Modeling emission reductions and forest carbon sequestration in GTAP:

Data Base and model improvements

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Selected Paper prepared for presentation at the 2017 Agricultural & Applied Economics Association Annual Meeting, Chicago, IL, July 30- August 1

DRAFT

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1. Introduction

Forest carbon sequestration (FCS) is considered a cost-effective method to mitigate climate change[1-6]. This has attracted the attention of policy makers and academics in the last quarter century. Thus, economic modeling focused on FCS supply has evolved at global and local scales [7-10]. Many of these studies used dynamic forestry models (e.g. Suttles, et al. [11], Rokityanskiy, et al. [12], Hartwick, et al. [13]) , benefit-cost analysis (e.g. Moulton and Richards [14]. Parks and Hardie [15]), and other environmental evaluation techniques [2], or are derived based on results from biophysical models such as general circulation models (e.g., Smith, et al. [16]). Several of these models consider in their framework forest management alternatives, forest types, international trade effects and greenhouse mitigation potential. Nevertheless, only few efforts have incorporated the FCS supply in a global economic modeling framework [17].

Most of the global economic models that have attempted to incorporate forest supply are based on partial equilibrium analysis [3,18,19]. In recent decades, Computable General Equilibrium (CGE) models have been increasingly used for the evaluation of policy analysis including climate change mitigation[17,20]. FCS is generally model as a complex dynamic process. Forest management requires investments in early period with expectations on future benefits (e.g., timber revenues, carbon sequestration)[21].

One of the first attempts to incorporate FCS in a global CGE framework was made by Ahammed and Mi (2007). They used the Global Trade and Environmental model (GTEM), a recursive dynamic CGE. Forest trees were classified by age group, allowing forest to move from one age class to another over time. This allows to account in differences in sequestration respect to the maturity of the forest. However, the model was unable to capture the potential for changes in the optimal rotation length. Sands and Kim (2007) used a recursive CGE model which accounts for distinction among forest age classes. This model also captures the carbon policy impacts on optimal rotations. Nevertheless, they assumed that forests are harvested from specific age groups and ignores the impacts of near-term climate policies. Thus, accounting for FCS as a complex dynamic behavior can become troublesome due to the difficulty in capturing the intertemporal forest management and the requirement for substantial computation resources[21]. In addition, it is difficult to isolate the effect of FCS on the global economy under a dynamic recursive CGE framework due to the interaction of many intertemporal variables. Thus, if the main interest is related to the general equilibrium effects of the sequestration policies, a comparative static analysis seems to be appropriate.

One of the first attempts to apply FCS into a static CGE framework was made by Hertel, et al. [22]. They introduced reduced-form marginal abatement cost (MAC) functions for forestry sequestration from a partial equilibrium model into a static CGE framework. This model considers near term mitigation alternatives and decomposes the sequestration response into intensive (management practices) and extensive (forest cover) margins. However, the MAC curves vary depending on the time horizon.

Posteriorly, Golub, et al. [10] developed GTAP-AEZ-GHG. This model is an extension of the Global Trade Analysis (GTAP) model, a well-known CGE model, and represents the global economy in 2001. It incorporated the so-called Kyoto GHG emissions (CO_2 and non-CO_2), and FCS modeling. Its database also introduces emissions on output and land. These emissions are assigned monetary values and linked to their emission sources. Regional annual carbon sequestration by forest is also introduced into the database. These values for each region of the world are derived originally from the Global

Timber Model (GTM) developed by Sohngen and Mendelsohn [23] which is a partial equilibrium, dynamic optimization model. These are then linked to a 'forestry land-biomass' composition nest. This nest associates forest land and self-used forest biomass. The model implements taxes on emissions for all the production and consumption sectors of the economy including transportation, services, manufacture and agriculture. The FCS subsidy is awarded as subsidy to the 'forestry land-biomass' nest.

The first version of the GTAP-AEZ-GHG aggregated the world in 3 regions: USA, China and the Rest of the World. , Golub, et al. [10] used this model to evaluate the GHG mitigation potential of land-based activities in agriculture and forestry at the global scale. FCS was found to be the dominant strategy for GHG emission reduction. Posteriorly, Golub, et al. [6] disaggregated the database into the standard 19 GTAP regions and divided the ruminant livestock sector in two: dairy farm and ruminant meat sector. Using this new version, Golub, et al. [6] analyzed the impact of policies that target GHG emission reduction on livestock sectors. This study implemented a FCS subsidy and carbon tax on many economic sectors including agriculture. Their findings suggest that a global FCS subsidy helps to control emission leakage when a carbon tax is imposed only to developed regions.

In an effort to improve and extend the literature, we used the principles on FCS and emissions implemented in the GTAP-AEZ-GHG model into the GTAP-BIO model (a well-known GTAP version that includes biofuels). We named our new static CGE model GTAP-BIO-FCS. Combining the features of both models, updating their database and improving their methodology, our new consistent model is suitable for climate change policy analysis of mitigation methods such as carbon tax, FCS and biofuels. In addition, we developed two applications for the model: The GTAP View (for checking consistency) and the Welfare decomposition (to analyze sources of welfare variation).

In this study, we first describe the new features for the model, data base. Then, we present the simulation results for a carbon reduction policy. The policy is designed to reduce GHG emissions by 50% globally (i.e. in order to achieve the mitigation target of the IPCC RCP4.5 scenario). We implemented a combination of a carbon tax and a forest sequestration subsidy under two alternative scenarios for the impacts of climate change on crop yields. The first scenario ignores the fact that climate change will affect crop yields. The second one takes into account impacts of climate change on crop yields. Fig. 1 represents the overall framework of the mechanism of implementing the taxes, FCS subsidies and the crop yield shocks. We also implemented these two scenarios in GTAP-AEZ-GHG model to verify consistency in our simulation results.

2. Modeling framework

2.1 *The GTAP-BIO model*

The standard GTAP model is a multi-sectorial CGE model which associates consumption, production, and trade in a multi-regional framework assuming perfect competition and constant returns to scale[24]. GTAO-BIO is a revised version of the GTAP model incorporates biofuels into its modeling framework and has been extensively used to evaluate the economic and environmental consequences of energy and biofuel policies. Its latest modification was developed by Taheripour and Tyner [25] (e.g. CARB1402). This version represents the global economy in 2004 and includes first-generation biofuels as substitutes for petroleum products, two types of biofuel by-products (dried distilled grains with solubles [DDGS] and vegetable oil by-products [VOBP]) and differentiates land conversion between forest and pasture to cropland. The GTAP-BIO database divides the world into 19 regions and classifies economic activities into 43 industries (agricultural, manufacture and service sectors), covers 48 tradable commodities (including biofuel byproducts) and has 18 endowments (18 AEZs, capital, skilled and unskilled labor and natural resources. This model has no technical issues and calculates welfare. Nevertheless, this model currently does not have non-CO_2 emissions and does not incorporate FCS.

2.2 The GTAP-BIO-FCS model: Overview

We use the GTAP-BIO version CARB1402 to develop our new comparative static CGE model. We improve the principles of the GTAP-GHG-AEZ model and incorporate them into the GTAP-BIO. Thus, the GTAP-BIO-FCS model has the following modifications and improvements

(1) It includes CO_2 and non-CO_2 GHG emissions as well as annual forest carbon stocks. We also incorporate both biofuel and FCS in our modeling framework.

(2) We split forest carbon sequestration into stock associated with forest land and stock associated with managing biomass used by forest industry. This permits us to implement sequestration incentives directly on these inputs. This also ensures the correct capture of subsidies and balance of the regional I-O tables.

(3) GHG emissions associated with: land used in rice production; capital used in livestock industry (dairy farm cattle, ruminant and non-ruminant livestock); and output of fossil fuel and agricultural sectors are included. We consider these emissions as dirty primary input factors. Thus, these GHGs are now included in the I-O tables as 'dirty' endowments. This improvement allows to keep the accounting balances consistent.

(4) We elaborated an "add-on" tool entitled GTAP-VIEW which provides checking of the equilibria and accounting balances in the model.

(5) We developed a welfare decomposition add-on which permits the evaluation of the contributions to the welfare variation (in $ of Equivalent Variation [EV]) such as allocation efficiency (i.e., changes due to reallocation of endowments), technical efficiency (due to improvements on productivity), and terms of trade, among others.

Thus, our GTAP-BIO-FCS model provides a more comprehensive basis for climate change mitigation including alternatives such as FCS and biofuels.

2.3 Data on GHG emissions

GTAP-BIO-FCS includes the so-called Kyoto GHGs: carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and fluoridated gases (F-gases). The annual GHGs are expressed in tons of carbon-equivalent (tC_2Oe). All emissions are associated to their respective economic source: combustion of fuels by firms, factor use (e.g. methane emitted by livestock or paddy rice land), production of some certain commodities, and household/government consumption of fossil fuels. These emissions are aggregated by GTAP region (table 1) and economic sector (table 2).

<Table 1>

<Table 2>

Emissions can differ by region and sector mainly due to two factors: (i) the economic activity of the sector and (ii) the sectorial emission intensity (i.e. GHG emissions by value of output in tCO_2e/$)[26]. Electricity is the sector which accounts for most of the quantity of emissions (30%), followed by transport (21%) and ruminant livestock sector (9%). Three regions - USA, China and the European Union - are responsible for about the half of the global GHGs in 2004 (table 2). Non-CO_2 emissions (9.4 $GtCO_2e$) are approximately one third (38.6%) of CO_2 emissions (23.3 $GtCO_2e$), being agricultural activities (crop and livestock production) its most important contributor.

2.4 Modeling GHG emissions

In both models, the emissions from consumption (either by private consumers or intermediate purchases from firms) are treated in a similar manner. For example, the GHG emissions from consuming a particular domestic good change proportionally to the quantity purchased of that good. Mathematically, this is represented in the following manner:

$$qoem_{i,r} = qpd_{i,r}$$

Thus, changes in the emissions [$qoem_{i,r}$] in tradable good ***i*** in region ***r*** are tied to the (domestic private) consumption [$qpd_{i,r}$]of the same good. The same formulation is implemented for imported domestic goods and domestic/imported intermediate purchases by firms.

In the production side, however, emissions in a given sector can be reduced by (i) lowering production of the sector or by (ii) reducing the sectorial GHG emission intensity by implementing better management practices or new technologies. Thus, emissions from production are not always released in fixed proportion with respect to their associated source. The improvements in emission intensities are reflected in the elasticity of substitution between the emissions and the factor source (land, capital or output). For example, paddy rice producers can respond to a tax in GHG emissions by (i) using less land and/or (ii) changing emission intensity of land (e.g. by moving to a more efficient management practice). To allow reduction in emission intensity, Golub, et al. [10] defined shadow values for these dirty inputs and evaluated their monetary values. Then, they established a nest to allow for substitution between emission and its source.

In our GTAP-BIO-FCS model, we follow the same principle, we allow improvements in the emission intensity to permit changes in management practices/technologies. The difference with our predecessor is the implementation of these emissions in the IO tables. The IO tables are the base for CGE modeling [27]. Thus, in order to keep track of the emissions, we treated these three types of emissions as dirty primary inputs to the I-O tables. This permits our model to keep the accounting balances in order to obtain consistent equilibria in the capital account and welfare. Thus, GTAP-BIO-FCS model consider 25 endowments: 18 AEZs, capital, skilled and unskilled labor, natural resources and 3 sources of emissions as dirty inputs. These 3 sources are from output (e.g. agricultural harvesting, combustion), capital (e.g. emissions from livestock) and land (e.g. methane emissions from paddy rice). They are inserted in the production nest structure (fig. 2 with the standard CES formulation followed in the GTAP-AEZ-GHG model.

<Figure 2>

Three new nests were established, for each type of emissions (land, capital, and output). Mathematically, this is represented as:

$$qoem_{k,j,r} = -af_{i,r} + qf_{kk,j,r} - \sigma_{k,j,r}[pfem_{k,j,r} - af_{i,r} + pf_{kk,j,r}]$$

Here, q and p refers to percentage changes in quantities and prices. Emissions (k: land, capital, output) can be reduced by improving technology [$af_{i,r}$] in industry *j* in region *r.* Likewise, emissions depend on the substitution [$\sigma_{k,j,r}$] between emission *k* and the emission source *j* inside the nest *kk*.

2.4 Implementation of the taxes of GHGs and FCS incentives in the model

The GTAP-BIO version provides the possibility of incorporating taxes on carbon emissions for consumption and production. We modified this formulation to tax all GHG emissions in the economy:

$$p = \theta[pm + t] + 100\emptyset\times\tau$$

As in GTAP-BIO, price [$\boldsymbol{p}$] of a commodity depends on its market price [pm], general taxes from the economy (e.g. carbon-exclusive taxes [$\boldsymbol{t}$]) and taxation on emissions [$\boldsymbol{\tau}$], relative to their respective weights. Here $\boldsymbol{\theta}$ is the share of the carbon-tax exclusive price which is similar to the previous formulation. The difference is in Ø, which represents now the value share of the taxation on all GHG emissions (i.e. emission intensity) rather than only in carbon emissions. Furthermore, we add this formulation to endowments in order to tax the three 'dirty' input factors. This means that the effect of the GHG taxation in a sector of the economy depends on the emission intensity Ø and the value of the tax $\boldsymbol{\tau}$ (in \$/tCO_2e).

2.5 Forest carbon sequestration

The GTAP-BIO-FCS model bases its regional FCS on forest carbon supply curves originally obtained from the 'Global Timber Model' (GTM) described in Sohngen and Mendelsohn [23] and calibrated regionally by Golub, et al. [10] using partial equilibrium modeling to make it suitable for the use in CGE modeling.

The GTM is a dynamic optimization model for timber and FCS at the global scale. Its objective is to maximize the net present value of consumers' surplus after forestry harvesting, maintenance and managing costs and the benefits (subsidy) from forest sequestration [10,23]. The FCS potential from the GTM is then used by Golub, et al. [10] for the regional calibration of the forest carbon responses to different levels of FCS subsidies, which was originally used in the GTAP-GHG-AEZ model.

In both models, under a given carbon price incentive, annual forest carbon sequestration can be increased by:

(1) *Rising biomass on existing forest (intensive margin)* – increasing carbon storage per hectare (i.e. modifying rotation ages trees, management of harvesting).

(2) *Expanding forest land (extensive margin)* – afforesting non-forested lands.

In the GTAP-AEZ-GHG model, the authors implemented a 'forest land-biomass sequestration' composite nest (fig. 3). Then, the subsidy was implemented to this nest, which posteriorly distributes its benefits to land and forest biomass.

<Figure 3>

In our GTAP-BIO-FCS model, we first split forest carbon stock into stock associated with forest land and stock associated with managing biomass used by forest industry. This modification provides two advantages: (i) the sequestration incentive can be implemented on these inputs separately; and (ii) it also ensures the capture of subsidies and balance of the regional I-O tables. Thus, the 'FCS nest' is modified (fig. 4) to provide the subsidies on input directly. The formulation of the changes in prices for both inputs (forest land at a given AEZ, forest biomass) follows a similar behavior as a negative tax. Thus, the input subsidies reduce the price for forest land and biomass:

$$pf_{m,FOR} = \theta\left[pm_{m,FOR} + t\right] - 100\vartheta \times s$$

Thus, in these new two equations (i.e. forestry land and self-use forestry biomass use), the price $[pf_{m,FOR}]$ depends on its market price $\left[pm_{m,FOR}\right]$, the subsidy [$\boldsymbol{s}$] (i.e. in $/t$CO_2$e) and the sequestration intensity [$\boldsymbol{\vartheta}$] (i.e. sequestration share of the total value]. Thus, the subsidy motivates changes in the forest inputs, and then in the forest output structure. The rest of the production nests follow the standard CES structure.

2.6 Net GHG emissions

The addition of FCS in the modeling adds a new layer in the formulation for the GTAP-BIO model: net emissions and gross emissions. The regional gross GHGs $[GHGQ_r]$ emission is given as the sum of the emissions from consumption and production. On the other hand, FCS $[CSTOCKFOR_{(r)}]$ reduces total GHGs. Thus, the regional net emissions $[EMITR]$ is then defined as the difference of the gross emissions and total carbon sequestration:

$$EMITR_{(r)} = GHGQ_r - CSTOCKFOR_{(r)}$$

Thus, for policy analysis, the target is to reduce net GHGs. This permits to observe the impacts of FCS incentives.

2.7 Updates in the net revenue from emission trading

Net revenue $[\pi]$ from emission trading in the model was adjusted in order to account for the total GHG emissions following McDougall and Golub [28] formulation:

$$\pi = 0.01 \times [EMITQ \times emq - EMITR \times emt] \times \Lambda + [EMITQ - EMITR] \times \lambda$$

Here, the variables ***EMITQ*** and ***emq*** represent the regional level and percentage change of GHG emissions quota, respectively; ***EMITR*** and ***emt*** are the level and percentage change of net GHG emissions per region. Λ is the net nominal taxation, which is obtained from the net effect of the GHG tax and the FCS subsidy implementation, whereas λ is the change in this net GHG tax rate.

2.8 Land structure

The GTAP-BIO-FCS model, as their predecessors, assumes that the landowner will allocate resources by maximizing net land rent in two steps. First, the landowner decides in which type of land cover (i.e. cropland, pasture land and forest cover) to produce. Second, if he/she decides to grow in cropland, then he/she allocates in a type of agricultural crop sector. Nevertheless, an advantage of building our model over the GTAP-BIO model version CARB1402 is that its structure can distinguish that converting managed pasture and grass to agricultural land has a different opportunity cost than converting managed forest into cropland.

2.9 Productivity of land by AEZ

Climate change and other technological changes can affect land productivity at the AEZ level. Therefore, in order to implement these external shocks on crop yields, we first defined the following relationship:

$$y_{Z,C}^{RG} = \frac{Q_{Z,C}^{RG}}{A_{Z,C}^{RG}}$$

where $y_{Z,C}^{RG}$, $Q_{Z,C}^{RG}$, $A_{Z,C}^{RG}$ are the productivity (in metric tons/ha), production (in tons) and harvested area (in hectares) of crop $\boldsymbol{C}$ at the agro-ecological zone $\boldsymbol{Z}$ and region $\boldsymbol{RG}$. The production and harvested area come from the database of the model. Posteriorly, we differentiate both terms to obtain the formulation in percentage terms:

$$\%\Delta y_{Z,C}^{RG} = \%\Delta Q_{Z,C}^{RG} - \%\Delta A_{Z,C}^{RG} = S_{Z,G}^{RG}$$

In this way, the percentage change of yield ($\boldsymbol{y_{Z,C}^{RG}}$) is equivalent to crop productivity shocks (i.e. $\boldsymbol{S_{Z,G}^{RG}}$) that we would want to incorporate in the model.

2.10GTAP-VIEW tool

One of the features that GTAP-BIO-FCS offers is the GTAP-VIEW tool. This add-on provides a summary of many consistency tests from the database before and after a simulation. This ensures that the accounting balances are preserved. An advantage of this tool is that if there is an imbalance, it detects where it can be the source: the capital account (i.e. net global savings equals to net global investments) or the current account (i.e. net global exports equal to net global imports). It also provides a summary of GDP indicators, value of outputs, and decomposition of the sources of income taxation.

2.11The welfare decomposition

The second "add-on" module developed was the "welfare decomposition" which calculates changes in welfare (measures in terms of Equivalent Variation (EV)) due to the changes in economic variables. It also determines major components of changes in welfare. We built up this module from the revised McDougall and Golub [28] version. Thus, we account for the addition of new GHG emissions, new sub-nesting commodities and FCS formulations. Arising from the previous versions, there are three major changes in the welfare decomposition that we added to the GTAP-BIO-FCS model:

(1) *Taxation on endowments* – We implemented in the formulation carbon taxation on endowments separately from other taxes on primary inputs. This modification is specifically implemented to tax emissions of the 'dirty' primary inputs. We also did this modification in the contribution to EV of changes in all endowments.

(2) *Subsidy on forest carbon sequestration* – The contribution to EV from the subsidy on FCS was included in the formulation as subsidy on endowments.

(3) *Adjustment in output technological changes* –The standard GTAP version provides one-to-one mapping from commodities to single-product sectors. Nevertheless, the inclusion of biofuel byproducts makes that some of these sectors can produce several commodities. We accounted for these changes and added in the welfare formulation.

3. Scenarios

There is a plethora of literature that describes the interaction among climate change, crop production, and food production. These studies show that under adverse effects of climate change on agricultural yield, many regions can suffer from deficiencies in their food supply[9,29-34]. These effects vary across the world depending on the location and type of crop [9,35-38].

Taking into account these facts, we use the GTAP-BIO-FCS model to evaluate the implementation of a carbon tax and an equivalent FCS subsidy in the global economy to better understand the importance of incorporating forest carbon sequestration in the economic and environmental analysis of climate change. We target a global net GHG emission reduction of 50% following the 'Mitigation scenario' of the Representative Concentration Pathway [39] (RCP 4.5) of the IPCC-WGIII [40] report. We called it our '***Base***' scenario. We then repeat the experiment adding crop productivity shocks induced by climate change under the RCP 4.5 scenario. This scenario is called our '***Crop Yield [CY]***' scenario. We also run both scenarios using the GTAP-AEZ-GHG model to ensure that our model followed similar patterns in the results with respect to its predecessor. To shorten the names of the models, we call GTAP-BIO-FCS as '*new* model' and its predecessor is referred as '*old* model'. We present the summary of the names of the scenarios in table 3.

<Table 3>

The data on crop productivity shocks

For the scenarios with crop yield (CY) shocks, we collected the productivities from the Agricultural Model Comparison and Improvement Project (AgMIP) [41] for the period 2000-2100. We used the following procedure to convert this information into the crop productivity shocks:

1) We downloaded projected yields $\boldsymbol{Y_{cit}}$ by $\boldsymbol{c}$ crop, at $\boldsymbol{i}$ grid cell level level (i.e. 0.5° × 0.5° resolution) and time $\boldsymbol{t}$, at the global scale for 2000-2100.

2) We calculated the average yields for the first ($\boldsymbol{Y_{cib}}$) and last ($\boldsymbol{Y_{cie}}$) 10 years by crop at the grid cell level at the global scale.

3) We then aggregated the crop yields ($\boldsymbol{Y_{czrb}}$ and $\boldsymbol{Y_{czre}}$) by region $\boldsymbol{r}$ and AEZ $\boldsymbol{z}$. We used harvested areas as weights in the aggregation process.

4) We finally calculated the %change in yields $\boldsymbol{y_{zr}}$ by region and AEZ using:

$$\boldsymbol{y_{zr}} = (\frac{\boldsymbol{Y_{czre}}}{\boldsymbol{Y_{czrb}}} - \boldsymbol{1})\times\boldsymbol{100}$$

In total, we obtained this information for eight different crops: maize, soybeans, millet, rice, rapeseed, sugarcane, sugar beets, and wheat by irrigation type (i.e. rainfed and irrigated). We aggregated the data according to the crop sector classification of our model.

4. Results

Our simulations display a wide range of results in terms of economic and environmental variables at the sectorial and regional level. Here, we only present the key results to highlight the impacts of targeting a 50% global emission reduction under two different scenarios - with and without climate change impacts on crop yields.

4.1 Tax requirements, GHG emissions and FCS

Fig. 4 portrays the mitigation of net GHGs emissions by region and scenarios, without (fig. 4a) and with (fig. 4b) crop yield shocks induced by climate change, respectively. Here, we see that in order to reduce global GHGs by 50%, the tax-subsidy rate required is \$80/tCO_2e. This monetary value is represented in 2004 dollars. According to the original set up developed by the Joint Global Climate Change Research Institute for the RCP 4.5, in order to achieve its target, carbon prices (expressed in 2005\$) should reach a value of \$85/tCO_2e by 2100[42]. This tax rate is close to the value we calculated in our simulation,

<Figure 4>

In our model, the FCS subsidy is given to its inputs (i.e., forestry land and biomass) directly. In terms of GHG emissions, we tax 'dirty' endowments, which are updated after simulation in the IO table to keep consistency in the accounting balances. FCS plays an important role in the GHGs emissions reduction (i.e., 21% share in the emission reduction). Emerging economies with vast forest and high sequestration intensity – such as Brazil, the rest of Latin America, and Sub-Saharan Africa – take advantage of the subsidy in forestry as a source of revenue. Although sequestration of CO_2 by forest trees and land accounts for approximately 3 GtCO_2e , the mitigation effort comes mainly from reduction in gross GHG emissions due to the tax regime. In particular, the \$80/tCO_2e tax encourages significant decreases in emissions for China, the EU and India.

When the climate change induced crop yield shocks are added into the picture, the tax-subsidy to achieve the same target increases due to the overall loss in agricultural productivity across the world (i.e. tax-subsidy rate becomes \$100/tCO_2e). There is considerably less forestry carbon sequestration due to the fact that land devoted to agriculture is overall less productive. Considering the increase in the tax rate on emissions, the reduction in gross GHGs releases is greater, which drives FCS share down (from 21% to 14% in contribution of emission reduction)

We run both experiments using our predecessor model, the GTAP-AEZ-GHG model. The simulations results point out to the same conclusion. Both models highlight the importance in mitigating emissions from livestock and electric sectors while also promoting FCS. This means that our implementation shows consistency with the literature.

<Figure 5>

<Figure 6>

4.2 Changes in land cover and harvested area

As previously mentioned, the effect of the FCS subsidy on forestry depends on (i) the regional forest area, (ii) how the FCS intensity is defined and (iii) the subsidy rate. The simulations show that the subsidy FCS on both inputs (land and biomass) encourages forest expansion across the regions. Comparing our results with its predecessor, the distribution of the forestry land follow is similar in both models, with no much variation in the results directions. This behavior is also similar with and without climate change effects on agricultural productivity (fig. 7 and 8).

<Figure 7>

<Figure 8>

The direction of regional changes in land cover is also consistent in both models. Regions with vast forest and high forest sequestration intensity (independently of its definition) expand significantly forest. This is the case for Latin America (e.g. especially countries in the Amazonian region) and Sub-Saharan Africa.

<Table 4>

<Table 5>

For comparison in terms of harvested area, we aggregated the GTAP-BIO-FCS crop sectors into the GTAP-AEZ-GHG sector using the mapping showed in table 4. Interestingly, table 5 depicts that overall the relative changes in crop sectors area with respect to the global harvested area is proportionally similar under both modeling frameworks.

4.3 Changes in food and forestry prices, and effects on GDP

In order to analyze food (household) price variation, we aggregated the crop sectors into a price index. We separated paddy rice because its land is methane emitter. We also elaborated a livestock index composed by two sectors (i.e. dairy farms and ruminant). In general, comparing both models, the effect on food prices is consistent and goes in the same direction - huge price increases occur in all the scenarios (tables 6 and 7). This occurs due to the land competition between forest expansion and agriculture.

The situation is exacerbated by the negative effects of climate change in crop yields, in which, because of the lower yields, more land is required to produce, increasing the food prices even more dramatically.

<Table 6>

<Table 7>

As previously mentioned, our model directly imposes the subsidy on two forest inputs (i.e. forest land and biomass). The results suggest that implementing a subsidy for FCS would increase the forest biomass price while reducing the land price. The economic theory suggests that implementing a subsidy should mitigate the endowment cost, so forest land price should decrease. Likewise, it is more valuable to retain forest biomass for sequestration. Thus, our model provides the correct direction in both (forest biomass and land) prices.

<Table 8>

On the other hand, as a result of the significant increases in food prices, decrease in private consumption, and other effects on the economy, regional income for many economies decreases (table 9). These consequences are similar in both scenarios, in which including the crop yield effects aggravates the situation mainly for developing countries, such as India, Sub-Saharan Africa and China. As expected, due to the high tax-subsidy rate, the model identifies greater negative effects, especially when induced adverse crop yields are included.

<Table 9>

4.4 Accounting balance

In order to evaluate the consistency for the accounting balances, we developed the GTAP-VIEW tool. To evaluate any possible imbalance, we corroborate our results looking at the slack variable *walraslack* which verifies if the Walras Law is fulfilled (i.e. when all markets are in equilibrium, *walraslack* should be close to zero).

As observed in table 10, our model shows consistency in the accounting balances, having a small variation despite the high size of the shock (with and without climate change).

<Table 10>

4.5 Welfare variation

Welfare is an indication of consumer's utility expressed in monetary value (measured in millions of USD$). In the GTAP model, this indicator is obtained as an equivalent variation (EV) in income. This variable can be calculated through two different ways. The first one ('direct method'), is obtained as the deviation from the original income. The second ('alternative') method is through the decomposition of the welfare into its components. Having these two ways is useful in order to check for consistency in the model, because both methods should generate similar results.

The welfare decomposition tool permits to evaluate different sources of variation such as allocative efficiency (due to reallocation of resources), endowment effect (due to changes in the amount of input factors), technological change and term of trade effects (as a consequence of changes in export/import prices), carbon trading and population effects. Thus, in order to have a more comprehensive view of these sources of variations we developed this tool for both models.
Analyzing the simulation results, we observe that our model presents consistency under both scenarios capturing adequately the sources of variation (tables 11).

<Table 11>

Conclusions

Expanding forest is one considered one of the policies to reduce greenhouses emissions through forest carbon sequestration (FCS). In an effort to quantify its effect in the global economy and have a more comprehensive global economic model, we extended a well-known computable general equilibrium model. We entitled this new model GTAP-BIO-FCS. As described in this paper, we implemented a novelty method to incorporate emissions in the input-output table, improving the subsidy formulation for forestry sequestration and developing tools such as welfare decomposition and accounting balance. Likewise, we compare the simulation results with its predecessor, the GTAP-AEZ-GHG model, reducing emissions by 50% globally, under two scenarios: with and without induced climate change crop yields. Our new model agrees with the directions of conclusions of its predecessor. Our model also shows consistency with the economic theory with respect to price directions and sources of variations as well as showing consistency in the accounting balance and welfare methods. Thus, this paper contributes to the literature by providing a reliable model that is able to evaluate climate change mitigation policies such as FCS, biofuels, and tax-subsidy policies.

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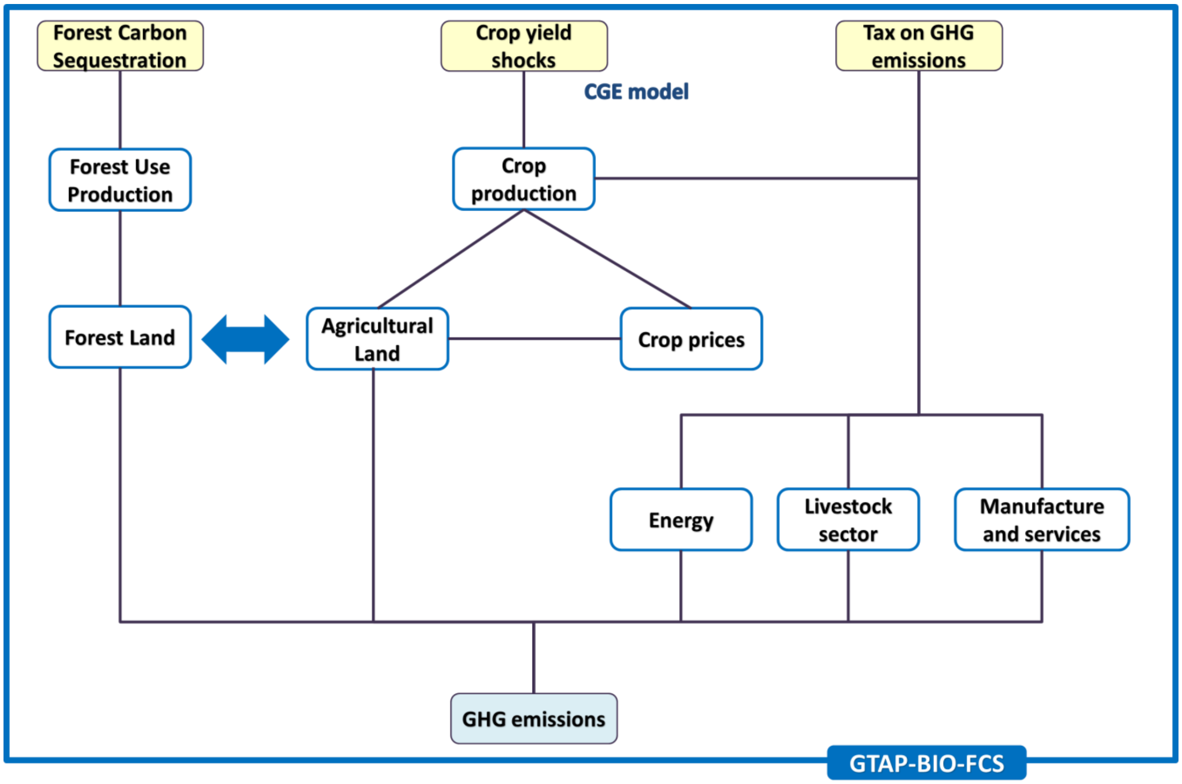


Fig. 1 GTAP-BIO-FCS framework

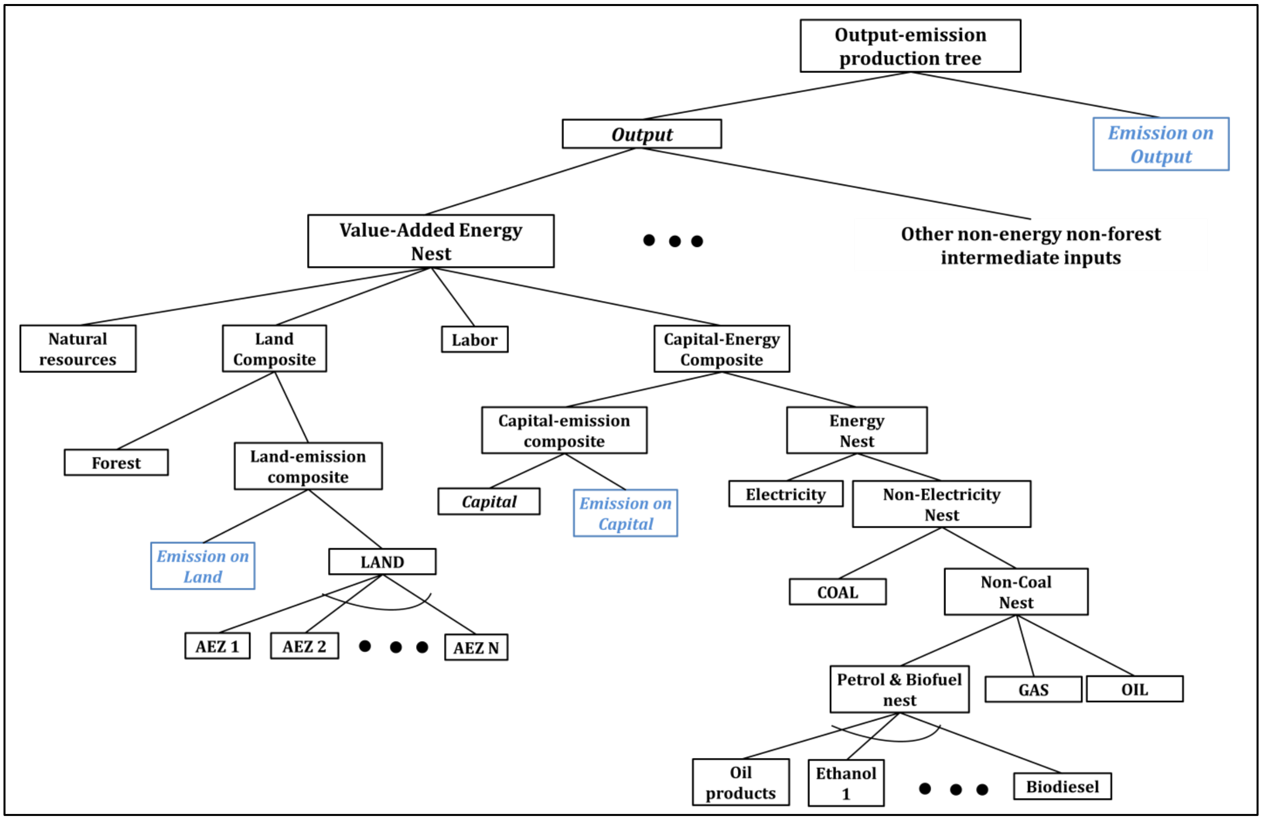


Fig. 2 Production structure

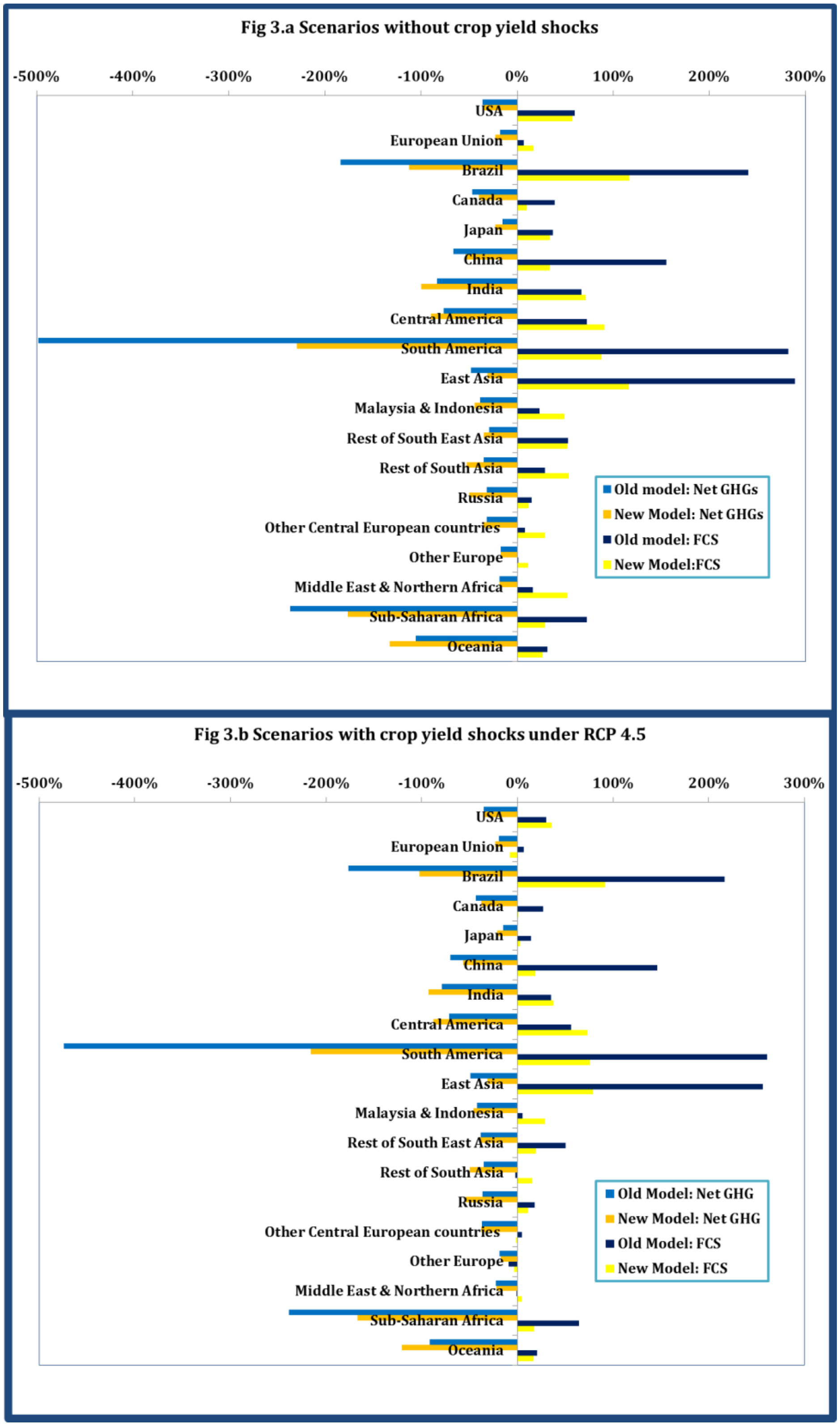
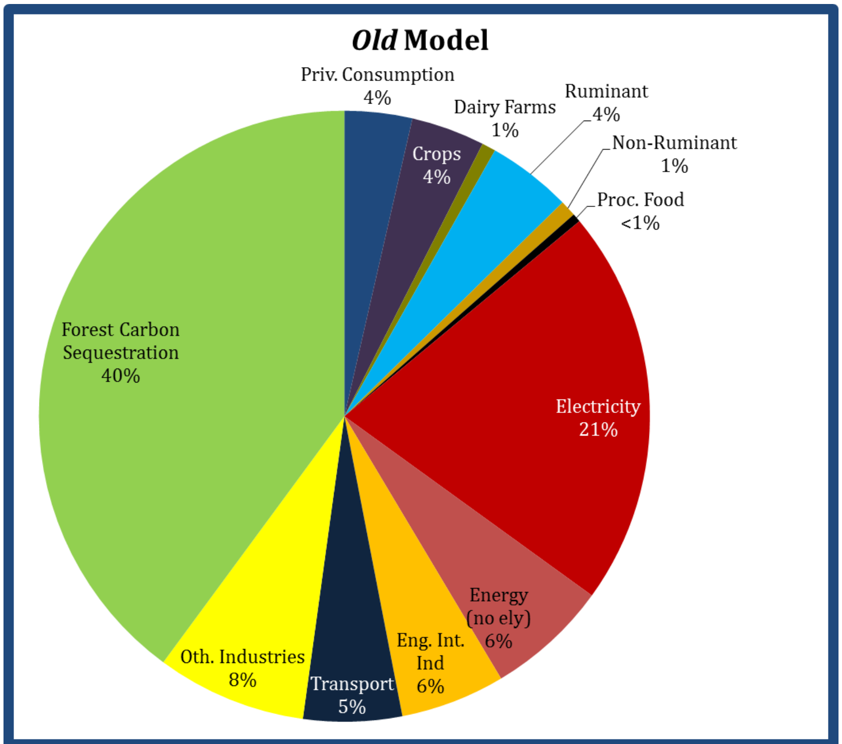


Figure 3. Changes in net GHG emissions and FCS (in %) by region



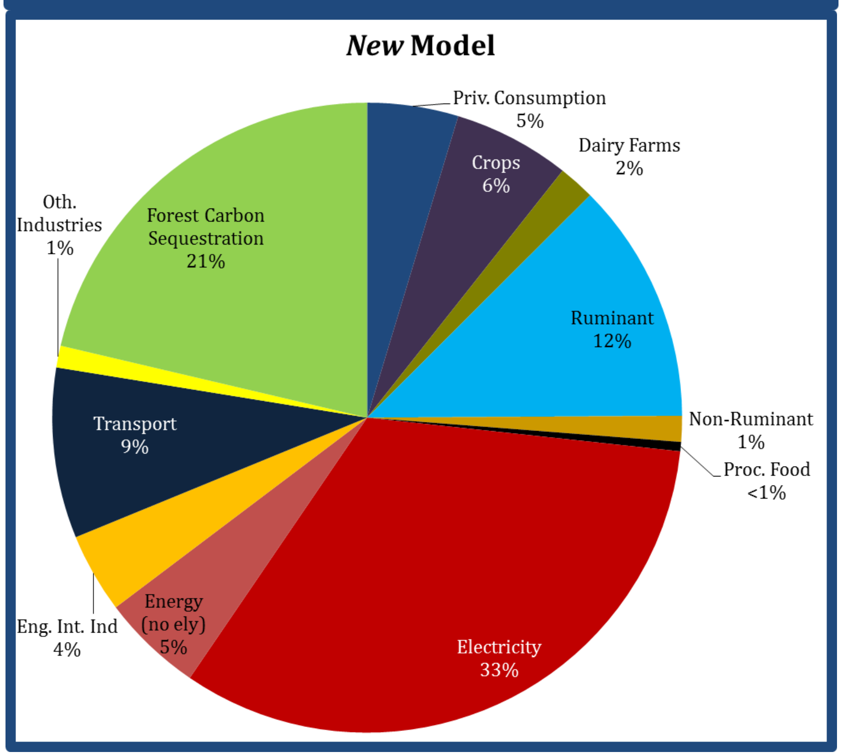


Figure 4. Contributions in net GHG emissions (in %) by economic sector per scenario [not including crop yield shocks]

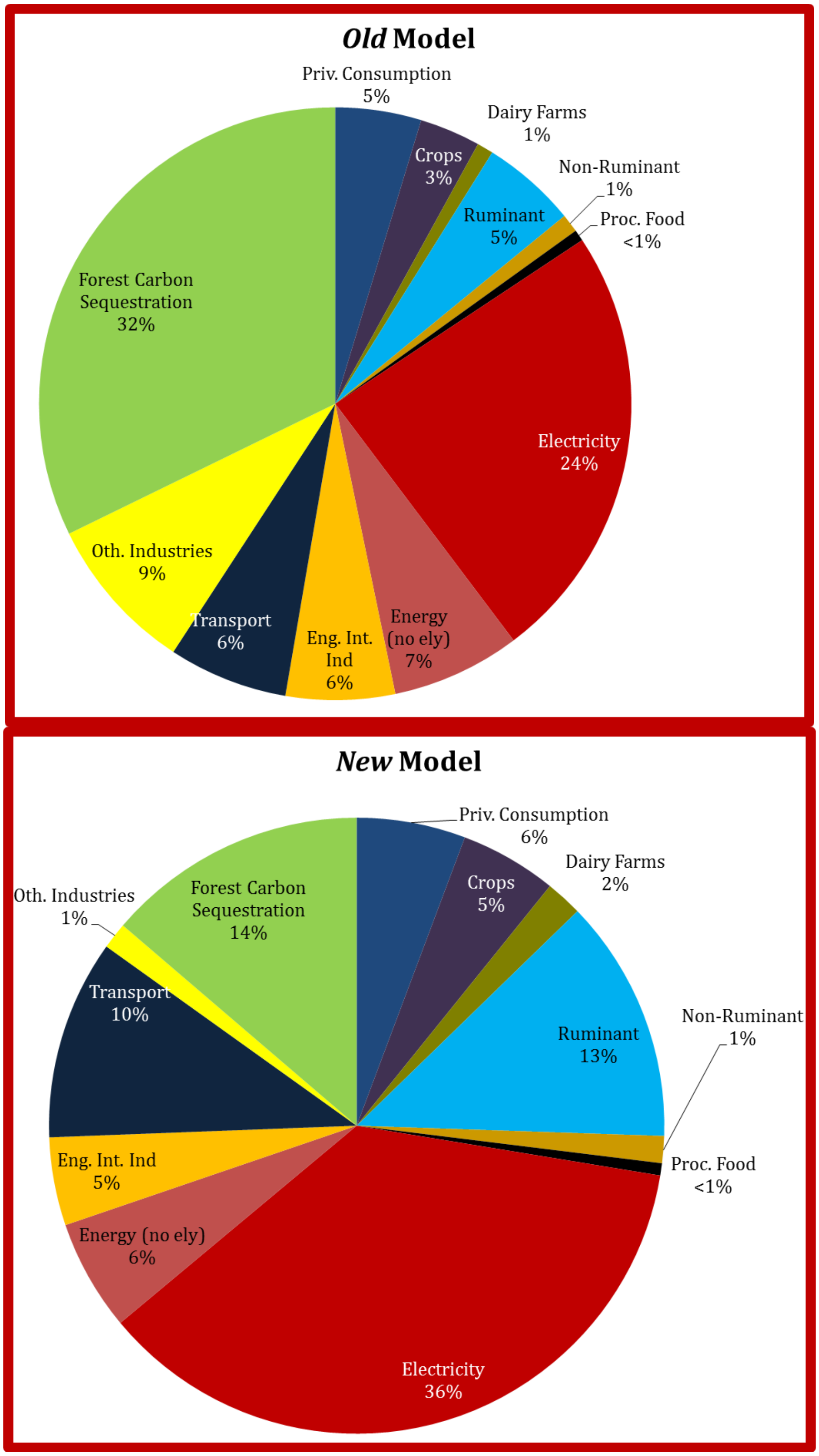
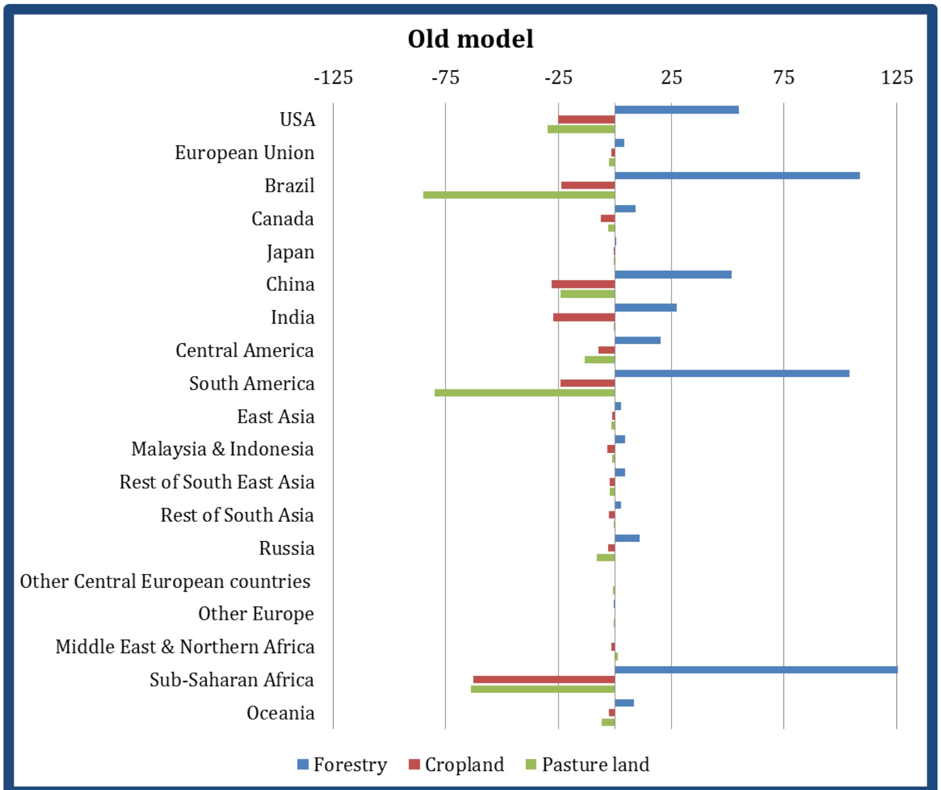


Figure 5. Contributions in net GHG emissions (in %) by economic sector per scenario [including crop yield shocks induced by climate change]



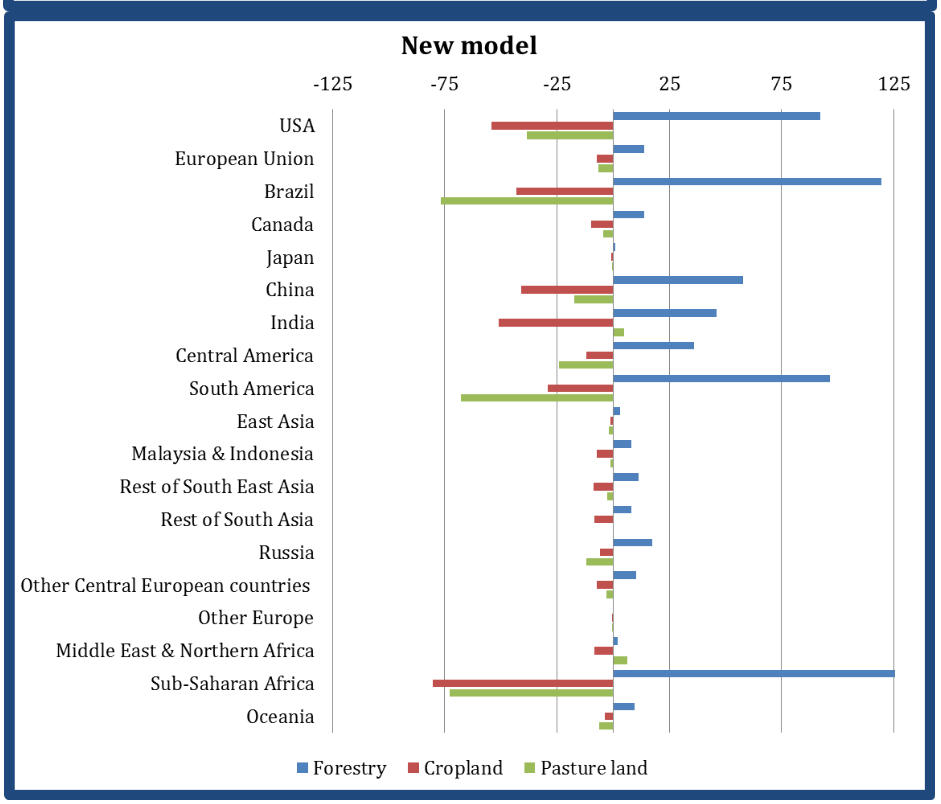


Figure 6. Changes in land cover (in million of hectares) [scenarios without crop yield shocks]

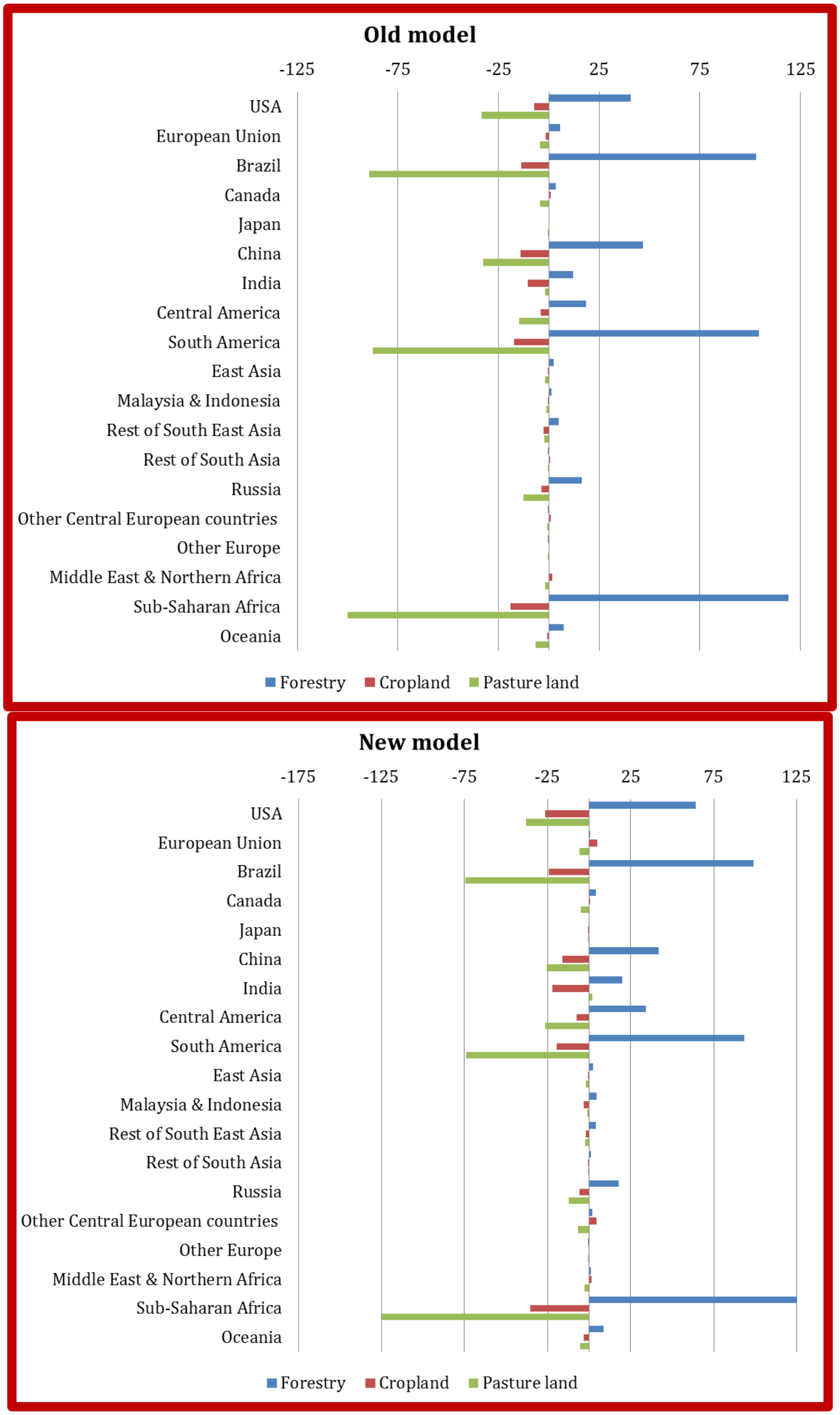


Figure 7. Changes in land cover (in million of hectares) [including adverse effects on crop yields]

Table 1. Emissions per Region (in $MtCO_2e$)

	CO_2	Non-CO_2	GHG
USA	5,591	1,085	6,675
European Union	3,904	937	4,840
Brazil	300	527	826
Canada	516	162	678
Japan	995	96	1,090
China	4,436	1,544	5,980
India	1,119	575	1,694
Central America	574	288	861
South America	431	514	945
East Asia	769	163	932
Malaysia & Indonesia	485	247	732
Rest of South East Asia	444	343	788
Rest of South Asia	173	270	443
Russia	1,312	387	1,698
Central Europe	972	592	1,564
Other European countries	111	23	134
Middle East & North Africa	1,377	487	1,864
Sub-Saharan Africa	481	971	1,452
Oceania	397	210	607
Total	**24,385**	**9,421**	**33,805**

The world is divided into the 19 GTAP regions. Values are expressed in megatons of CO_2-equivalent (MtCO2e).

Table 2. Emissions per sector (in $MtCO_2e$)

Source	Emissions
Private consumption	3,690
Agricultural crops	2,348
Dairy Farms	539
Ruminant	2,469
Non-Ruminant	540
Processed Food	291
Electricity	10,297
Energy (no electricity)	2,237
Energy Intensive Industries	2,124
Transport	7,261
Other Industries	2,011
TOTAL GHG	33,805
Forest carbon stock	5,352
Net GHG	**28,453**

Global GHG divided in sectors of the economy. Values are expressed in megatons of CO_2-equivalent (MtCO2e).

Table 3. Scenarios of the study

Shocks / Model	No crop yield shocks	Including crop yield shocks
Old: GTAP-AEZ-GHG	Old-50	Old50+CY
New: GTAP-BIO-FCS	New-50	New50+CY

Global GHG divided in sectors of the economy. Values are expressed in megatons of CO_2-equivalent (MtCO2e).

Table 4. Mapping sectors from GTAP-BIO-FCS to GTAP-AEZ-GHG

GTAP-BIO-FCS	GTAP-AEZ-GHG
Paddy Rice	Paddy Rice
Wheat	Wheat
Sorghum Other Coarse Grains	Coarse Grains
Rapeseed Soybeans Palm Other Oilseeds	Oilseeds
Sugar Crops	Sugar Crops
Other Agricultural products	Other agricultural products

Table 5. Changes in harvested area (in Mha, and percentage change of global change)

		Old Model		New model	
		Global Changes (ΔMha)	Change relative to global area	Global Changes (ΔMha)	Change relative to global area
Without Induced Crop Yield Shocks	Rice	-38.1	17%	-60.4	17%
	Wheat	-21.1	9%	-36.6	10%
	Coarse Gr	-53.6	24%	-79.3	22%
	Oilseed	-35.4	16%	-61.6	17%
	Sugar crops	-5.3	2%	-7.1	2%
	Others	-69.0	31%	-112.9	32%
With Induced Crop Yield Shocks	Rice	-8.7	10%	-13.8	11%
	Wheat	-8.3	9%	-7.6	6%
	Coarse Gr	-21.3	24%	-22.7	18%
	Oilseed	7.2	-8%	-12.2	10%
	Sugar crops	-2.9	3%	-2.7	2%
	Others	-56.0	62%	-67.2	53%

Global changes are expressed in millions of hectares (Mha). Changes relative to global area are calculated as the change in the sector divided by the overall global harvested area.

Table 6. Changes (in %) of food prices without crop yield shocks

Region	Paddy Rice		Crops sectors		Ruminant Livestock	
	Old model	New model	Old model	New model	Old model	New model
USA	30	53	13	25	13	23
European Union	13	25	7	12	15	22
Brazil	39	47	22	27	73	120
Canada	27	50	13	22	15	36
Japan	14	17	7	16	10	21
China	54	92	15	29	74	81
India	52	76	18	32	22	70
Central America	26	49	15	29	30	81
South America	64	90	30	40	81	150
East Asia	11	43	18	32	23	44
Malaysia & Indonesia	41	67	12	25	151	75
Rest of South East Asia	43	80	7	19	220	170
Rest of South Asia	29	58	10	20	48	38
Russia	56	53	6	8	41	22
Central European countries	2	48	3	12	16	35
Other Europe	17	32	7	12	11	22
Middle East & Northern Africa	7	18	2	9	19	41
Sub-Saharan Africa	28	77	14	22	135	258
Oceania	22	45	12	21	31	46

Note: 'Crops sectors' is an aggregation of the agricultural sectors other than paddy rice. Ruminant livestock is an index composed by dairy farm and the ruminant sector.

Table 7. Changes (in %) of food prices including adverse effects on crop yields

Region	Paddy Rice		Crops sectors		Ruminant Livestock	
	Old model	New model	Old model	New model	Old model	New model
USA	147	243	92	130	33	41
European Union	90	148	61	97	27	39
Brazil	213	219	143	152	102	172
Canada	105	184	82	117	38	52
Japan	108	99	67	84	35	46
China	130	184	70	95	64	76
India	714	516	126	187	40	152
Central America	200	272	89	158	56	110
South America	309	360	173	202	69	130
East Asia	96	188	83	127	60	88
Malaysia & Indonesia	222	211	104	114	56	79
Rest of South East Asia	189	222	88	103	81	81
Rest of South Asia	241	282	93	97	45	50
Russia	130	141	46	88	64	41
Central European countries	87	109	47	79	42	68
Other Europe	87	161	54	90	20	40
Middle East & Northern Africa	49	95	54	91	22	53
Sub-Saharan Africa	151	239	101	156	200	199
Oceania	126	160	104	163	37	49

Note: 'Crops sectors' is an aggregation of the agricultural sectors other than paddy rice. Ruminant livestock is an index composed by dairy farm and the ruminant sector.

Table 8. Changes (in %) of forest biomass and land prices for each scenario

Region	No Climate Change Shocks				Include crop yield shocks			
	Forest biomass		Forest land		Forest biomass		Forest land	
	Old model	New model	Old model	New model	Old model	New model	Old model	New model
USA	-31	25	499	-2	-20	19	701	-2
European Union	-15	9	32	-4	-8	-2	69	1
Brazil	236	60	3777	-14	334	57	4984	-12
Canada	-32	4	202	-2	-19	2	346	-1
Japan	-31	30	113	-8	-8	1	224	0
China	-28	22	317	-6	-8	17	496	-4
India	-52	61	485	0	-47	46	662	0
Central America	-28	43	420	-1	-6	38	599	-1
South America	268	37	4008	-17	377	36	5262	-15
East Asia	2	181	670	-23	33	107	953	-14
Malaysia & Indonesia	-35	33	102	0	-15	21	193	0
Rest of South East Asia	-40	44	100	-4	-30	-3	175	0
Rest of South Asia	-32	16	120	0	-20	4	217	0
Russia	-22	2	57	0	-12	14	117	0
Central European countries	-22	19	1	-1	-16	-2	37	0
Other Europe	-12	2	11	-1	2	-3	56	1
Middle East & Northern Africa	-28	38	47	-5	-8	11	116	-1
Sub-Saharan Africa	35	17	785	-1	74	20	1091	-1
Oceania	-31	-5	1782	2	-17	4	2355	-1

Table 9. Changes in Gross Domestic Product (in %) for each region and scenario

Region	No Shocks		Crop Yield Shocks	
	Old Model	New Model	Old Model	New Model
USA	-0.3	-0.7	-0.8	-1.3
European Union	-0.4	-0.2	-1.3	-1.4
Brazil	-1.9	-2.2	-4.7	-6.1
Canada	-0.7	-0.8	-1.7	-1.7
Japan	-0.2	-0.2	-0.5	-0.6
China	-3.1	-5.7	-6.5	-9.4
India	-2.6	-5.1	-12.0	-14.9
Central America	-0.8	-3.3	-2.2	-7.4
South America	-2.6	-2.9	-5.8	-6.9
East Asia	-0.9	-1.1	-2.2	-1.9
Malaysia & Indonesia	-1.1	-2.8	-5.1	-7.6
Rest of South East Asia	-0.8	-2.3	-3.9	-4.9
Rest of South Asia	-1.2	-3.2	-9.4	-9.1
Russia	-3.7	-3.2	-6.2	-6.5
Other Central European countries	-3.0	-4.8	-11.6	-9.6
Other Europe	-0.2	-0.2	-0.6	-0.6
Middle East & Northern Africa	-1.1	-1.8	-3.5	-4.5
Sub-Saharan Africa	-5.0	-4.4	-11.3	-11.4
Oceania	-0.7	-1.0	-2.0	-2.4

Table 10. Verification of the imbalances in the models

Region	No Shocks		Crop Yield Shocks	
	Old Model	New Model	Old Model	New Model
Sum of imbalances (in million $)	823	64	2,118	197
Capital account imbalance (in million $)	-787	30.7	-1972	-88.9
Deviation from net savings (%)	0.02336	-0.00071	0.05918	0.00207
Slack variable for Walras Law (*walraslack* in %)	0.02336	-0.00087	0.05898	0.00162

Note: All these values should be close to zero.

Table 11.a Welfare comparison (in billions of USD) under no crop yield shocks

	Old Model		New Model	
Region	**Direct**	**Alternative**	**Direct**	**Alternative**
USA	-20,041.9	-20,008.1	-52,496.8	-52,496.9
European Union	-24,044.4	-24,020.2	10,897.0	10,896.8
Brazil	-8,722.3	-8,708.6	-9,509.3	-9,509.4
Canada	-3,076.7	-3,073.1	-7,793.5	-7,793.5
Japan	-5,650.6	-5,648.5	3,840.7	3,840.7
China	-42,175.0	-42,133.7	-113,465.5	-113,465.6
India	-11,140.1	-11,123.4	-29,838.8	-29,838.8
Central America	-8,358.9	-8,352.8	-37,324.0	-37,324.1
South America	-17,449.1	-17,439.8	-17,563.7	-17,563.8
East Asia	-4,870.6	-4,864.8	-7,499.3	-7,499.3
Malaysia & Indonesia	-4,043.5	-4,036.5	-11,712.9	-11,712.9
Rest of South East Asia	-2,144.2	-2,134.4	-7,128.1	-7,128.1
Rest of South Asia	-1,905.8	-1,900.5	-6,220.2	-6,220.2
Russia	-12,594.4	-12,583.2	-32,088.3	-32,088.4
Central European countries	-8,302.1	-8,285.3	-25,805.2	-25,805.2
Other Europe	-3,828.7	-3,828.1	-7,965.9	-7,965.9
Middle East & Northern Africa	-25,023.0	-25,012.2	-70,902.9	-70,902.8
Sub-Saharan Africa	-18,830.9	-18,806.9	-32,633.8	-32,633.9
Oceania	-644.9	-640.8	-1,994.3	-1,994.3
Total	222,847.0	222,601.0	457,204.8	457,205.7
Difference		**-246.0**		**0.9**

Table 11.b Welfare comparison (in billions of USD) including the crop yield shocks

	Old Model		New Model	
Region	**Direct**	**Alternative**	**Direct**	**Alternative**
USA	-58,787.0	-58,751.5	-95,295.0	-95,295.1
European Union	-113,264.4	-113,239.3	-162,451.4	-162,452.1
Brazil	-19,740.1	-19,724.5	-20,027.6	-20,027.8
Canada	-4,141.0	-4,136.8	-11,301.2	-11,301.2
Japan	-31,649.6	-31,647.0	-24,582.3	-24,582.3
China	-89,275.7	-89,230.9	-188,896.1	-188,896.2
India	-59,035.5	-59,016.3	-96,313.8	-96,313.9
Central America	-21,595.0	-21,588.2	-85,457.5	-85,458.0
South America	-34,460.8	-34,450.0	-31,301.9	-31,302.1
East Asia	-21,936.1	-21,929.9	-24,821.1	-24,820.8
Malaysia & Indonesia	-13,549.5	-13,542.0	-29,116.6	-29,116.7
Rest of South East Asia	-12,180.8	-12,171.6	-13,974.4	-13,974.5
Rest of South Asia	-15,145.4	-15,138.6	-19,493.2	-19,493.2
Russia	-22,116.1	-22,103.8	-55,515.8	-55,515.8
Central European countries	-28,761.4	-28,742.6	-45,895.4	-45,895.1
Other Europe	-6,810.1	-6,809.5	-13,296.4	-13,296.5
Middle East & Northern Africa	-54,488.2	-54,475.6	-115,327.9	-115,327.9
Sub-Saharan Africa	-38,284.5	-38,256.8	-70,129.7	-70,129.8
Oceania	698.7	702.3	-4,045.8	-4,046.0
Total	644,522.5	644,252.8	1,107,243.3	1,107,245.0
Difference		**-269.7**		**1.7**