTAP-AEZ-GHG model (Golub et al. 2010) incorporates many features of the GTAP-E model (Burioux and Troung 2002; McDougall and Golub, 2007) designed for energy-economy-environment interactions. Thus, GTAP-AEZ-GHG is very suitable for analysis of various international sector-based scenarios of climate change policy. It includes both non-CO_2 and CO_2 GHG emissions database, as well as a spatial AEZ data base which captures the heterogeneous environmental and economic characteristics of land-based activities. The integration of these data with forest carbon sequestration (Sohngen and Mendelsohn 2007) and agricultural mitigation (USEPA 2006b) data provides a comprehensive framework for the rigorous accounting of the opportunity costs associated with land-based mitigation.

Earlier analysis of GHG mitigation in livestock sectors within this modeling framework revealed that emission intensities, measured in emissions per dollar of output, differ significantly across sectors, by animal species and by region (Avetisyan et al. 2011). These emission intensities determine both the economic cost and the size of the mitigation incentive provided by the carbon tax in each regional livestock sector. High intensity sectors suffer a greater cost increase and therefore lose competitiveness relative to the low intensity sectors. Avetisyan et al. (2011) 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 can be attributed to differences in the economic value of annual output per animal. Countries with highly productive livestock industries (high dollar of output/animal), generally have higher physical emissions intensities (emissions/animal), and consequently have much lower economic emissions intensities (emissions/dollar of output).

Golub et al. (2010) consider several climate change mitigation policy scenarios which differ by participation/exclusion of agricultural sectors and non-Annex I countries, as well as by policy instrument – carbon tax or mixed instrument. The mixed instrument is applied to non Annex I agricultural producers, by taxing their GHG emissions and then returning the cost of the tax to these producers as an output subsidy in order to offset the price-increasing aspect of the mitigation effort. In the absence of such a subsidy, the agricultural carbon tax raises the price of food, adversely affecting food consumption, especially in developing countries. The results from Golub et al. (2010) also highlight the effectiveness of forest carbon sequestration incentives in controlling emissions leakage from non-Annex I agriculture when mitigation policies are only imposed on Annex I regions.

Contributions of this study

Earlier research into livestock-based GHG emissions using the GTAP-AEZ-GHG model considered highly stylized policy scenarios. The goal of this paper is to refine the policy scenarios to better reflect ongoing policy developments and negotiations at both international and national levels. First, the mixed instrument specified in the earlier work is refined to more precisely target abatement effort. This includes the application of a subsidy based on actual emissions abated, rather than using the subsidy as a compensation mechanism for carbon tax expenses. Second, the implications of livestock sectors with large informal markets in some developing countries for the effectiveness of mitigation policies and the resulting effects of the policies on changes in food consumption are explored. Difficulties in observing and quantifying production, let alone emissions, in informal markets will limit the overall penetration of market-based mitigation policies in these regions.

Changes in regional livestock emissions, output, and food consumption and nutrition in undernourished regions are analyzed in response to these refined mitigation policy scenarios.

Methodology

Modeling framework

The paper builds on a global general equilibrium (GE) model, called GTAP-AEZ-GHG, documented in Golub et al. (2009) and further extended in Golub et al. (2010). This is a single consistent framework that links the agricultural, forestry, food processing and other sectors through land, other factor markets and international trade, and incorporates different land-types, land uses and related GHG emissions and sequestration. The model draws on a detailed non-CO_2 GHG emissions database by Rose et al. (2007). The database provides highly disaggregated emissions information and is mapped directly to countries and economic sectors (Rose and Lee, 2009). The model also incorporates mitigation cost curves for different regions and sectors based on data from the USEPA (USEPA, 2006b) by calibrating relevant parameters in the GTAP-AEZ-GHG model to these curves. [1] The forestry component of the model is calibrated to the results of the state of the art partial equilibrium global forestry model of Sohngen and Mendelsohn (2007). Forest extensification (more hectares) and intensification decisions (more carbon per hectare) are modeled separately to better isolate the land competition between agriculture and timber products.

Mitigation

The economic impacts and the effectiveness of climate policies in each sector depend on their marginal costs of abating emissions. As mentioned the marginal costs of various agricultural mitigation options in the study are drawn from the US EPA global mitigation report (USEPA 2006b). For livestock, mitigation options include feed management measures and dietary additives that can directly reduce CH_4 emissions per animal, herd management (e.g. intensive grazing) and technical measures for raising productivity which reduce CH_4 emissions per unit of output, and practices to tackle both N_2O and CH_4 emissions from manure management. Figure 3 summarizes the percentage abatement response for the livestock sectors in each region at a marginal cost of 27 $/t$CO_2$eq.

Scenarios

Table 1 summarizes the policy scenarios examined in this study. The check marks in this table indicate participation by sectors and regions in each scenario. Since non-Annex I countries are

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[1] The adjustments to the production structure and calibration procedure are described in Golub et al. (2009).

not subject to mitigation targets under the Kyoto Protocol, the impacts of a 27$/t$CO_2$eq tax combined with a forest carbon sequestration subsidy in Annex I only are modeled in scenario *A1taxF*. To provide an estimate of the total global abatement potential, a carbon tax is applied to all emitting sectors in all regions in scenario *GtaxF*. In this setting, the world allowed to take advantage of all model-based mitigation possibilities. Indeed, the greater the number of sectors and regions that the abatement policies cover, the lower the average cost per tonne of CO_2eq abated, based on any given mitigation quantity (e.g., de la Chesnaye and Weyant, 2006). However, a global emissions tax is unlikely to be politically acceptable, particularly among developing countries where near term food security and rural development objectives justifiably take priority over the economically efficient management of long run environmental issues. Moreover, it fails to consider the differing needs and mitigation responsibilities of developed and developing countries as specified under the UNFCCC. These objectives are better reflected in more complex scenarios *A1taxGF*, *GtaxFS* and *GtaxFSC.*

In scenario *A1taxGF*, sectoral GHG emissions are taxed in Annex I only, but the sequestration subsidy is introduced globally. Since non-Annex I countries are not obliged to meet their own mitigation costs under the UNFCCC, the forest carbon sequestration subsidy in non-Annex I is paid by Annex II regions (see table A1 in Appendix for definitions of Annex I, Annex II and non-Annex I regions). In *GtaxFS*, the carbon tax and sequestration subsidy are introduced in all sectors of both Annex I and non-Annex I. However, all producers in non-Annex I countries are given an output subsidy based on actual emission reduction achieved. Thus, non-Annex I producers can choose between (1) continue to emit and pay carbon tax on emissions and (2) reduce both emissions and carbon tax paid and receive output subsidy based on emissions abated (abatement subsidy). Annex II countries are assumed to foot the bill for both the output and forest carbon sequestration subsidy in non-Annex I.

To account for the reduced effectiveness of market-based mitigation policies in non-Annex I countries with large informal livestock markets, the carbon tax in scenario *GtaxFSC* is deflated by the share of total livestock sector output that goes directly to private consumption (e.g. if 20% of ruminant sector output is consumed directly in a given country, and 80% is sold to the meat processing sector, then the 27 $/tCO2eq tax is reduced to 27*(1-0.2) = 21.6 $/tCO2eq). This share provides a crude proxy for the relative importance of the informal livestock sector in each region.[2] Finally, scenario *GnAgtaxFS* excludes agriculture from GHG mitigation efforts to evaluate GHG mitigation losses and avoided reduction in food consumption.

Results

Overview of results

An overview of the changes in emissions is presented in table 2. Rows refer to the scenarios outlined in table 1. Columns refer to the sector/source of emissions. The first column reports total abatement, which is the sum of forest carbon mitigation, agricultural mitigation and abatement in all other activities combined. Changes in emissions from livestock are reported separately, given that it is the focus of this study

In scenario *A1taxF* global emissions are reduced by 3,633 MtCO_2eq. However, limiting the carbon tax and sequestration subsidy to Annex I countries alone, leads to significant carbon leakage elsewhere. Viewed as a share of Annex I abatement, the leakage of emissions into non-Annex I regions amounts to 7% = 100*(279/3912). While leakages are observed in all sectors,

[2] There are several ways to implement this in the model. In Avetisyan et al. (2011) the carbon tax in livestock sectors is reduced according to the initial share of private consumption in total output. In this study, the output share sold to private consumption is allowed to adjust in response to the incentives to reduce carbon tax burden.

they are higher in agriculture in general (25%), and especially high in livestock sectors (35%). Moreover, in the absence of climate mitigation policies in the non-Annex I region, agricultural producers expand their area, thereby increasing emissions from deforestation. If these emissions are attributed to agriculture, then the leakage of agricultural emissions increases from 25% to 55% of Annex I agricultural mitigation.

The extension of carbon policies to non-Annex I countries in scenario *GtaxF* generates a more than three-fold increase in global mitigation from 3,633 to 12,105 MtCO_2eq, and as one would expect, eliminates carbon leakage. However, non-Annex I emissions reductions come at the cost of reduced food consumption (figures 7a-c) throughout the developing world. Having established this estimate of the maximum global mitigation potential for mitigation at this particular carbon price, we turn to the question of how to design a global mitigation policy to achieve as much of this mitigation potential as possible, by eliminating emissions leakage, without compromising food security and the development of agriculture in non-Annex I countries. This is the purpose of the remaining scenarios.

In scenario *A1taxGF,* the non-Annex I forest carbon sequestration subsidy is combined with Annex I mitigation policies implemented in *A1taxF* scenario. Comparison of *A1taxGF* with *A1taxF* reveals that extension of the forest carbon subsidy to non-Annex I countries generates more than a two-fold increase in global mitigation, increasing the forestry sector's share in global mitigation from 17% to 60%. Furtherer, because the carbon subsidy raises returns to forestry in non-Annex I countries, the forestry sector bids land away from agriculture, which eliminates agricultural emissions leakage and reduces crop and livestock emissions in non-Annex I regions (figure 5). This leads to a 50% increase in agricultural mitigation from 224 to 336 MtCO_2-eq, and 86% increase in livestock sector mitigation from 106 to 192 MtCO_2eq.

These agricultural mitigation levels are still far below those achieved with the global tax scenario, *Gtax*F. However, the impacts on food consumption in scenario *A1taxGF*, are significantly lower than those experienced by developing countries under *GtaxF*.

Scenario GtaxFS explores the potential for obtaining the greater mitigation benefits of the global carbon tax, while maintaining food security by compensating non-Annex I producers for their abatement effort. The payment to non-Annex I producers is modeled as an output subsidy, paid by Annex II countries. The magnitude of the subsidy to each sector depends on abatement achieved, and is calculated as product of carbon price (27 $/tCO_2$eq) and emissions reduction by the sector. As we move from *A1taxGF* to the *GtaxFS* scenario, we see that inclusion of non-Annex I sectors and private consumption in mitigation policies increases global abatement by 46%. Agricultural abatement in non-Annex I countries expands from 71 to 795 MtCO_2eq with livestock's contribution increasing from 39 to 482 MtCO_2eq. At the same time, the contribution of Annex I agriculture is reduced from 265 to 227 MtCO_2eq, with most of the reduction in abatement coming from the livestock sectors in this region. The fact is, that even with the opportunity for carbon abatement payments, livestock sectors in the developing countries experience an output reduction as we move from *A1taxGF* to *GtaxFS.*

It is also useful to compare scenarios *GtaxFS* with the earlier *GtaxF* scenario which only differs due to the support offered by Annex II to non-Annex I in the form of forest carbon sequestration and output subsidies. Global abatement achieved in *GtaxFS* scenario is 11,454 MtCO_2eq, about 5% below 12,105 MtCO_2eq reported for the "no support" *GtaxF*. The abatement subsidy prevents sectoral output from falling as sharply in non-Annex I countries, thereby giving smaller emission reductions across all sectors. The difference is especially pronounced in livestock sectors, where the emissions reduction in the presence of the carbon abatement subsidy is 23% ((482-626)/626*100) lower, as compared to *GtaxF*.

Emission reductions observed in non-Annex I regions under the both the *GtaxF* and *GtaxFS* scenarios are likely to be overestimated due to the presence of informal markets for agricultural products, including home consumption of livestock products. Firm data on the extent of informal markets is not readily available (that is why they are informal). However, the estimated share of total sector output destined for home consumption may serve as a useful proxy. Where this is large, markets are likely to play a lesser role in the allocation of products. These home consumption shares are calculated using the GTAP data base and are reported in table A2 in Appendix. Among non-Annex I countries, the South Asia countries have the largest shares across all agricultural sectors indicating low effectiveness of market-based carbon policies. In scenario *GtaxFSC* (where "C" is added for the omission of direct consumption), the carbon tax imposed in agricultural sectors of non-Annex I is deflated by the shares reported in table A2[3]. As a consequence, the carbon tax on dairy sector emissions in India is only about 4$/t$CO_2$eq under this scenario. Exemption of home consumption of agricultural products in non-Annex I in *GtaxFSC* scenario results in 63 MtCO_2eq less abatement in livestock sectors in non-Annex I than in *GtaxFS*.

Due to concerns about food security and agricultural development in many non-Annex I countries, exemption of agricultural sectors from mitigation efforts should also be considered. Morevoer, concerns about fairness and emissions leakage (see scenario A1taxF above) may ultimately justify exclusion of agriculture in both Annex I and non-Annex I regions. This

[3] Only carbon tax on output related emissions is deflated by the direct consumption share. The deflation of carbon tax affects mostly livestock sectors because in the model most of the emissions from livestock production are tied to sector output.

situation is considered in scenario *GnAgtaxFS* representing the global sequestration subsidy, accompanied by a carbon tax on GHG emissions in all non-agricultural sectors. We also include a carbon tax on fossil fuel combustion related emissions in agriculture, but exempt non-CO2 emissions there. Thus, emissions from paddy rice production, fertilizer application, manure management and enteric fermentation are not penalized. Once again, Annex II regions are assumed to transfer money to non-Annex I producers, based on actual abatement achieved. Compared to *GtaxFSC* scenario, exemption of agriculture results in 8% ((10533-11406)/11406) reduction in global abatement. Non-Annex I livestock and other agriculture emissions are reduced because of the contraction of the agricultural sectors in the presence of forest carbon sequestration subsidy. Annex I agriculture, however, shows a small amount of emissions leakage (5 $MtCO_2eq$) due to expanded production in response to higher export demand from non-Annex I markets.

Livestock sector impacts

The economic impacts of the market-based climate policies on the livestock sector depend on both abatement opportunities, as embodied in the marginal abatement costs, as well as the emissions intensity of output, by sector and region. Note that, while the emissions contribution of the non-ruminant sector is small relative to other livestock sectors (figure 1), 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.

Figure 4 summarizes livestock emission intensities per dollar of output ($kgCO_2eq/\$$). The emission intensities of the ruminant sector are significantly higher than the emission intensities of non-ruminant production in all regions and higher than the dairy sector 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 Other Europe (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.

Changes in livestock emissions, decomposed into changes in sector output and changes in emissions per unit of output, across the various scenarios are presented in figures 6a-e. Firstly, note how the abatement mechanisms differ across the livestock sectors. The abatement opportunities in the ruminant sector are small (figure 3) and the only option available to adjust to the economic burden of the carbon tax is to scale back production. In contrast, the dairy and nonruminant sectors have greater scope to implement practices which can reduce emissions while avoiding large output reductions.

Comparison of *A1taxF* and *GtaxF* (figures 6a and 6c) scenarios reveals the implications of regional vs. global carbon policies. Under the Annex I only policy, *A1taxF*, livestock output and emissions expand in all non-Annex I regions. In contrast, the global climate policy leads to vary large reductions in livestock output in those regions and sectors with the highest emission intensities (e.g. the Rest of Southeast Asia). In Annex I, dairy and nonruminant sectors show similar emissions and output changes across the two scenarios. In Japan and Oceania, ruminant output reductions are smaller under the global policy to support demand from non-Annex I regions where ruminant sectors experience very large reductions in output.

Scenarios *A1taxF* and *A1taxGF* have very similar consequences for output and emissions in livestock sectors (figures 6a and 6b). In *A1taxF* scenario, non-Annex I livestock sectors expand their outputs (and emissions) in response to livestock output reduction in Annex I under the imposition of carbon tax (figure 6a). In *A1taxGF* scenario expansion of non-Annex I livestock sectors is slightly smaller because forests expand in the presence of the sequestration subsidy. In some regions, however, the sequestration subsidy results in a contraction in ruminant production. This is observed in Brazil, other South America countries (S_o_Amer) and Sub Saharan Africa (S_S_Africa), where ruminant production is land extensive and emissions intensive, and avoided deforestation and afforestation are cost effective abatement strategies.

It is also important to consider the role of transfer payments from Annex II to non-Annex I under the various scenarios. The *A1taxGF* scenario involves sequestration subsidies paid from the Annex II countries, and this tends to boost land rents and support agricultural prices in developing countries, relative to the case no transfer payment is made. Scenarios *GtaxFS* and *GtaxF* differ due to the transfer from Annex II to non-Annex I producers. This includes forest carbon sequestration subsidy as well as output subsidy to non-Annex I producers to support their abatement efforts. In general, the subsidy results in smaller livestock output reductions in non-Annex I (figure 6d), which is the purpose of the subsidy (e.g. dairy output reduction in Brazil is 9% in *GtaxF* and 4% in *GtaxFS* scenarious). However, this mechanism does not work very well in sectors where abatement opportunities are very small and emission intensities are large. As an example, ruminant producers in Rest of Southeast Asia experience a 43% output reduction under *GtaxF* scenario and a 30% reduction under *GtaxFS*. The latter is smaller, but still represents a very large reduction in output.

Not surprisingly, the carbon policy may not reach many producers in non-Annex I countries because of the presence of informal markets. This is investigated in scenario *GtaxFSC* (figure 6e), where carbon tax is deflated by the shares of output sold directly to private households (table A2). In *GtaxFSC* both emission and output reductions are smaller than in *GtaxFS* in all livestock sectors. Presence of large informal markets reduces both emission abatement and output reductions in dairy sector of Sub Saharan Africa by 8%, in ruminant sector of Rest of Southeast Asia and in dairy sector of India by 7%.

Food security

As noted previously, one of the biggest concerns with a climate policy that embraces low cost abatement opportunities in agriculture is the potential impact on food availability, prices, consumption and hence nutrition. Figures 7a-b explore this issue for the six alternative scenarios, focusing on per capita caloric intake as well as protein consumption. From these results, it is clear that the global carbon tax (*GtaxF*) could have severe food security implications, with reductions in caloric intake of 7 – 8% in South America and about 5% in China and Sub-Saharan Africa (SSA). Reductions in protein intake are even larger. Fortunately, these effects can be sharply mitigated, and even reversed in some regions, as we change the policy implementation. Food security actually improves in Sub Saharan Africa and most of South America once abatement and sequestration subsidies are provided by Annex II regions. The region that benefits least from the Annex II carbon payments is the Middle East and North Africa. Here, fewer forest sequestration and agricultural abatement opportunities translate into smaller payments and lesser differences across this range of scenarios.

Conclusions and future research

Summary

While recent research has shed light on the cost effective contribution that agriculture can make to global GHG mitigation, there is still much to be learnt about the policy options available to exploit this potential. This study has shown that the design and coverage of mitigation policy options, both by region and by sector, matter a great deal in terms of effectiveness, but also in terms of their impacts on agricultural production and food security.

Unsurprisingly, direct tradeoffs between mitigation and food security objectives were observed, particularly where a carbon tax is applied to sectors with high emission intensities and limited abatement potential (*GtaxF*). Adverse food security impacts are particularly acute in the ruminant sectors of developing regions, where undernourishment is a problem. However, the potential for informal agricultural markets in developing countries to reduce the effectiveness of market-based mitigation instruments means that these impacts, and the potential size of non-Annex I agricultural abatement, are likely to be exaggerated.

Alternative policy combinations were shown to improve food security outcomes, but were less effective at mitigating agricultural emissions. For example, exempting non-Annex I regions from all carbon policies (*A1taxF*) markedly improves agricultural production and consumption outcomes in these regions. However, agricultural mitigation in this scenario is only around 20% of that achieved under global carbon taxation. Part of this reduction stems from a 25% leakage of emissions mitigated by Annex I producers into non-Annex I regions. The extension of the forest carbon sequestration subsidy to all regions, while still exempting Annex I producers from a carbon tax (*A1taxGF*), was shown to eliminate this leakage and boost agricultural mitigation to 33% of that achieved under the global taxation scenario. Indeed, the efficacy with which forest carbon sequestration incentives can contain agricultural emissions leakage is one of the more striking findings of this study.

Of all the policy scenarios assessed, the Annex I carbon tax combined with the global forest carbon subsidy (*A1taxGF*), appears to strike the best balance between agricultural mitigation and food security objectives. The policy also aligns well with the differentiated regional mitigation responsibilities specified in the UNFCCC, and acknowledges the large financial resources that being mobilized under the United Nations program for reducing emissions from deforestation and forest degradation in developing countries (UN-REDD).

Future research

The use of an abatement subsidy instead of a carbon tax, particularly in non-Annex I regions, could also be used to reconcile mitigation and food security objectives. This possibility was explored in this study by using a blend of tax and subsidy incentives (*GtaxFS*). However, further work is needed to balance these incentives to ameliorate the negative socio-economic and food security impacts of the carbon tax in non-Annex I regions.

The presented research, assessing mitigation policies for livestock-based GHG emissions using the GTAP-AEZ-GHG model, is limited in several important ways. Specifically, (1) the model does not adequately reflect the potential for livestock intensification in response to GHG mitigation policies; (2) the dairy meat is combined with non-dairy meat within GTAP "ruminants" sector, while the two have fundamentally different emissions intensities and abatement possibilities; (3) the ruminant and non ruminant sectors represent an aggregate of different animal species – each with different emissions intensities and abatement possibilities.

A version of GTAP-AEZ-GHG that addresses these limitations is now under construction.

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Table 1 Mitigation policy scenarios

Scenario	Forest carbon seq. subsidy		Carbon tax in agricultural sectors		Carbon tax in non-ag. sectors		Output subsidy based on actual abatement	Home consumption of agricultural products is exempt from carbon tax
	Annex I	Non-Annex I	Annex I	Non-Annex I	Annex I	Non-Annex I	Non-Annex I	Non-Annex I
A1taxF	✓	-	✓	-	✓	-	-	-
GtaxF	✓	✓	✓	✓	✓	✓	-	-
A1taxGF	✓	✓	✓	-	✓	-	-	-
GtaxFS	✓	✓	✓	✓	✓	✓	✓	-
GtaxFSC	✓	✓	✓	✓	✓	✓	✓	✓
GnAgtaxFS	✓	✓	-	-	✓	✓	✓	-

Table 2 Changes in GHG emissions under different policy assumptions, $MtCO_2eq$ (negative numbers denote mitigation)

	Total			Forest carbon sequestration			Agricultural sectors			Livestock sectors (within agriculture)			Other sectors and private consumption		
Scenario	Global	Annex I	Non-Annex I	Global	Annex I	Non-Annex I	Global	Annex I	Non-Annex I	Global	Annex I	Non-Annex I	Global	Annex I	Non-Annex I
A1taxF	-3633	-3912	279	-631	-722	91	-224	-298	74	-106	-163	57	-2777	-2891	114
GtaxF	-12105	-3720	-8385	-4902	-686	-4216	-1204	-230	-974	-745	-119	-626	-5999	-2804	-3195
A1taxGF	-7845	-3883	-3962	-4736	-694	-4042	-336	-265	-71	-192	-153	-39	-2809	-2924	115
GtaxFS	-11454	-3748	-7706	-4778	-681	-4097	-1022	-227	-795	-605	-123	-482	-5654	-2840	-2814
GtaxFSC	-11388	-3755	-7633	-4772	-682	-4090	-963	-233	-730	-561	-129	-419	-5653	-2840	-2813
GnAgtaxFS	-10533	-3512	-7021	-4749	-688	-4061	-152	5	-157	-106	-7	-99	-5632	-2829	-2803

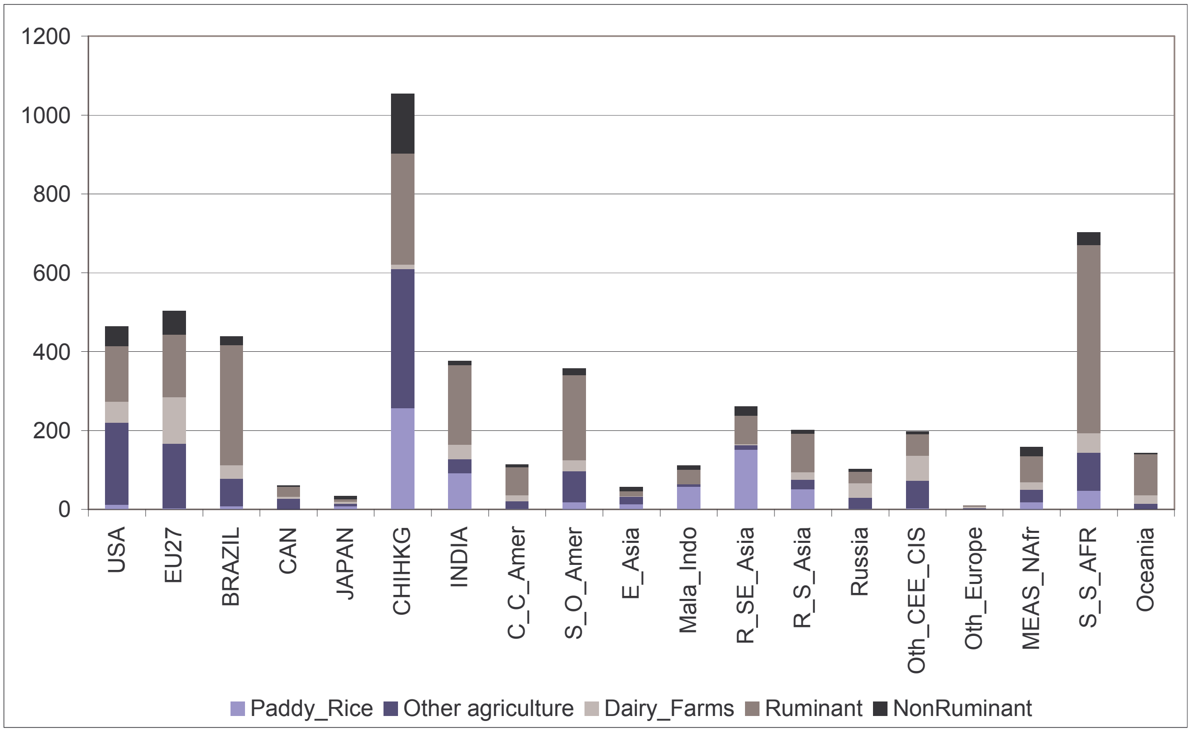

Figure 1 Non-CO_2 GHG emissions by agricultural sector and region, $MtCO_2eq$

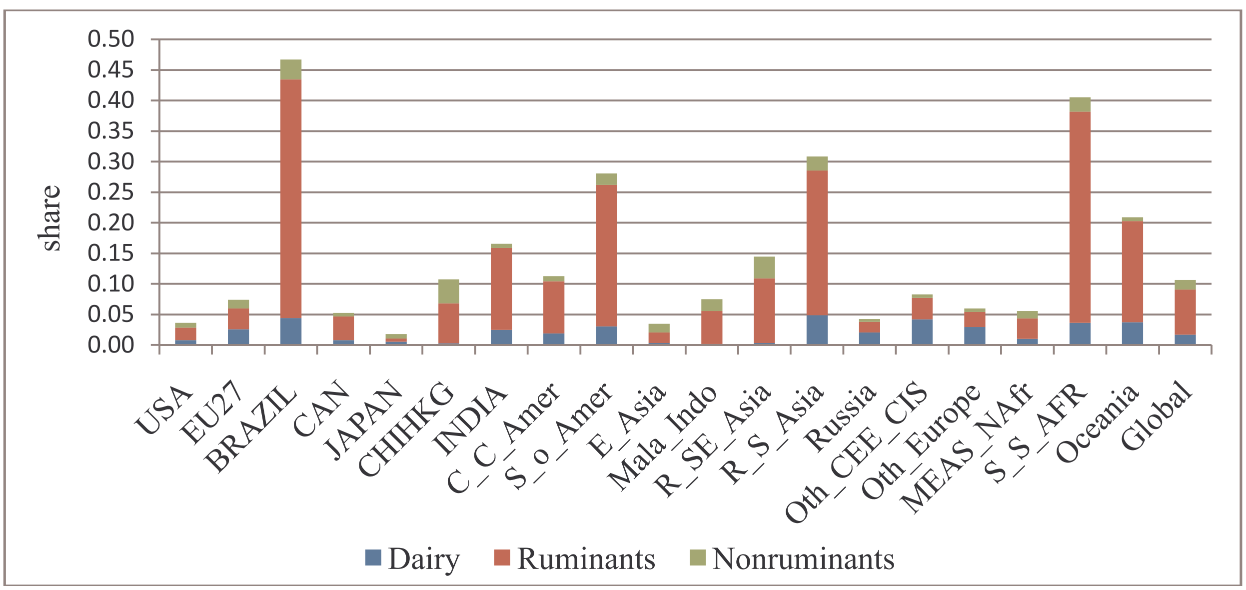

Figure 2 Livestock GHG emissions as share of total emissions (agricultural, industrial and private consumption, excluding terrestrial carbon flaxes)

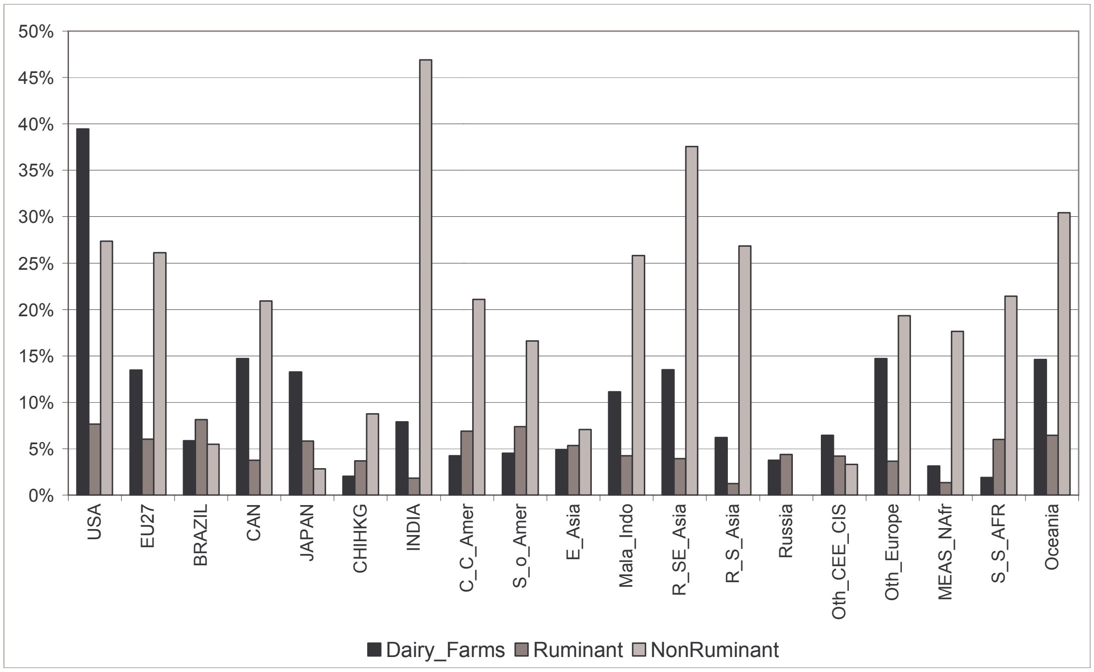

Figure 3 Partial equilibrium % abatement responses for the livestock sectors, at 27 $/tCO_2$-eq

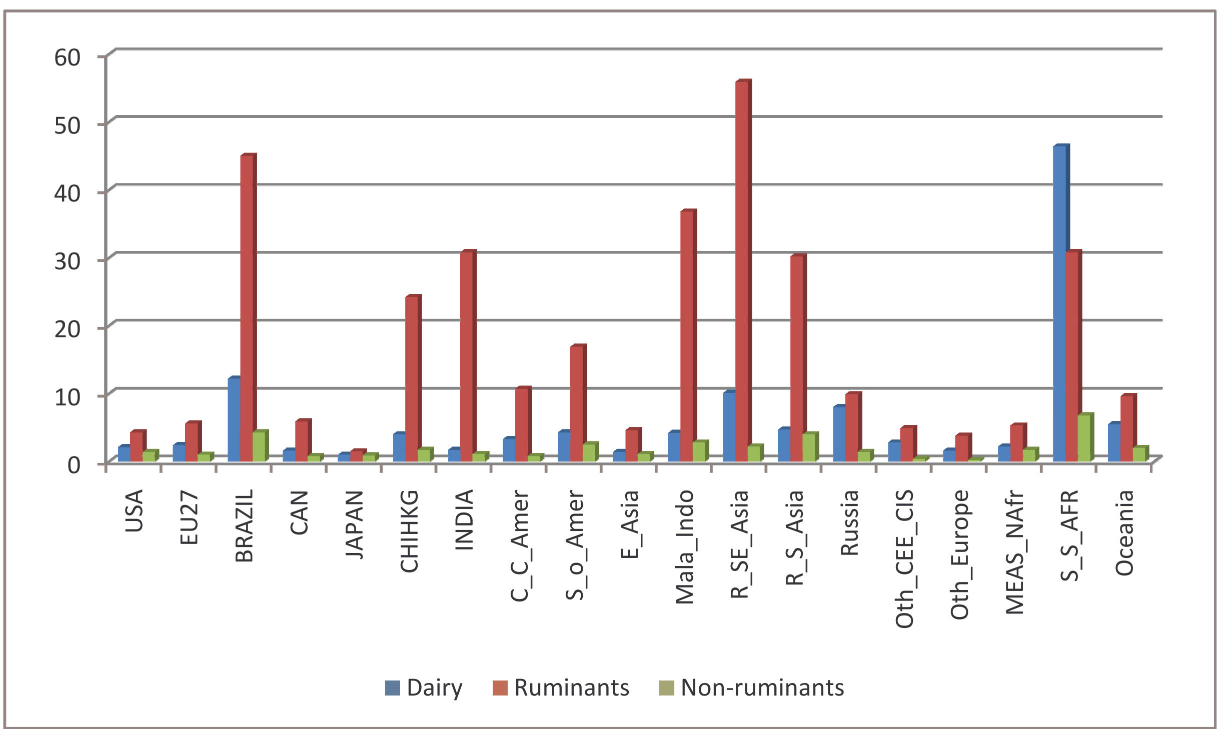

Figure 4 Emission intensity of output when all livestock sector non-CO_2 emissions, including emissions related to factors and intermediate input use, are tied to output (kgCO_2eq/$ of output)

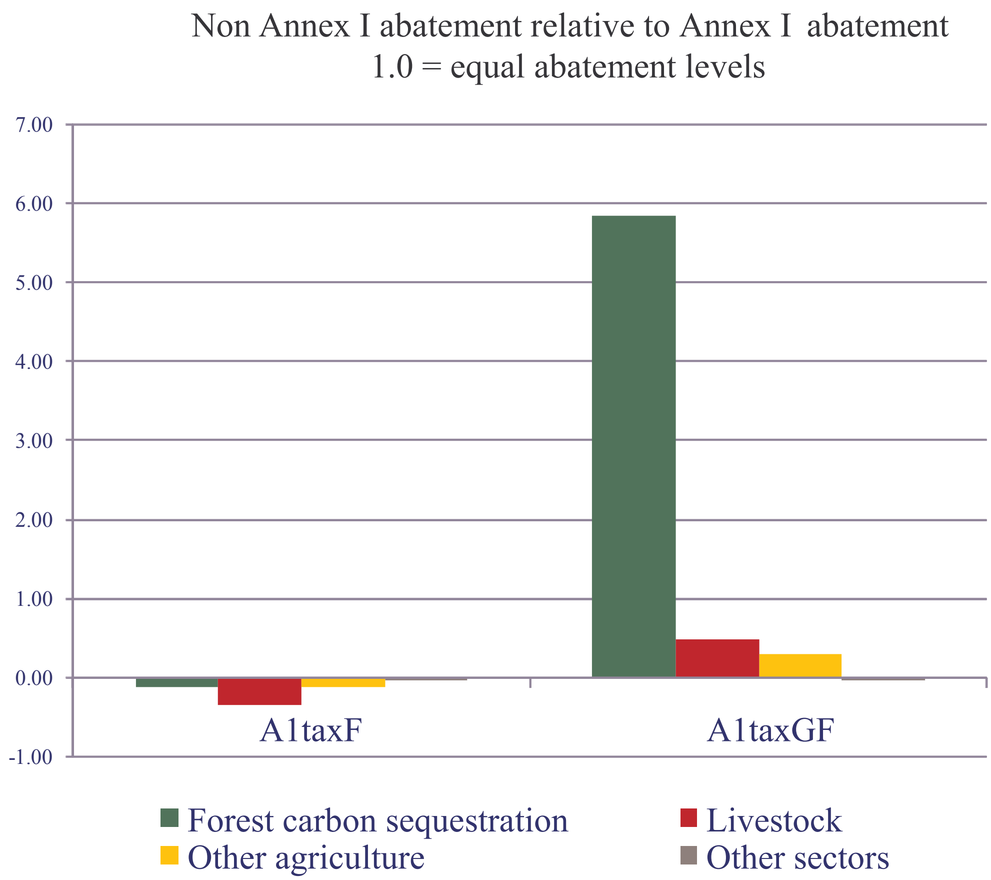

Figure 5 Carbon leakage

Note: Non-Annex I abatement relative to Annex I abatement. 1 indicates equal abatement levels.

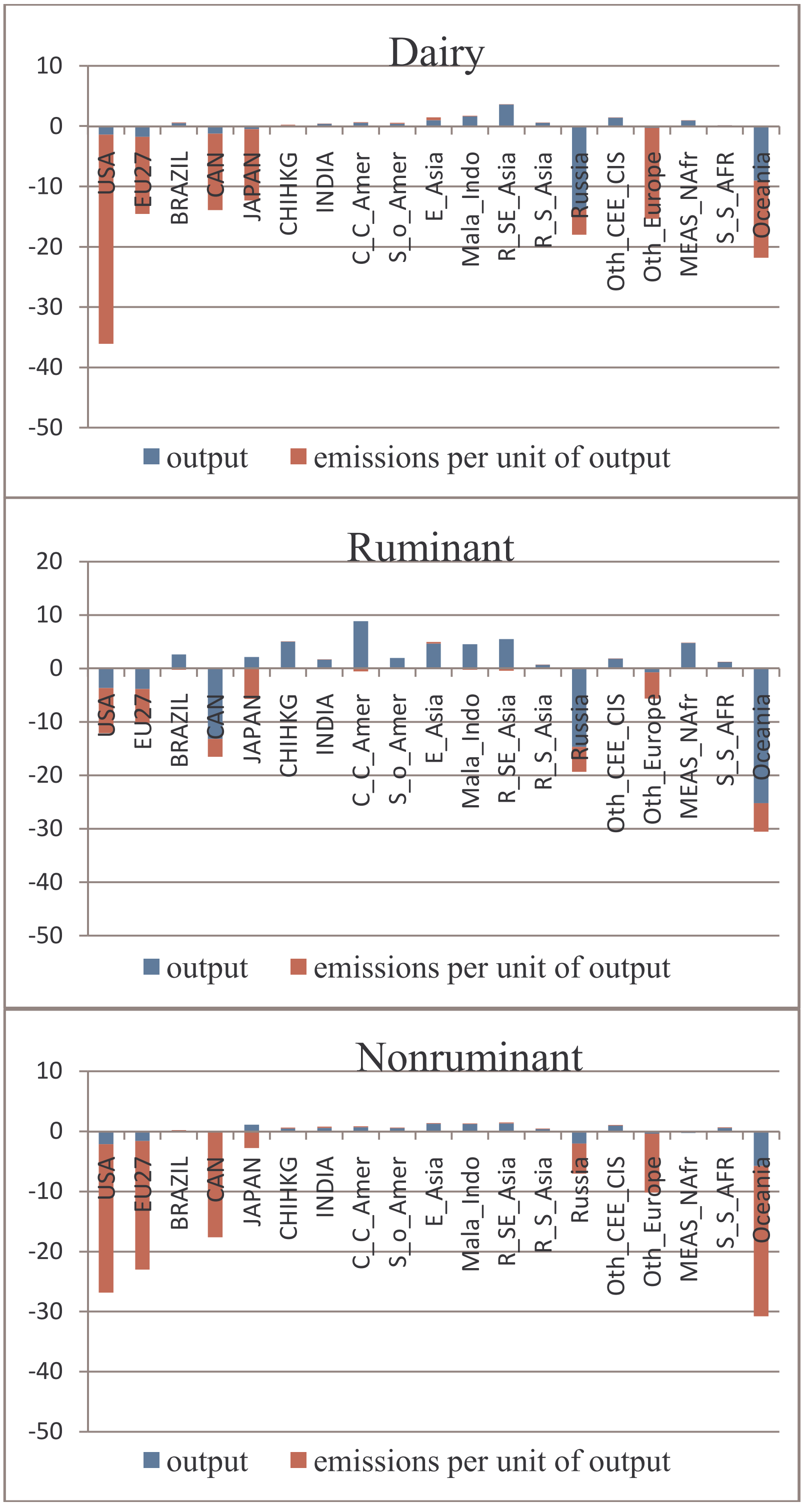

Figure 6a Livestock emission reductions in A1taxF scenario, decomposed into output and emissions per unit of output changes, %

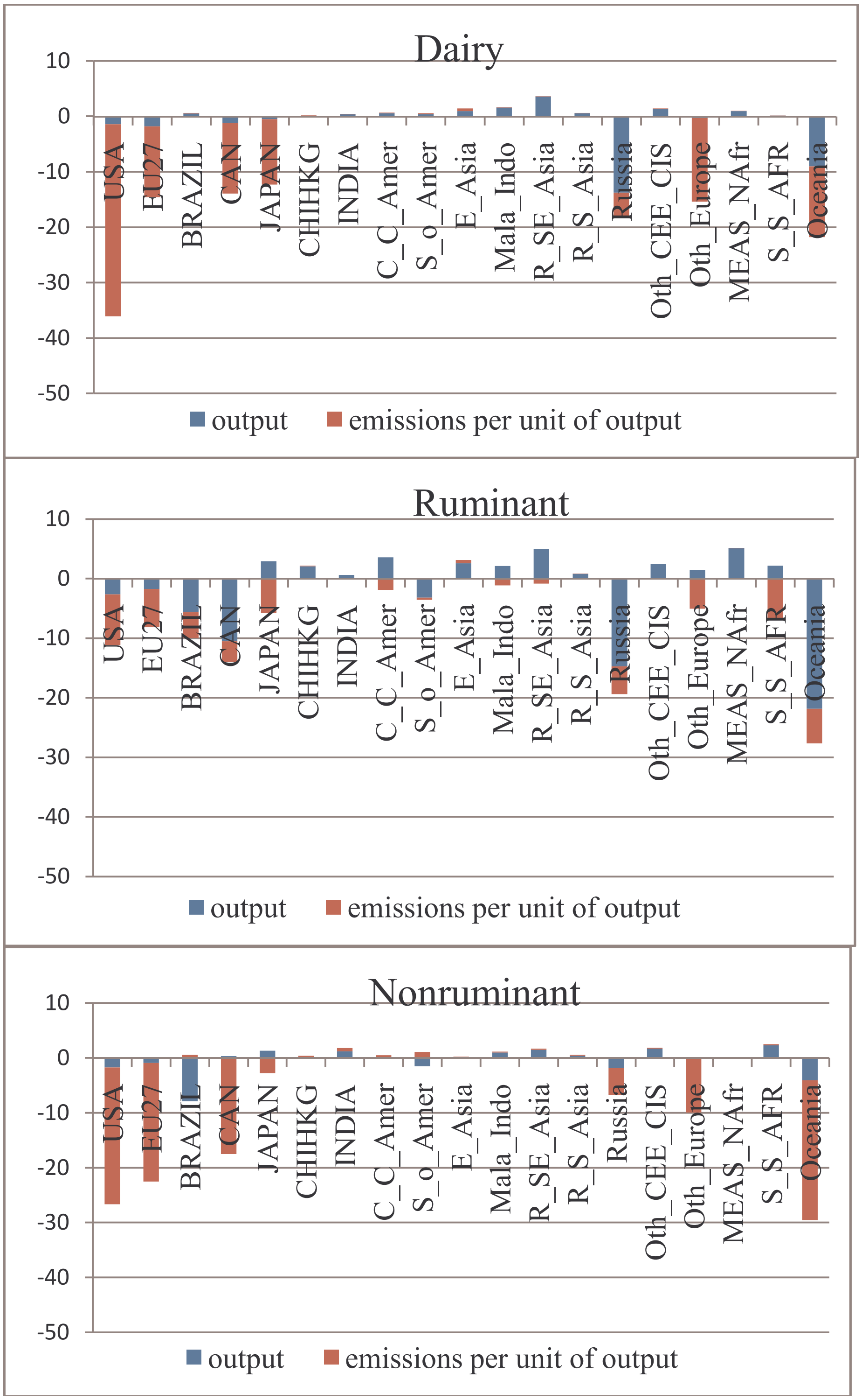

Figure 6b Livestock emission reductions in *A1taxGF* scenario, decomposed into output and emissions per unit of output changes, %

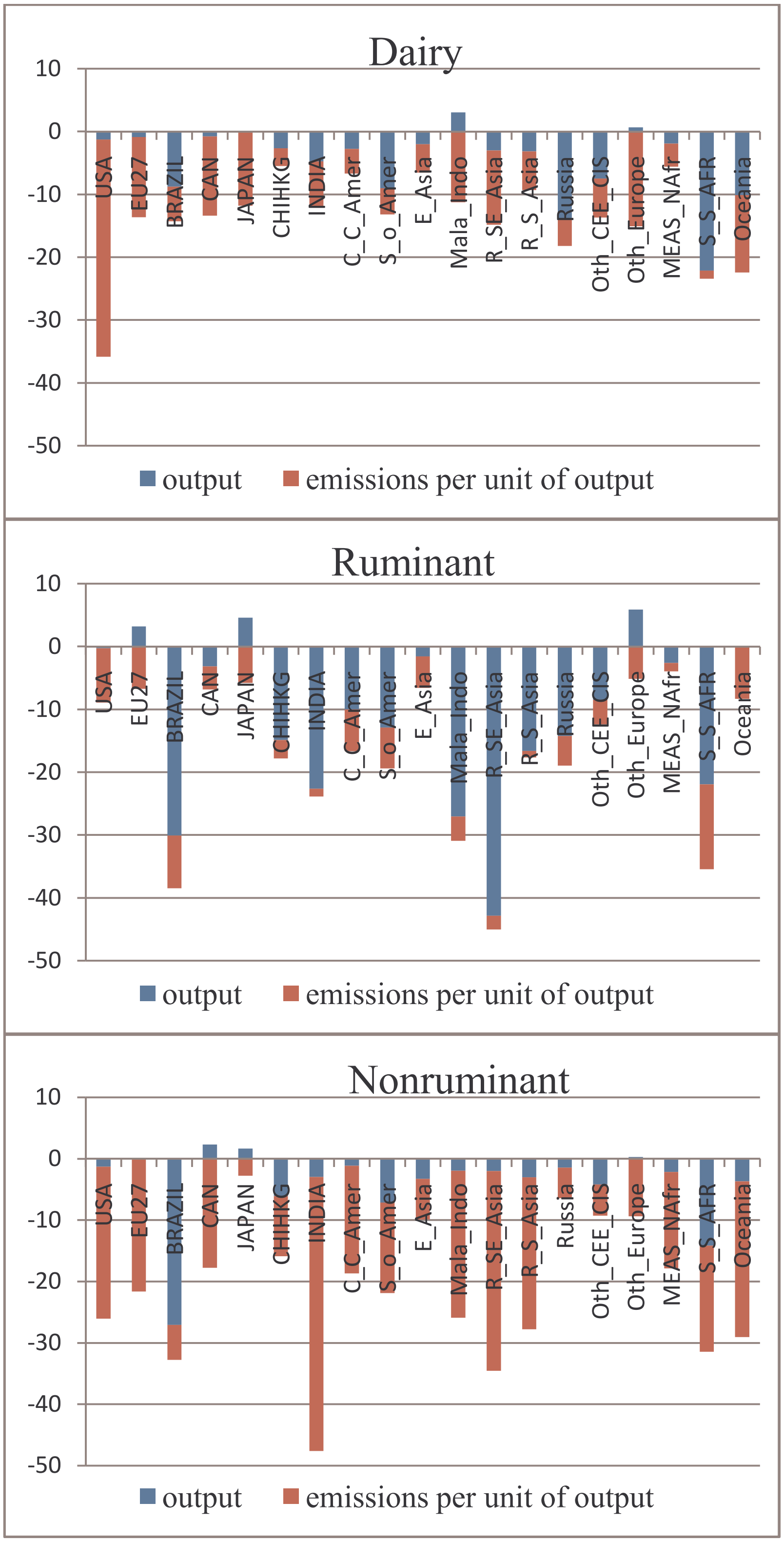

Figure 6c Livestock emission reductions in *GtaxF* scenario, decomposed into output and emissions per unit of output changes, %

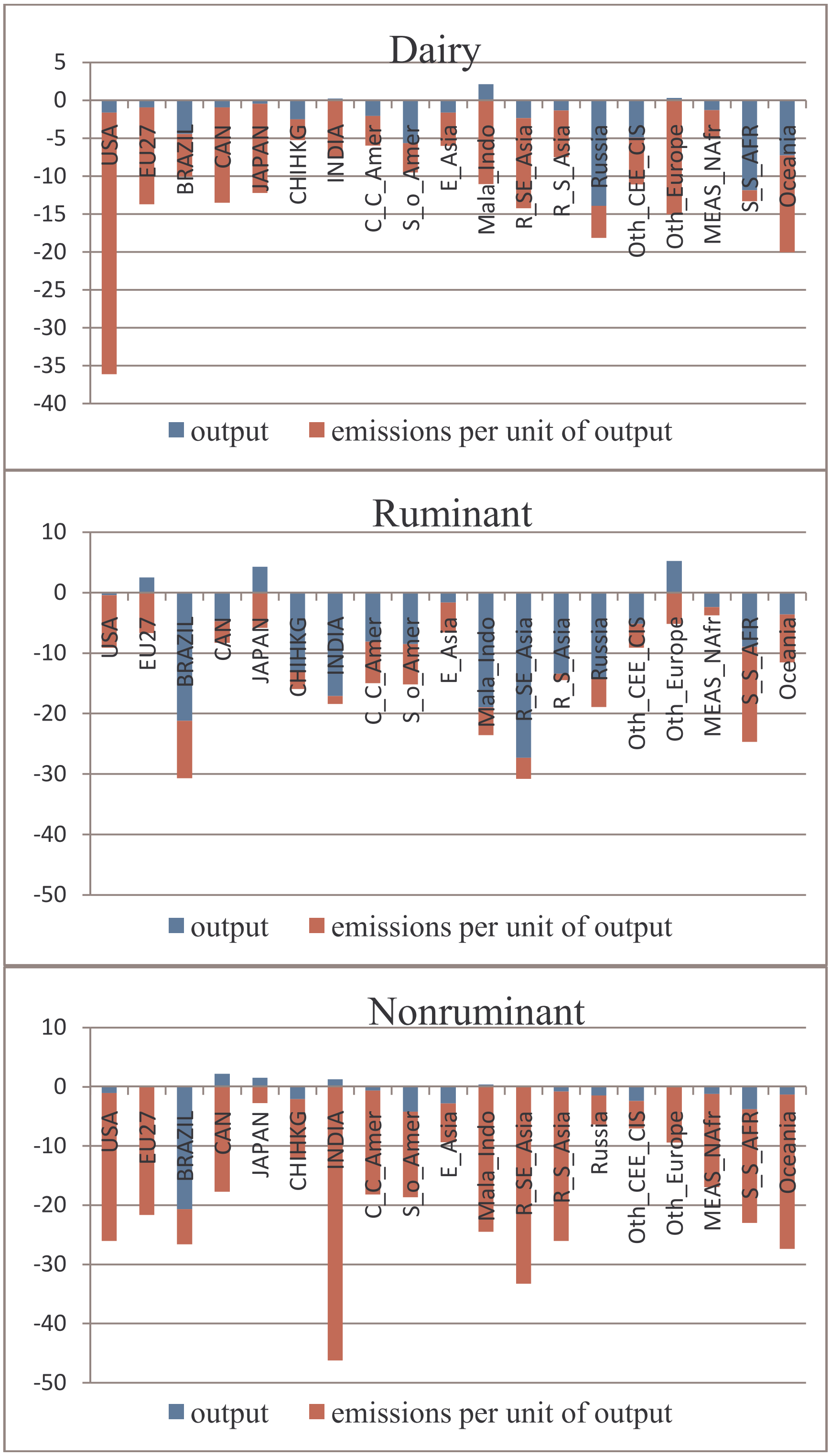

Figure 6d Livestock emission reductions in *GtaxFS* scenario, decomposed into output and emissions per unit of output changes, %

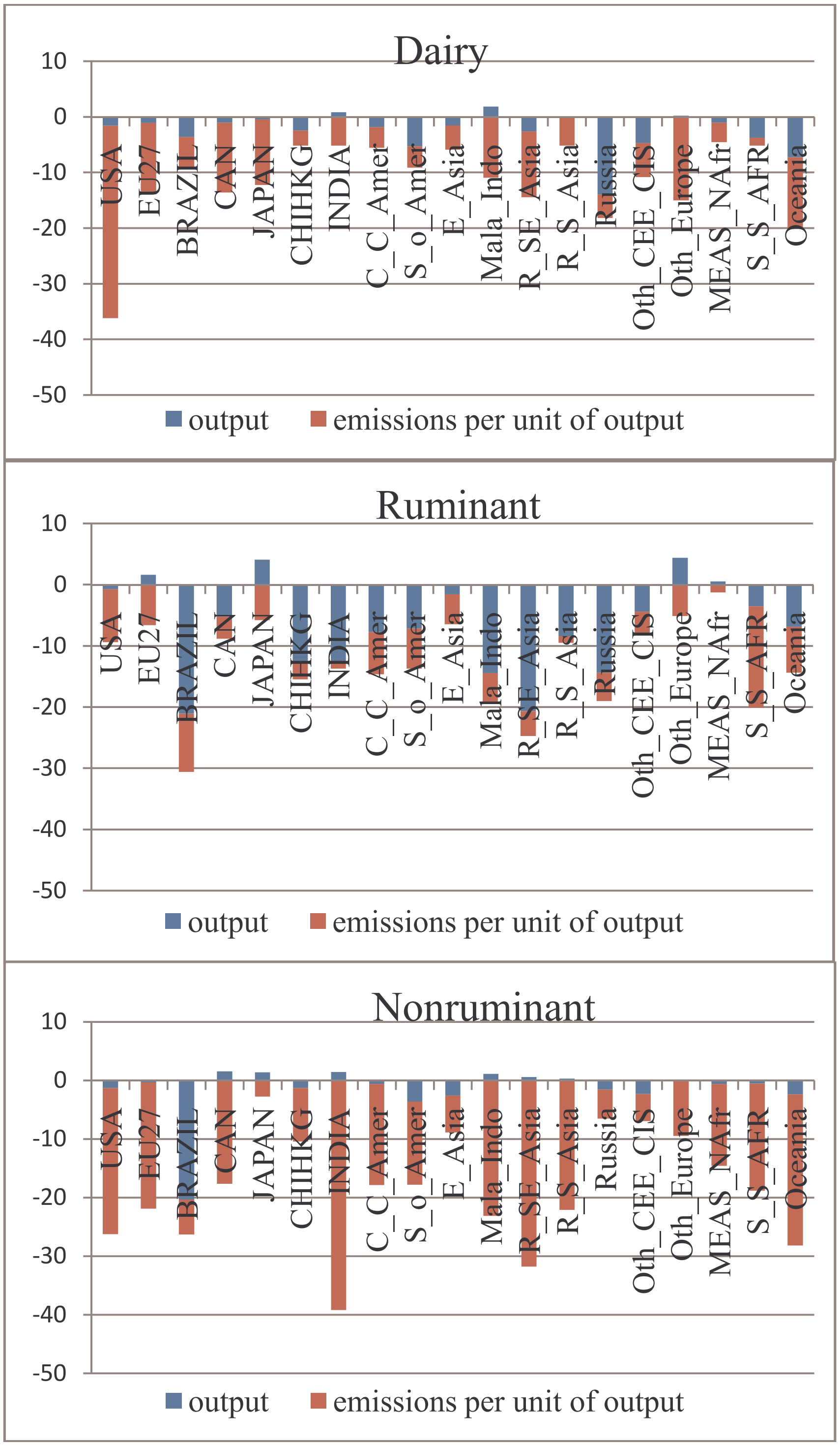

Figure 6e Livestock emission reductions in *GtaxFSC* scenario, decomposed into output and emissions per output changes, %

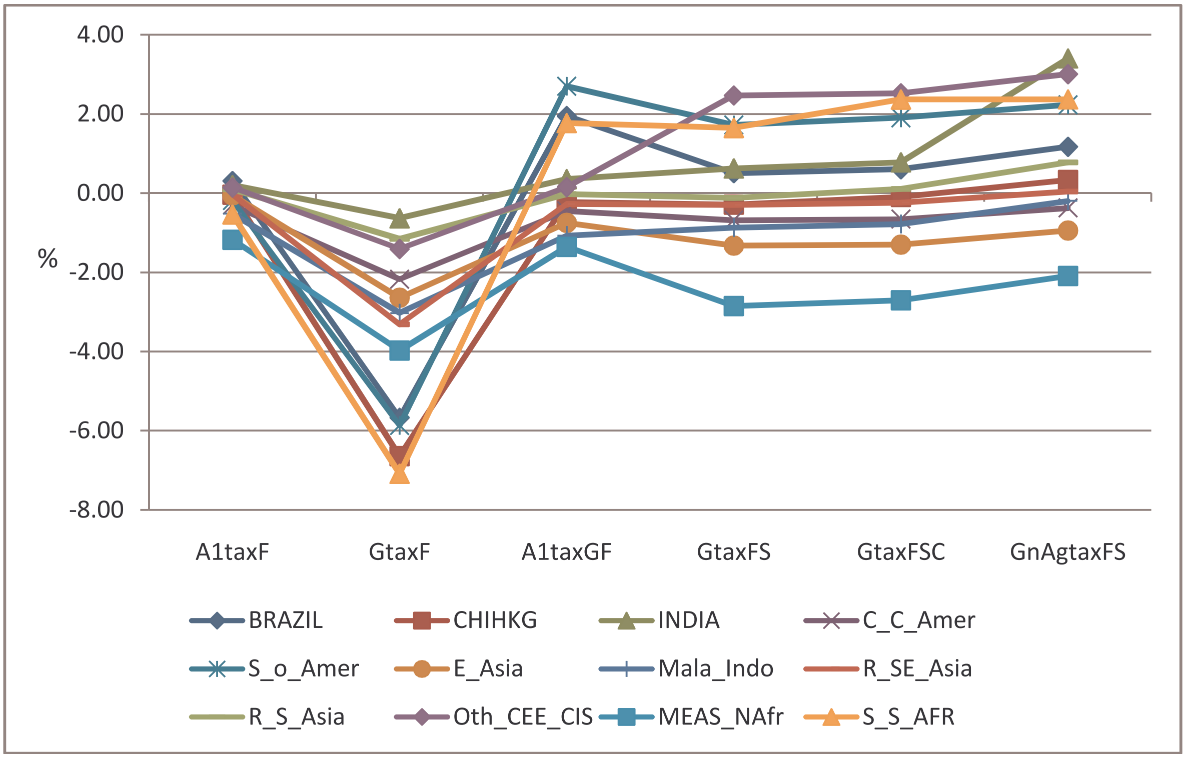

Figure 7a Change in per capita consumption quantity index in non-Annex I

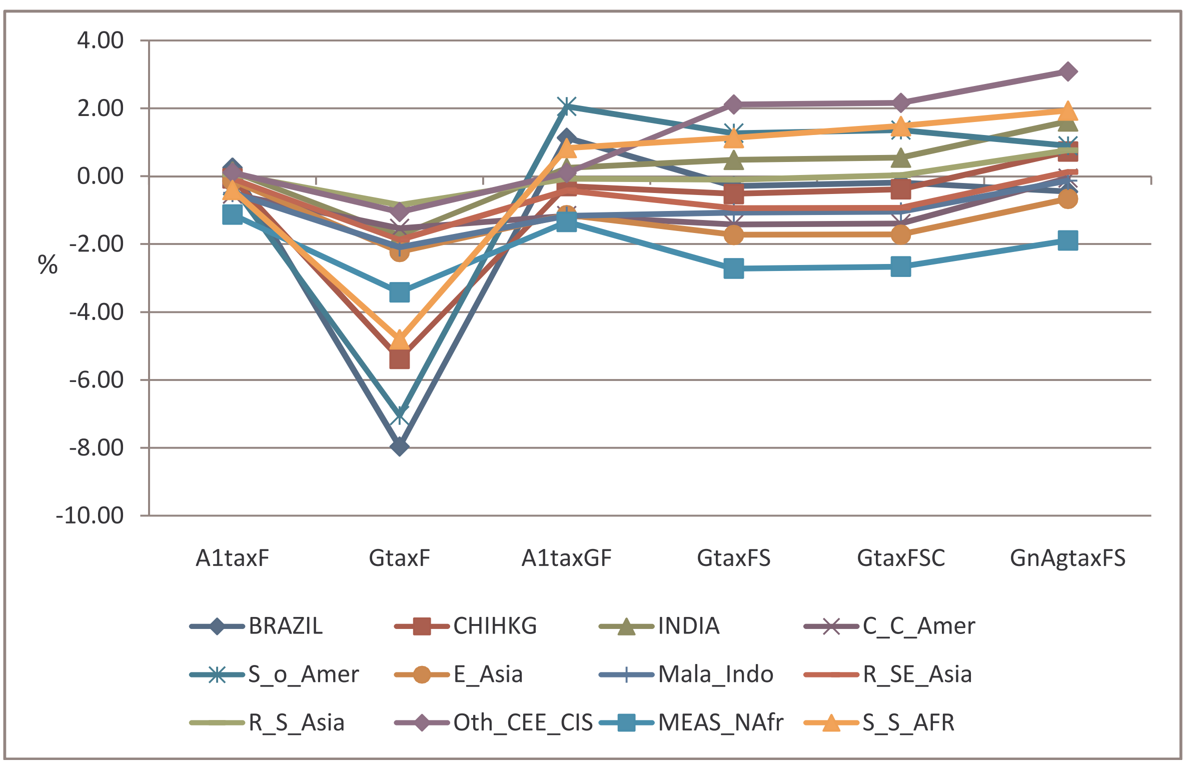

Figure 7b Change in caloric intake in non-Annex I, % change in Kcal/person

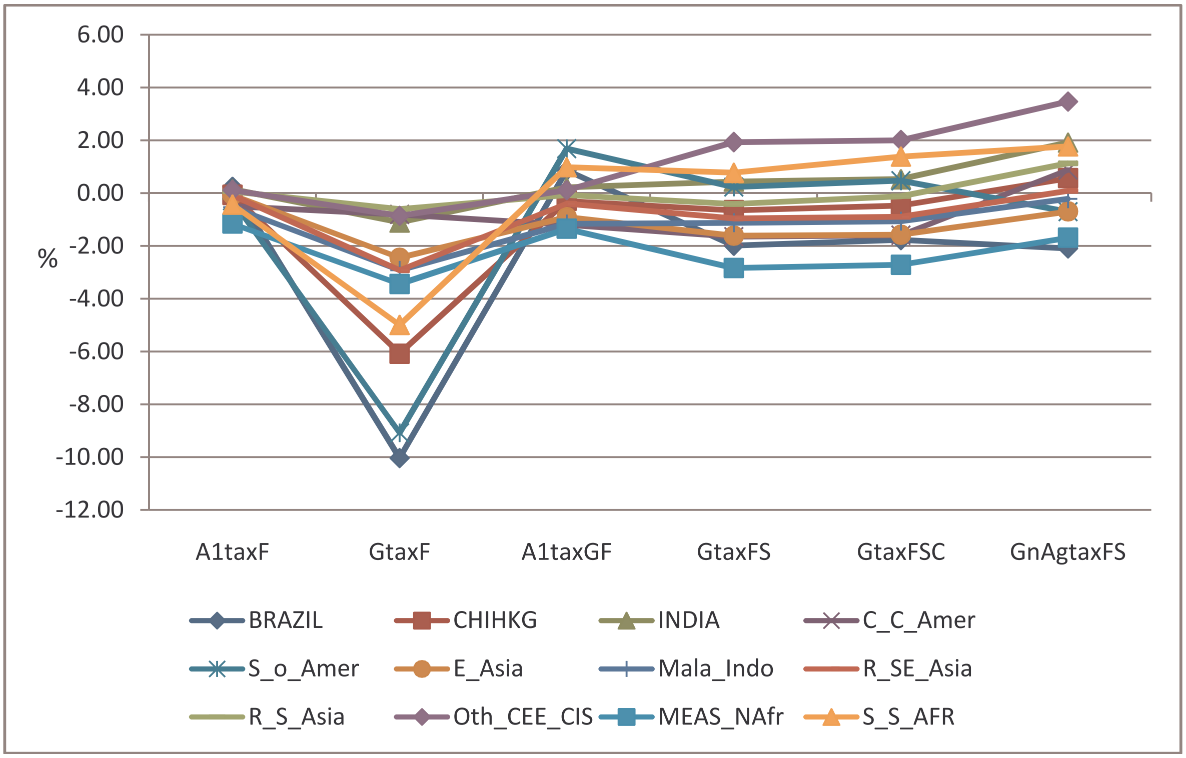

Figure 7c Change in protein consumption in non-Annex I, % change in grams of protein/person

Appendix

Table A1 Aggregation of GTAP regions

Code	Region in the model	GTAP regions	Group
USA	United States	United States	Annex I and II
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
BRAZIL	Brazil	Brazil	Non-Annex I
CAN	Canada	Canada	Annex I and II
JAPAN	Japan	Japan	Annex I and II
CHIHKG	China, Hong Kong	China, Hong Kong	Non-Annex I
INDIA	India	India	Non-Annex I
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
S_O_Amer	South and Other Americas	Colombia, Peru, Venezuela, Rest of Andean Pact, Argentina, Chile, Uruguay, Rest of South America	Non-Annex I
E_Asia	East Asia	Korea, Taiwan, Rest of East Asia	Non-Annex I
Mala_Indo	Malaysia and Indonesia	Indonesia, Malaysia	Non-Annex I
R_SE_Asia	Rest of South East Asia	Philippines, Singapore, Thailand, Viet Nam, Rest of Southeast Asia	Non-Annex I
R_S_Asia	Rest of South Asia	Bangladesh, Sri Lanka, Rest of South Asia	Non-Annex I
RUSSIA	Russia	Russian Federation	Annex I
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
Oth_Europe	Rest of European Countries	Switzerland, Rest of EFTA	Annex I and II
MEAS_NAfr	Middle East and North Africa	Rest of Middle East, Morocco, Tunisia, Rest of 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
Oceania	Oceania	Australia, New Zealand, Rest of Oceania	Annex I and II

Table A2 Share of agricultural output sold to private households in non-Annex I regions

	BRAZIL	CHIHKG	INDIA	C_C_Amer	S_o_Amer	E_Asia	Mala_Indo	R_SE_Asia	R_S_Asia	Oth_CEE_CIS	MEAS_NAfr	S_S_AFR
Paddy_Rice	0.00	0.07	0.44	0.01	0.08	0.00	0.01	0.03	0.24	0.37	0.91	0.04
Wheat	0.10	0.03	0.77	0.07	0.09	0.52	0.00	0.02	0.68	0.07	0.65	0.09
CrGrains	0.01	0.03	0.88	0.47	0.11	0.21	0.31	0.07	0.85	0.02	0.55	0.69
Oilseeds	0.01	0.04	0.56	0.02	0.02	0.30	0.23	0.12	0.52	0.15	0.39	0.32
Sugar_Crop	0.00	0.31	0.51	0.27	0.04	0.06	0.07	0.03	0.38	0.04	0.00	0.18
OthAgri	0.30	0.48	0.56	0.30	0.41	0.68	0.37	0.33	0.61	0.29	0.64	0.44
Dairy_Farms	0.20	0.13	0.85	0.20	0.10	0.12	0.02	0.02	0.66	0.10	0.15	0.59
Ruminant	0.02	0.06	0.31	0.05	0.25	0.04	0.32	0.33	0.42	0.21	0.38	0.47
NonRuminant	0.14	0.59	0.68	0.12	0.20	0.26	0.34	0.30	0.62	0.06	0.54	0.44