The Economic Benefits and Costs of Mitigating Climate Change: Interactions among Carbon Tax, Forest Sequestration and Climate Change Induced Crop Yield Impacts

By

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Abstract

This paper uses an advanced computable general equilibrium model to evaluate the extent to which incorporation of climate change induced changes in crop yields could impact forest carbon sequestration with a carbon tax. We find that the reduction in crop yields in many regions does negatively impact the potential for forest carbon sequestration. The yield reduction causes more land to be needed for crop production making less available for forest. In addition, the crop yield reduction reduces overall crop production and significantly increases crop and livestock prices. These prices increase substantially even though demand has been reduced due to the negative economic impacts of the carbon tax. Developing countries have much more negative economic impacts than rich countries.

Keywords: Forest carbon sequestration, Emissions, General Equilibrium, climate change, crop yield

JEL codes: Q15, R52, Q54.

Introduction

The Intergovernmental Panel on Climate Change Working Group III (IPCC-WGIII) report (2007, 2014b) states that humans are responsible for 90% of the GHG emissions that causes climate change. Among the anthropogenic GHG emissions, the most important sectors that directly emitted GHGs (measured in 2010) were: power generation (25%) and forestry, agriculture and other land use (i.e. AFOLU) (24%) (IPCC-WGIII, 2014b, World Resources Institute, 2006).

<Figure 1 here>

Annual emissions by human actions have increased by 10 gigatonnes of CO_2 equivalent emissions ($GtCO_2e$) from 2000 to 2010 (IPCC-WGII, 2014a). As a consequence, the concentration of CO_2e in the atmosphere in 2011 was estimated to be 430 parts per million (ppm) CO_2-equivalent (CO_2e), which is 54% higher than industrial revolution levels (IPCC-WGIII 2014a). Current levels of GHG emissions are the highest in 650,000 years (Siegenthaler, et al., 2005).

Because of the quantity of direct emissions that they represent, changes in energy supply, agriculture production and forestry potentially can play very important roles to mitigate climate change. Energy substitution toward cleaner technologies (e.g. wind power, biofuels, etc.) has been extensively studied in the literature (Suttles, et al., 2014). Likewise, carbon forest sequestration has been pointed out as a great alternative, especially for non-CO_2 GHG emissions because its low marginal cost compared to other options (Golub, et al., 2009).

Many studies state that crop yield can change due to a variation in the climate depending on the crop, region and agro-ecological zone (AEZ) where the production is located (Nelson, et al., 2010, Ouraich, et al., 2014, van der Mensbrugghe, 2013). Despite these facts, existing studies have not explicitly modeled whether forest carbon sequestration is still a good alternative when

climate change affects crop yields. Thus, the question that motivates this paper is: *what are the consequences of climate change induced crop yields on the implementation of forest carbon sequestration as a mitigation policy?*

In this paper we pay particular attention to forest carbon sequestration as a mitigation policy for climate change. We use a well-known Computable General Equilibrium (CGE) model: the GTAP model, specifically the extended version GTAP-AEZ-GHG version that explicitly relates GHG emissions (i.e. carbon dioxide, methane and nitrous oxide) with their sources (i.e. crop production, livestock, fossil fuel combustion) and takes into account forest carbon sequestration, which is the focal point of this paper.

In this paper, we implement a GHG tax-subsidy regime (including a uniform carbon tax and a forest carbon sequestration subsidy) to reduce global emissions by 50% during the time period of 2001-2100 in the presence and absence of changes in crop yields due to climate change. We implemented this regime to represent reduction in emissions projected by the IPCC-WGIII AR5 scenario known as RCP 4.5 (i.e. Representative Concentration Pathway with radiative forcing 4.5 W/m^2 by 2100). RCP 4.5 is known to be a "Mitigation Scenario" and was developed by the Pacific Northwest National Laboratory modeling team (RCP Database Webmaster, 2009). This scenario predicts a global increase in temperature of 2.4°C by 2100, with an atmospheric concentration of 650 ppm CO_2 (Wayne, 2013).

We compare the results with and without the climate induced crop yield impacts in terms of social welfare, changes in GDP, land use change, carbon sequestered by forest, crop output, and changes in consumer price index under the same tax regime. The expected changes in crop yields for the time period of 2000-2100 were obtained from Agricultural Model Comparison and Improvement Project (AgMIP) which calculated the yields using a General Circulation Model (i.e.

HadGEM2-ES) together with a crop model (i.e. LPJmL) under the RCP 4.5 scenario projections. Our results indicate that as would be expected, including the climate change induced yield shocks does reduce the potential for forest carbon sequestration. They also show that the adverse economic impacts of GHG reduction are much higher when the yield changes are included.

Literature review

Factors that affect the impacts of GHG emissions on agriculture

Climate change is one of the most significant factors that can influence future crop yields. Crop species are affected by variations in GHG emissions, through which an increase in atmospheric CO_2 can alter the plant physical structure: its capacity to absorb carbon (Qaderi and Reid, 2009) and other nutrients (Torbert, et al., 2004), resistance to drought stress (Robredo, et al., 2007) and tolerance to pests and herbivores (Heagle, 2003). Thus, the responses of agriculture to GHG emissions have to be studied using variability at a local scale rather than using a global average trend (IPCC, 2007, Qaderi and Reid, 2009). In other words, crop productivity is affected by climate change depending mainly on the type of plant-crop, the location (e.g. local weather), the availability of nutrients and water, and the intensity of CO_2 in the atmosphere (Nelson, et al., 2010, Ouraich, et al., 2014, Stern, 2007).

Focusing on average effects can be misleading (Ouraich, et al., 2014). For example, developing countries depend largely on climate sensitive sectors such as agriculture (Manne, et al., 1995). The World Bank states that in countries between US$400-1,800, agriculture represents 20% of GDP on average; and for the poorest people (who live mostly in rural areas) is 70% of the GDP. Hence an increase in GHG could affect more these countries (GCEC, 2014).

Forest carbon sequestration as climate change mitigation policy

The United States Department of Energy (US-DOE) in its 2010 report states that carbon sequestration is a potentially effective method to mitigate GHG effects (US-DOE, 2010). The United States Environmental Protection Agency (US-EPA) mentions that forest biomass can store carbon from the atmospheric CO_2. Thus, forestry can be considered as a long-term carbon sink (Sheeran, 2006, US-DOE, 2010) and an important issue in climate change mitigation (Suttles, et al., 2014).

In 1998, it was estimated that 18% of the GHG emissions were due to deforestation, which is higher than the emissions coming from transport and aviation together (Nations, 1998). Hence, in 1997, Kyoto Protocol implemented the Reducing Emissions from Deforestation and Degradation (REDD) policy with the goal of designing a framework that could abate global deforestation while reducing poverty and preserving the biodiversity and ecosystems (Holloway and Giandomenico, 2009, Suttles, 2014).

As pointed out by Golub (2010), land use is one of the clear links between agriculture and forestry. Forestry, agriculture and other land use (i.e. AFOLU) accounted in 2010 for 24% of direct emissions (IPCC-WGIII, 2014b). In the 1980s, deforestation represented more than 90% of the carbon released from land use (IPCC, 2000).

Land use change also can affect (i) carbon uptake rate by forest trees and (ii) forest storage stock of carbon. Thus, forest clearing and restoring acts as two different forces that determine the changes in the storage capacity of carbon. This means that lowering the rate of tropical deforestation could lead to a reduction in global carbon emissions (Sheeran, 2006). However, one of the challenges that policy makers need to address is reforesting without risking food security

(Golub, et al., 2010, Golub, et al., 2012), especially for developing countries that depend primarily on agriculture production (Stern, 2007).

Previous papers have argued the importance that reforestation, better forest management practices (Suttles, 2014), protection against wildfires (Fiorese and Guariso, 2013, Thomson, et al., 2008) and reduction of deforestation as ways to increase the forest carbon sequestration effect, which is considered as one of the most cost-efficient methods to mitigate climate change (Golub, et al., 2009). The rate of CO_2 uptake by forest varies depending on forest growth or reforestation (Post, et al., 2009, Pregitzer and Euskirchen, 2004) making this the basis for forest management (Birdsey, et al., 2006, Post, et al., 2009).

In order for carbon sequestration to be an attractive alternative, the incentives have to be high enough to overcome the opportunity cost associated with implementing/maintaining the carbon sequestration practices (e.g. timber harvest and timing of harvesting) (Brown and Sampson 2007). In the past decades, the cost of existing forest-based carbon mitigation project (not considering the opportunity cost) was between \$0.1/ton-CO_2e and 28\$/ton-CO_2e (IPCC 2000, Faeth 1994, Trexler and Haugen 1995, Brown et al. 1997 and Totten 1999). Considering, the opportunity cost, according to a study made in Philippines, the range of the cost of forest sequestration projects could be between \$46/tonCO_2e - \$106/tonCO_2e depending on the type of tree of being preserved (Sheeran, 2006).

Golub et al. (2010) elaborated a CGE model that was able to analyze implementation of different mitigation practices such as forest carbon sequestration, better fertilization, land use change away from paddy rice and ruminant livestock and other miscellaneous activities at a global scale. This model was an extension of the Global Trade Analysis Project (GTAP) which was called GTAP-GHG-AEZ, and it covered three regions: China, United States and the Rest of the World.

In their study, Golub et al. (2010) found when a carbon tax was implemented (e.g. incrementally from \$1/tonCO_2e to \$100/tonCO_2e), forest carbon sequestration represented the biggest share in abatement of GHG emissions.

In an extension of this paper, Gollub et al (2013): (i) disaggregated into more regions incorporating more detailed information on GHG emissions, and (ii) divided the ruminant sector into two sectors: dairy and ruminant meat sectors. They evaluated different mitigation methods (e.g. forest carbon sequestration, land use change) depending on different international cooperation groups (i.e. Annex I, non-Annex I and Annex II countries) specified by the UNFCCC[1]. They imposed a tax of 27 \$/tonCO_2e. They found that not including non-Annex I in the effort could result in deterioration of livestock and agricultural sectors; however, this leakage can decrease if the non-Annex I countries receive incentives for forest carbon sequestration.

Nevertheless, these studies do not take in consideration the significant changes in agricultural productivity, which is one of the most prominent consequences of climate change. A decrease in crop yield would require more land in order to obtain the same quantity of production. In this sense, our paper evaluates to what extent forest carbon sequestration is still a good alternative when changes occur in agricultural productivity due to climate change. This is a relevant question to address in order to provide a better understanding of the interplay between climate change, food security, mitigation policies, and their global economic impact.

[1] Annex I are industrialized countries with the compromise of mitigate GHG emissions, Annex II Parties to Convention are a sub group from Annex I with the commitment of helping less developed countries with financial resources and technologies to help them to ease GHG mitigation (Golub et al. 2012).

Methodology

The GTAP-AEZ-GHG model

GTAP is a multi-regional CGE model widely used for trade policy analysis. The original GTAP model was designed to analyze international trade by region at a global scale. The GTAP-AEZ-GHG model is an extended version of the standard GTAP (Hertel, 1999), which offers an appropriate framework to accomplish the goals of this research for the following reasons:

- It traces land cover (including forest, pasture, and cropland), harvested area, and crop production by region at the Agro-Ecological-Zones (AEZ). It also models competition for land among the major land using sectors (including crop, livestock, and forestry) by region at the AEZ level. These are important features which will help us to better examine consequences of climate change for agricultural activities and land use change. There are in total 18 AEZs in the model, which differ in two dimensions: (i) 6 growing periods (e.g. 60, 120, 180, 240, 300 and 360 days) which depends on the soil, temperature, precipitation and topography, and (ii) 3 climatic zones (i.e. tropical (AEZs 1-6), temperate (AEZs 7-12) and boreal (AEZs 13-18) climate).

- It incorporates a detailed GHG emissions (i.e. CO_2, and non-CO_2 gases) database with their respective economic source (e.g. crop production, ruminant and non-ruminant emissions, fossil fuel combustion) and provide different mitigation methods such as forest carbon sequestration, better fertilization, land use change away from paddy rice and ruminant livestock and other miscellaneous activities at a global scale. Additionally, it can distinguish between diary and ruminant meat sectors. The model also takes into account substitution among energy source and between energy and capital as well.

We use a 19 region disaggregation. The mapping that describes the aggregation of nations into the 19 GTAP regions is described in Golub et al (2010). We model 29 sectors of the economy; among them we have agricultural products, livestock, forestry, processed food, and energy sectors.

We introduced proper changes in the GTAP-AEZ-GHG model to simulate changes in agricultural productivity per region, AEZ and crop sector. These changes are described in Annex A1.

IPCC assessment report 5 (AR5) scenarios

The IPCC provides a set of standard reference starting points in order to obtain common scenarios that could represent the major driving forces (i.e. geo-physical, ecological and socioeconomic forces) from climate change and possible responses of the global socioeconomic and environmental systems. These scenarios are called the *Representative Concentration Pathways* (RCP), which are the basis for the Fifth Assessment Report (AR5) released in 2014 (Wayne, 2013). The RCPs attempt to provide a better understanding of the possible consequences of climate change in the future rather than trying to predict it (RCP Database Webmaster, 2009).

The RCP scenarios delineate a specific GHG emission trajectory and concentration by the year 2100 given a level of radiative forcing. RCPs are identified according to the approximate level of radiative forcing in 2100 relative to 1750 (in W/m^2). For example, RCP2.6 (figure 2) means that the path scenario assumes an overall radiative forcing for GHG emissions of 2.6 W/m^2 by 2100 (IPCC-WGIII, 2014a). The higher the radiative forcing, the bigger the global impact.

<Figure 2 here>

Crop yield shocks

The online package developed by Agricultural Model Comparison and Improvement Project (AgMIP) and available at the GEOSHARE website, it is known as the AgMIP @ GEOSHARE project. This online tool provides 5 Global Circulation models (CGMs) and 7 different Crop Simulation Models (CSMs) that can be selected using global grid climate data (Villoria et al. 2014).

GCMs are models that represent biophysical and geochemical processes in the atmosphere, ocean and land surface. They are used to simulate the effects of GHG emissions in the global climate. They use grid cells over all the globe using high resolution (e.g. 30 min × 30 min). Thus, GCMs relate the effects of GHG emissions to bio-geochemical-physical process and translate them to values temperature, precipitation and other climate parameters outputs (RCP Database Webmaster, 2009). For our scenarios, the GCM selected is the Met Office Hadley Centre - Earth System (hadGEM2-ES model); this decision was made in order to follow the Stern Review which used the Hadley Group database.

CSMs can estimate crop productivity (and other parameters of crop production) of different crops/plants as a function of weather and soil conditions, and different crop management practices (USDA, 2007). Thus, the climate parameters from the GCMs are incorporated into crop models which utilize biophysical formulation to simulate the impacts of the weather to transform their values into agricultural productivity of crops. The crop model selected was the Lund-Potsdam-Jena managed Land (LPJmL) (Lapola, et al., 2009), because it provides the widest range of modeled crops, and it is the only model that is able to simulate dynamic land use at a global scale including forestry and vegetation patterns, which fits adequately with our of studying the forest carbon sequestration method.

The data is grouped by the AGMIP aggregation tool by country and AEZ. The crop productivity is obtained in tons per hectares (ton/ha) per year from 2000 to 2099 for eight different crops: maize, soybeans, millet, rice, rapeseed, sugarcane, sugar beets, and wheat.

Aggregation of crop productivity shocks

We collect the annual crop productivity from AGMIP by collected crop, region, AEZ and type of irrigation (i.e. fully irrigated or rainfed) from 2000 to 2099. These values are used to obtain the changes in crop productivity during this time horizon.

1) Initial and final productivities: From the database, we first obtain the initial and the final productivity (in tons/ha). Nevertheless, the data present high variability in yields from one year to the next. To avoid this issue we define our initial productivity as the average of the productivities of 2000-2009. In the same way, the final productivity is the average of the yields from 2091-2099. These yields are defined by region, AEZ, irrigation method and crop.

2) Aggregation weights: In order to aggregate our productivities from 161 countries to the 19 GTAP regions, we use as weights the production of each grid cell which is obtained from Villoria (2015), a main contributor of the AGMIP project. These values were aggregated to the country level by AEZ and crop. Then, the weight per crop was calculated as the production in that country divided by the total production of the region at the AEZ level.

3) Regional crop productivity shocks: The aggregated initial (final) productivities (per region, AEZ, irrigation method and crop) were calculated as the weighted average of the initial (final) productivities depending of the region located. We used the weights calculated in the previous step. We took the percentage difference between the final and initial productivities to obtain the agricultural productivity shocks per crop, region, AEZ, and irrigation method.

4) Aggregation of the types of irrigation: We proceed to combine the types of irrigation (i.e. fully irrigated and rainfed) into one productivity shock. In order to do that, we use the production of each irrigation method of the corresponding GTAP sector as weights. These values (by irrigation type, GTAP region, AEZ, and GTAP sector) were provided by Taheripour (2015) for the 2001 production. Thus, we obtain crop productivity shock by GTAP region, AEZ and crop sector.

5) Getting the final aggregated crop yield shocks: We finally aggregate the productivities from step 4 into crop yield shocks per GTAP sector, region and AEZ using the mapping described in Annex A2. These are considered as the climate change induced agricultural productivity shocks that we will implement in the GTAP-AEZ-GHG model.

These crop yield shock values are for each of the crop sectors, by AEZ and region. For the case of paddy rice, there is an overall reduction in crop yields, with few exceptions. Similarly, there is a decrease in productivity for wheat, coarse grains and oilseeds in most of the regions-AEZs. For the sugar sector, the changes are mixed, because this sector combines sugar cane (cultivated mainly in tropical regions) and sugar beet (cultivated in colder regions).

We consider four IPCC AR5 scenarios (figure 2):

- RCP2.6, it is a mitigation scenario that drives forcing levels down substantially;
- RCP4.5 and RCP6.0, considered as stabilization scenarios; and
- RCP8.5, a scenario with a very large increase of GHG emissions.

Experiments

To accomplish our objective, we followed RCP 4.5 which is considered a "cost-minimizing pathway" mitigation scenario (Thomson, et al., 2011) as an emission reduction scenario. We reduce emissions in the GTAP-AEZ-GHG model by 50% to represent the emission reduction

projected in this RCP. Additionally, we shock the crop yields corresponding to this emissions scenario.

In order to fulfill evaluate the interplay of forest carbon sequestration, the tax incentives and the change in agricultural productivity due to climate change we implement two scenarios:

Scenario 1: Only tax-subsidy regime

We set a carbon tax on emissions/ of 175 $/ton-$CO_2$e, which is uniformly applied to all the regions and sectors that emit GHG emissions. The forest industry receives the same subsidy for carbon sequestration. We followed the procedure defined and implemented by Golub et al. (2012) for the tax implementation[2]. The 175$/ton-$CO_2$e carbon tax/incentive was used to achieve a reduction of 50% in GHG emissions, which is consistent with the target of the IPCC-WGIII AR5 RCP 4.5 scenario.

Scenario 2: Tax-subsidy region plus changes in crop yields due to climate change

For this scenario we implemented the same carbon tax regime/incentive of 175 $/ton-$CO_2$e as described in the forest scenario. Additionally, we incorporate crop yield shocks per region, crop, and AEZ which are produced due to climate change. This scenario was implemented to evaluate what is the extra cost for the society of implementing forest carbon sequestration in the presence of crop yield shocks due to climate change.

We will analyze both scenarios in terms of the impacts on the global economy: changes in prices, carbon sequestered from the atmosphere, consumption and production, welfare and land use change in cropland, pasture and forestry.

[2] The abatement in emissions does not consider in their calculations the reduction of land related emissions (Golub et al 2010). However, the decrease in emissions is approximately 60% (from 641 MMTCO_2e to 251 MMTCO_2e) when implementing the tax regime of 175 $/ton-$CO_2$e.

Results and discussion

Our simulations display a wide range of results in terms of economic and land use variables at the sectorial and regional level. Here we only present the key variables including reductions in CO_2 and Non-CO_2 emissions, changes in land cover, impacts on outputs and prices of some selected commodities, and changes in in welfare, real GDP, and consumer price index.

GHG emissions and forest carbon sequestration

Here we first examine the reduction in GHG emissions per region. We calculate the reduction as the difference between each simulated scenario and the baseline. Table 1 displays induced changes in GHG emissions due to the imposition of the tax regime (scenario 1) and also under the presence of carbon yield shocks (scenario 2). Changes are reported for non-CO_2 gases (in $MMTCO_2e$), CO_2 emissions and total GHG emissions. The decreases in emissions are a result of changes in government/private domestic/imported consumption, outputs and endowments of production and firm usage of domestic/imported products.

<Table 1 here>

As shown in table 1 – scenario 1, at 175 \$/ton-CO_2e tax to all the regions and sectors of the economy, the model predicts that 4.8 $GtCO_2e$ and 11.5 $GtCO_2e$ of non-CO_2 and CO_2 are reduced from changing consumption and production behavior, respectively. Carbon sequestered by forest was 7.8 $GtCO_2e$, resulting in a total global GHG emission reduction of 24.1 $GtCO_2e$, making forest carbon sequestration about one-third of the total.

The large share of forest sequestration highlights the relevance that previous studies have devoted to this mitigation method (e.g. Golub et al (2012)). This occurs specially in places with vast forest: China, United States (mainly in the western region), South America (e.g. Amazon

Region), and Sub-Saharan Africa (e.g. composed by mainly forest-savanna mosaic and tropical rainforest).

The model achieved the emission target of decreasing approximately 50% compared to the baseline scenario (e.g. 32.2 $GtCO_2e$). China and the United States are mainly responsible for this decrease in emissions (e.g. 18% and 19% of the global GHG reduction, respectively) followed by South America (14%), the European Union (8%) and Sub-Saharan Africa (7%).

As shown in table 2, the reductions in global GHG emissions are 4% smaller (e.g. 956 $MMTCO_2e$) under the presence of climate change induced agricultural yield shocks (scenario 2). While total emissions fall 4%, forest carbon sequestration falls by 15%. This result clearly demonstrates that forest carbon sequestration becomes somewhat less attractive once climate induced crop yield changes come into the picture. One of the possible explanations is that, due to decreases in crop yields, it is necessary to increase cropland and decrease forest expansion. As a consequence, forest carbon sequestration is lower, forcing other adaptation methods to have a bigger role.

<Table 2 here>

Changes in land cover

We present in tables 3 and 4 the changes in forest cover, cropland and pastureland of each scenario with respect to the baseline by AEZ and region, respectively. In both scenarios, land is converted from cropland and pasture to forest as would be expected. However, in scenario 2 with decreased crop yields, only half as much cropland is converted. There is also less total addition to forest in scenario 2. Nine percent more pasture is converted in scenario 2. With the reduced crop yields, less land is available for forest carbon sequestration, so there is less total forest land added and more pasture converted.

<Table 3 here>

<Table 4 here>

The main increases in forest cover occur in the tropical climate with long growth period (e.g. AEZs 4-6) and the template climate with growth period longer than 360 days (AEZ 12) for both scenarios. This occurs especially for the South American countries that possess the vast Amazon region, and also Sub-Saharan Africa, United States and the European Union.

Changes in harvested area of crops

Tables 5 and 6 present the changes in harvested areas per agricultural sector (in Mhas) of each scenario with respect to the baseline by AEZ and region, respectively.

<Table 5 here>

<Table 6 here>

The presence of the tax regime on GHG emissions motivates a decrease in production of agricultural commodities. This happens especially in paddy rice (which is associated with methane emissions), coarse grain and other agricultural products. Regions such as Sub-Saharan Africa, China, India and South East Asia are the most affected.

Under the presence of crop yield decreases, there is still a reduction in harvested area, but much less. In fact, the reduction in harvested area is less than half that of scenario 1 except for the other crops category.

Price and production impacts

Here, we examine the changes outputs and prices of some selected commodities for each scenario from the base data of the GTAP-AEZ-GHG model. For ease of exposition, we focus the discussion on agricultural products, forestry and livestock. Tables 7 and 8 provide the percentage

changes in output and supply prices per region for scenario 1. Tables 9 and 10 present these changes for scenario 2.

<Table 7 here>

<Table 8 here>

For scenario 1, there is an overall reduction in agricultural and livestock production in almost all of the sectors and regions due to the tax regime of \$175/ton-CO_2e. This is mainly because forestry area expands in response to the sequestration subsidy reducing land as endowment for other production, especially land intensive outputs. In addition, the carbon tax reduces economic activity in general which reduces the demand for agricultural and other products. As a result, prices go up for all the agricultural commodity and livestock prices. Likewise, for most of the regions and sectors, the changes in output prices are much higher than the change in output. Few regions, such as Other European countries, Japan and Middle East & North Africa regions have an increase in output in almost all their sectors even though they face rises in prices.

Forestry output (e.g. timber) has a notable increase in all the countries of the world due to the forest expansion, especially in Latin America, China and India. Timber price response is mixed, for Latin America, East Asia (including China but not India), Oceania and Sub-Saharan Africa there is an increase whereas in the other regions price goes down.

<Table 9 here>

<Table 10 here>

For scenario 2, in presence of crop yield shocks, output for agricultural commodities gets reduced by more than two times that of scenario 1. This is mainly caused by the decrease in cropland together with the loss in agricultural productivity in different regions. The supply prices

rises abruptly in this scenario. The prices for most agricultural and livestock products are often more than double their original value. Thus, the loss in productivity will reflect most of its response in prices. For developing regions such as Sub-Saharan Africa, India and Central America the rise in price is higher than 200% for almost all of the agricultural and livestock commodities.

Macroeconomic variables

As discussed in the previous section, the tax regime increases the supply prices of different commodities, especially agricultural and livestock outputs. As a consequence, consumers suffer an increase in the general price level. Table 11 shows changes in the consumer price and GDP price indices. The most affected regions are Russia, Sub-Saharan Africa and India. The least affected are the US and Japan followed by Canada.

<Table 11 here>

The carbon tax policy decreases real GDP across the world. Emerging economies such as Sub-Saharan Africa, Central and Eastern Europe, China, India and Brazil suffer the most (table 12). Countries and regions the least affected are Japan, US, EU and other Europe. The situation gets much worse for these regions under the presence of crop yield shocks (there is an additional fall in regional GDP of 4.5%-11%). The adverse impacts on GDP are more severe in general for developing countries and regions. This result may have impacts on the acceptability of a global carbon tax.

<Table 12 here>

The implemented carbon policy reduces welfare (measured in terms of equivalent variation (EV)) across the world. The values are presented per region in the table 13. Implementing forest sequestration with an incentive of 175 \$/ton-CO_2e under the presence of climate change induced

agricultural productivity shocks represented losses in social welfare at the global scale of $1900 billion.

Comparing both scenarios, the additional loss due to the incorporation of crop yield shocks is about $586 billion (45% of total welfare loss). This suggests a significant underestimation of social welfare losses if the agricultural productivity variation is not included in the carbon sequestration model.

<Table 13 here>

Every region but one suffers a loss in welfare. In general larger economies suffer larger losses because the welfare losses are aggregate and not per capita. In presence of the climate change impacts on crop yield, we observe that the European Union is the region with worst social welfare changes with additional losses of -$123 billion followed by China (-$66 billion), the United States (-$61 billion) and India (-$60.7 billion).

Interestingly, Canada is the only region with slightly better social welfare when there is presence of crop yield shocks ($0.7 billion), which suggests that under climate change this region is not affected heavily but instead receives benefits from climate change. This is consistent with Stern (2007), van der Mensbrugghe (2013) and Ouraich et al. (2014) studies. Yield changes are sometimes positive for regions that have colder climates.

Likewise, regions such as Russia, Oceania, Other European countries and South East Asia do not have significantly changes in social welfare under the presence of crop yield variations. This suggests that the underestimation of the forest sequestration costs is heterogeneous depending on the region located.

Conclusions

In this paper we have investigated the extent to which forest carbon sequestration is impacted when climate change induced changes in crop yields are included in the analysis. We use and modify the global computable general equilibrium GTAP-AEZ-GHG, which is an extended version of the standard GTAP model, developed and modified by Golub et al (2009, 2012). The model explicitly analyzes the effects of forest carbon sequestration in reducing GHG emissions and relates different sources to their respective type of emissions.

With this framework, we implement a carbon tax of 175 $/ton-$CO_2$e to reduce the emissions by approximately 50% per annum GHGs to obtain the targets described in IPCC RCP 4.5 projections (IPCC-WGII, 2014a). This RCP was selected because it is considered a mitigation scenario for climate change, where it is required to impose a tax regime to the entire world and to move towards cleaner energy technologies and reforestation efforts (Thomson, et al., 2011). In order to evaluate the role of forest sequestration under the presence of climate change induced agricultural yield shocks, we incorporate a scenario where we implement these shocks together with the tax regime in the GTAP-AEZ-GHG model. The crop yield shocks were collected from AGMIP, which calculated these values combining two types of models: the HadGEM2-ES (a global circulation model) together with the LPJmL (a crop model), under the projections of the RCP 4.5.

The two scenarios were compared in terms of GHG emission reductions, changes in land cover, harvested area, outputs of production, prices and social welfare (in terms of equivalent variation). In the absence of crop yield shocks, the GHG emission reduction was achieved to be 50% of the baseline where forest sequestration represented about 32% of the GHG emission reduction. Thus, forest area had to increase whereas pastureland and cropland had to decrease

globally. The reduction in cropland induced decreases in agricultural and livestock production and increases in prices of agricultural commodities, dairy and ruminant outputs. These changes resulted in increased prices and losses in social welfare for the global economy, which varied significantly by region

Under the presence of climate change induced agricultural yield shocks and the tax regime of 175$/$CO_2$e we observed that cropland reductions were smaller in order to compensate the overall negative impacts of crop productivities. Thus, forest cover does not increase as much as in the first scenario, which results in a decrease of the forest role in sequestering carbon. However the loss of crop yields decreases significantly the output of agricultural products and livestock; but the most dramatic changes are in the rise of supply prices of these products. This suggests that, prices are more sensitive that the outputs. Prices in several regions-sectors go up by more than 200% of the original baseline. Social welfare as measured by equivalent variation falls in every country but Canada. Welfare falls 45% more when the crop yield shocks are included.

When climate change induced yield shocks are included, there is less forest carbon sequestration as would be expected. Real GDPs decline more across the world, and welfare losses are higher as well. Generally developing countries suffer much greater losses than richer countries. There is less cropland converted to forest. Agricultural production falls, and agricultural prices increases are much larger. These results highlight the importance of including climate change crop yield impacts in any analysis of GHG reduction including forest carbon sequestration.

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Table 1. Reduction in GHG emissions from the baseline per scenario (in MMT CO_2e) due to changes in consumption and production

Region	Scenario 1 (Only tax regime)			Scenario 2 (tax + yield shocks)		
	Non-CO_2 GHG gases	CO_2	GHG emissions	Non-CO_2 GHG gases	CO_2	GHG emissions
United States	-616	-2922	-3537	-574	-2953	-3526
European Union	-408	-1442	-1849	-350	-1463	-1813
Brazil	-309	-131	-440	-308	-143	-452
Canada	-80	-256	-336	-70	-259	-329
Japan	-25	-259	-284	-28	-271	-299
China	-839	-1986	-2824	-834	-2031	-2864
India	-285	-597	-882	-304	-639	-943
Central America	-102	-232	-333	-104	-241	-346
South America	-218	-188	-406	-226	-197	-423
East Asia	-78	-259	-337	-82	-273	-354
Malaysia & Indonesia	-126	-223	-348	-137	-234	-371
South East Asia	-211	-156	-367	-209	-163	-372
South Asia	-119	-76	-194	-123	-81	-204
Russia	-217	-991	-1207	-218	-999	-1217
Other Central Europe	-298	-616	-914	-288	-632	-920
Other European countries	-10	-36	-46	-8	-36	-45
Middle East & North Africa	-192	-635	-827	-194	-667	-861
Sub-Saharan Africa	-590	-289	-880	-633	-294	-927
Oceania	-82	-219	-302	-68	-223	-291
TOTAL	**-4803**	**-11511**	**-16315**	**-4758**	**-11799**	**-16556**

Table 2. Reduction of GHG emissions by forest carbon sequestration and other changes (difference from the baseline, in MMT CO_2e), changes in share of forest carbon sequestration in the emission reduction (in %) per scenario

Region	Scenario 1				Scenario 2			
	Forest Sequestration	Reduction from other activities	Total GHG reduction	Share Forest sequestration	Forest Sequestration	Reduction from other activities	Total GHG reduction	Share Forest Sequestration
United States	733	3537	4270	17%	487	3526	4013	12%
European Union	77	1849	1926	4%	39	1813	1852	2%
Brazil	762	440	1203	63%	718	452	1170	61%
Canada	148	336	483	31%	106	329	435	24%
Japan	115	284	399	29%	58	299	357	16%
China	1656	2824	4480	37%	1475	2864	4340	34%
India	524	882	1406	37%	342	943	1285	27%
Central America	382	333	715	53%	318	346	664	48%
South America	1835	406	2241	82%	1744	423	2168	80%
East Asia	313	337	650	48%	272	354	626	43%
Malaysia & Indonesia	76	348	424	18%	47	371	418	11%
South East Asia	59	367	426	14%	41	372	412	10%
South Asia	62	194	256	24%	24	204	227	10%
Russia	18	1207	1225	1%	14	1217	1231	1%
Other Central Europe	36	914	950	4%	18	920	938	2%
Other European countries	1	46	47	3%	0	45	45	1%
Middle East & North Africa	26	827	853	3%	8	861	868	1%
Sub-Saharan Africa	868	880	1748	50%	809	927	1736	47%
Oceania	126	302	428	29%	99	291	390	25%
GLOBAL	**7817**	**16315**	**24131**	**32%**	**6619**	**16556**	**23175**	**29%**

Table 3. Changes in land cover per AEZ (in millions of hectares from the baseline) per scenario

	Scenario 1			Scenario 2		
AEZ	**Forest cover**	**Cropland**	**Pastureland**	**Forest cover**	**Cropland**	**Pastureland**
AEZ 1	1.1	-5.1	4.0	1.2	-2.5	1.3
AEZ 2	5.0	-18.0	13.0	6.3	-10.7	4.4
AEZ 3	55.4	-45.2	-10.2	40.2	-21.9	-18.2
AEZ 4	158.8	-58.6	-100.2	133.9	-23.8	-110.0
AEZ 5	194.4	-64.3	-130.2	165.5	-30.5	-134.9
AEZ 6	124.1	-46.7	-77.4	101.0	-22.6	-78.4
AEZ 7	21.5	-2.5	-18.9	21.6	-10.0	-11.6
AEZ 8	46.4	-26.7	-19.7	44.9	-18.0	-26.9
AEZ 9	75.6	-42.3	-33.3	61.2	-24.4	-36.8
AEZ 10	117.4	-73.3	-44.1	76.9	-26.9	-49.9
AEZ 11	79.6	-51.7	-27.8	55.7	-22.9	-32.8
AEZ 12	110.2	-57.8	-52.3	93.3	-37.0	-56.3
AEZ 13	9.1	-1.8	-7.3	8.1	-2.3	-5.9
AEZ 14	22.7	-6.1	-16.6	18.8	-1.9	-16.9
AEZ 15	46.5	-14.1	-32.4	37.1	-4.6	-32.6
AEZ 16	6.7	-0.9	-5.8	6.3	-0.5	-5.8
AEZ 17	0.4	0.0	-0.4	0.4	0.0	-0.4
AEZ 18	0.0	0.0	0.0	0.0	0.0	0.0
TOTAL	**1074.8**	**-515.1**	**-559.7**	**872.5**	**-260.6**	**-611.9**

Table 4. Changes in land cover per region (in millions of hectares from the baseline) per scenario

	Scenario 1			Scenario 2		
Region	**Forest cover**	**Cropland**	**Pastureland**	**Forest cover**	**Cropland**	**Pastureland**
United States	107.2	-55.8	-51.4	75.2	-24.9	-50.4
European Union	32.8	-19.1	-13.7	18.3	-3.3	-15.0
Brazil	147.2	-33.2	-114.0	138.3	-24.2	-114.1
Canada	21.9	-16.3	-5.6	10.0	-3.2	-6.8
Japan	1.6	-1.4	-0.2	0.4	-0.2	-0.2
China	131.4	-84.9	-46.6	105.3	-51.2	-54.1
India	67.8	-67.5	-0.3	34.6	-33.3	-1.2
Central America	39.8	-15.3	-24.4	33.8	-9.1	-24.7
South America	145.0	-34.6	-110.4	141.2	-27.1	-114.2
East Asia	5.8	-2.7	-3.1	4.7	-1.4	-3.2
Malaysia & Indonesia	14.9	-13.2	-1.7	8.1	-6.3	-1.7
South East Asia	21.8	-18.4	-3.4	12.0	-8.6	-3.4
South Asia	11.4	-10.8	-0.6	2.1	-2.2	0.1
Russia	43.6	-13.9	-29.7	37.0	-7.7	-29.4
Other Central Europe	27.3	-18.0	-9.3	11.4	-0.9	-10.6
Other European countries	0.3	-0.1	-0.2	0.1	0.2	-0.2
Middle East & North Africa	1.2	-9.8	8.5	0.8	1.3	-2.2
Sub-Saharan Africa	238.3	-97.1	-141.2	224.4	-51.2	-173.3
Oceania	15.2	-2.8	-12.4	14.7	-7.3	-7.4
GLOBAL	**1074.8**	**-515.1**	**-559.7**	**872.5**	**-260.6**	**-611.9**

Table 5. Changes in harvested area per AEZ (in millions of hectares from the baseline) per scenario

	Scenario 1						Scenario 2					
AEZ	**Paddy Rice**	**Wheat**	**Coarse Grains**	**Oilseed**	**Sugar**	**Other Ag. Products**	**Paddy Rice**	**Wheat**	**Coarse Grains**	**Oilseed**	**Sugarcane**	**Other Ag. Products**
AEZ 1	-0.3	-0.1	-2.5	-0.4	0.0	-1.7	0.2	0.1	-0.9	-0.1	-0.1	-1.4
AEZ 2	-0.5	-0.4	-10.4	-2.5	0.0	-4.2	-0.4	-0.1	-3.2	-1.5	0.0	-4.4
AEZ 3	-7.9	-4.9	-12.5	-6.6	-0.9	-12.4	-2.0	-0.8	-4.2	-1.7	-0.3	-10.6
AEZ 4	-20.8	-2.0	-11.7	-5.5	-0.8	-17.9	-5.3	-0.1	-3.4	-1.3	-0.4	-10.9
AEZ 5	-19.2	-0.7	-10.2	-9.4	-2.6	-22.2	-6.2	0.3	-3.9	-3.6	-1.1	-13.5
AEZ 6	-13.7	-0.5	-6.8	-6.1	-3.2	-16.5	-6.3	-0.3	-2.9	2.0	-2.3	-10.9
AEZ 7	-0.2	-2.1	-0.4	0.1	0.0	0.0	0.0	-2.1	-1.2	-0.4	0.1	-5.1
AEZ 8	-0.7	-8.0	-7.7	-2.9	-0.2	-7.3	-0.7	-3.9	-2.5	0.5	-0.1	-8.9
AEZ 9	-1.1	-11.2	-12.0	-5.5	-0.4	-12.1	-0.9	-5.1	-7.2	0.2	-0.1	-8.7
AEZ 10	-2.0	-12.4	-22.8	-12.3	-1.0	-22.8	-1.3	-6.0	-11.7	0.9	-0.2	-5.9
AEZ 11	-6.4	-8.9	-10.2	-11.0	-0.4	-14.8	-2.3	-4.9	-5.6	-4.0	0.0	-4.3
AEZ 12	-15.4	-5.2	-7.7	-13.7	-0.6	-15.2	-7.5	-3.8	-5.3	-8.0	-0.7	-9.0
AEZ 13	0.0	-0.9	-0.3	-0.2	0.0	-0.4	0.0	-0.8	-1.0	0.1	0.0	-0.5
AEZ 14	0.0	-2.3	-1.4	-0.4	0.0	-2.0	0.0	-0.7	-0.7	0.1	0.0	-0.4
AEZ 15	-0.2	-3.6	-3.3	-1.3	0.0	-5.7	-0.2	-0.9	-2.1	0.1	0.0	-1.2
AEZ 16	0.0	-0.2	-0.2	-0.1	0.0	-0.3	0.0	-0.1	-0.2	0.0	0.0	-0.1
AEZ 17	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
AEZ 18	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
TOTAL	**-88.4**	**-63.3**	**-119.9**	**-77.7**	**-10.4**	**-155.4**	**-32.9**	**-29.3**	**-56.1**	**-16.8**	**-5.2**	**-95.7**

Table 6. Changes in harvested area per region (in millions of hectares from the baseline) per scenario

Region	Scenario 1						Scenario 2					
	Paddy Rice	Wheat	Coarse Grains	Oilseed	Sugarcane	Other Ag. Products	Paddy Rice	Wheat	Coarse Grains	Oilseed	Sugarcane	Other Ag. Products
United States	-0.9	-8.1	-15.7	-15.0	-0.4	-15.7	-0.4	-2.8	-8.6	-3.5	0.2	-7.1
European Union	-0.2	-5.0	-6.4	-0.5	-0.4	-6.6	0.2	-4.8	-6.2	3.8	0.5	3.5
Brazil	-2.1	-1.3	-8.0	-10.8	-3.5	-7.5	-1.0	-0.9	-5.9	-6.4	-2.0	-6.8
Canada	0.0	-5.0	-3.4	-3.2	0.0	-4.6	0.0	-0.8	-0.7	1.1	0.0	-1.9
Japan	-0.6	-0.1	0.0	0.0	0.0	-0.6	-0.1	0.0	0.0	0.0	0.0	-0.1
China	-21.0	-15.4	-15.0	-12.0	-0.6	-20.9	-10.5	-12.0	-6.5	-5.4	-0.6	-11.4
India	-22.6	-7.3	-7.9	-8.9	-1.5	-19.4	-3.7	-2.0	-3.2	-2.8	-0.6	-17.0
Central America	-0.5	-0.2	-6.9	-0.5	-1.5	-5.7	-0.2	-0.1	-4.1	-0.3	-0.8	-3.0
South America	-1.5	-5.1	-5.3	-10.8	-0.7	-11.3	-1.1	-4.2	-4.1	-7.4	-0.6	-8.6
East Asia	-0.9	-0.2	-0.4	-0.3	0.0	-0.9	-0.4	-0.1	-0.2	-0.2	0.0	-0.5
Malaysia & Indonesia	-6.7	0.0	-0.9	-3.1	-0.1	-2.3	-3.5	0.0	-0.6	1.2	-0.1	-2.4
South East Asia	-18.4	0.1	-1.0	0.9	0.0	0.0	-9.5	0.1	-1.2	3.5	-0.2	-0.4
South Asia	-7.1	-1.2	-0.3	-0.7	-0.2	-1.4	-0.4	1.2	-0.4	-0.1	-0.1	-1.6
Russia	-0.2	-4.7	-3.5	0.7	-0.1	-6.1	-0.1	-3.9	-0.2	1.6	-0.1	-4.3
Other Central Europe	0.0	-5.2	-4.9	-1.1	-0.4	-6.4	0.1	2.2	-3.3	2.4	-0.1	-1.6
Other European countries	0.0	0.0	0.0	0.0	0.0	-0.1	0.0	0.0	0.0	0.0	0.0	0.1
Middle East & North Africa	-0.5	-3.0	-2.2	-0.5	-0.2	-3.3	0.8	0.3	0.1	0.8	-0.1	-0.4
Sub-Saharan Africa	-5.2	-1.4	-37.7	-11.8	-0.7	-40.4	-3.3	-1.0	-12.3	-4.9	-0.6	-25.5
Oceania	0.0	-0.1	-0.4	-0.1	-0.1	-2.2	0.2	-0.6	1.2	-0.2	-0.1	-6.9
GLOBAL	-88.4	-63.3	-119.9	-77.7	-10.4	-155.4	-32.9	-29.3	-56.1	-16.8	-5.2	-95.7

Table 7. Changes in output (%) for scenario 1 (only tax regime/incentive for forest carbon sequestration)

Region	Paddy Rice	Wheat	Coarse Grains	Oilseed	Sugarcane	Other Ag. Products	Forestry	Dairy	Ruminants	Non Ruminants
United States	-19.6	-22.1	-16.0	-8.5	-2.8	-4.7	71.5	-6.4	-1.8	-5.5
European Union	73.7	-8.6	-5.0	26.8	-2.1	5.3	34.7	-5.1	6.3	-1.2
Brazil	-15.0	-54.1	-39.2	-50.1	-13.7	-31.3	311.9	-30.1	-58.4	-53.1
Canada	0.0	-26.0	-8.8	-6.2	-2.2	-15.3	63.6	-4.2	-25.4	13.0
Japan	10.6	17.0	15.8	7.5	-2.9	1.1	82.3	-3.3	25.9	4.9
China	-35.9	-41.7	-25.2	-34.3	-16.1	-19.9	331.9	-15.7	-44.0	-29.2
India	-15.0	-13.4	-11.6	-19.0	-11.1	-19.8	89.0	-23.8	-54.1	-15.7
Central America	2.8	-3.9	-9.5	-13.8	-8.8	-17.4	136.0	-14.3	-29.7	-6.8
South America	-37.8	-36.6	-27.2	-40.8	-13.3	-34.1	370.6	-27.6	-33.9	-25.8
East Asia	-24.1	-28.5	-20.5	-39.2	-9.6	-22.7	524.2	-13.5	-15.7	-19.0
Malaysia & Indonesia	-24.3	0.0	-6.8	7.8	-11.4	-19.7	55.7	5.7	-60.2	-12.5
South East Asia	-51.7	150.7	-17.7	18.4	-8.1	1.8	167.9	-32.3	-79.0	-18.8
South Asia	-14.7	-17.4	-10.8	-18.1	-8.5	-10.3	56.6	-21.2	-45.6	-19.3
Russia	-99.2	-30.0	-25.4	22.2	-20.5	-18.6	43.5	-50.1	-52.6	-30.7
Other Central Europe	37.5	-20.9	-28.9	-7.8	-24.7	-12.1	111.1	-30.9	-23.4	-22.0
Other European countries	354.7	-10.1	-4.5	0.5	-5.1	6.4	22.1	-0.1	25.4	2.1
Middle East & North Africa	14.0	19.9	4.4	10.5	-10.6	3.5	70.0	-9.4	-16.7	-12.5
Sub-Saharan Africa	-25.2	-30.7	-15.7	-0.9	-24.4	-16.7	118.8	-67.9	-57.7	-45.4
Oceania	126.6	26.9	14.3	42.5	-2.3	-2.4	35.2	-39.6	-10.8	-17.3

Table 8. Changes in supply prices (%) for scenario 1 (only tax regime/incentive for forest carbon sequestration)

Region	Paddy Rice	Wheat	Coarse Grains	Oilseed	Sugarcane	Other Ag. Products	Forestry	Dairy	Ruminants	Non Ruminants
United States	129.1	48.3	66.0	56.3	56.2	41.5	-19.1	41.5	92.4	22.7
European Union	38.2	36.5	35.4	27.4	33.0	22.2	-9.9	46.8	104.8	26.6
Brazil	118.4	93.8	99.5	100.1	107.4	64.3	1433.5	239.8	861.8	91.3
Canada	1.3	47.4	51.8	53.9	52.9	46.3	-6.5	47.1	121.5	22.5
Japan	33.9	31.6	30.7	29.3	26.0	27.5	-14.6	40.0	57.1	22.6
China	342.4	91.4	83.6	62.1	73.9	67.3	200.9	118.9	499.8	54.0
India	269.8	77.4	71.6	57.0	51.7	57.7	-38.7	36.7	570.4	6.7
Central America	99.6	41.8	54.6	58.7	59.6	51.3	175.6	94.0	239.0	25.4
South America	256.0	69.1	86.3	91.6	110.1	86.6	1613.7	139.6	358.4	47.7
East Asia	86.7	83.8	80.6	78.6	63.0	79.6	401.4	74.4	136.5	37.2
Malaysia & Indonesia	266.0	-20.2	49.5	71.1	58.3	48.4	1.5	77.2	803.5	41.0
South East Asia	383.5	21.8	13.8	40.4	28.2	31.6	-5.7	176.5	1242.4	47.6
South Asia	137.1	60.0	55.4	44.2	28.5	33.5	-33.4	73.5	552.1	46.9
Russia	654.1	31.1	21.3	14.5	5.4	12.0	22.8	175.3	199.8	34.5
Other Central Europe	16.7	27.4	39.5	17.9	22.6	14.7	-33.7	60.0	97.5	28.4
Other European countries	28.3	38.0	35.0	45.8	38.4	20.9	-13.5	36.5	79.4	14.3
Middle East & North Africa	34.6	6.0	6.6	8.2	6.2	3.9	-20.2	38.5	102.2	16.7
Sub-Saharan Africa	100.0	43.7	48.7	22.7	71.8	35.4	527.8	786.3	606.3	95.8
Oceania	91.6	30.4	28.8	36.9	35.5	33.8	12.8	85.1	185.4	31.6

Table 9. Changes in output (%) for scenario 2 (tax regime/incentive and crop yield shocks)

Region	Paddy Rice	Wheat	Coarse Grains	Oilseed	Sugarcane	Other Ag. Products	Forestry	Dairy	Ruminants	Non Ruminants
United States	-42.9	-26.7	-35.7	-26.8	-7.1	-20.1	54.9	-10.3	-3.8	-4.1
European Union	44.7	-39.4	-33.6	14.2	-4.2	8.5	21.2	-5.6	4.6	-5.2
Brazil	-48.2	-68.7	-54.2	-65.1	-26.2	-55.9	294.6	-33.4	-59.7	-54.0
Canada	0.0	2.9	-39.8	7.5	-22.0	-21.6	48.9	-8.5	-34.9	-7.2
Japan	-1.3	4.9	10.6	3.0	-8.2	-7.4	44.9	-9.3	-3.6	-5.8
China	-40.0	-47.6	-32.2	-32.1	-19.2	-26.8	297.7	-21.3	-46.5	-37.9
India	-30.5	-23.0	-25.0	-39.0	-27.9	-34.4	63.8	-41.4	-53.8	-31.3
Central America	-53.1	-28.8	-23.9	-49.8	-21.0	-33.2	115.3	-21.3	-33.2	-16.5
South America	-62.1	-64.5	-47.1	-60.9	-26.5	-56.0	353.2	-33.0	-37.8	-33.5
East Asia	-41.1	-42.0	-28.1	-47.0	-5.7	-28.7	457.0	-25.6	-37.5	-33.9
Malaysia & Indonesia	-43.3	0.0	-32.8	-17.1	-32.7	-45.4	39.5	-2.9	-63.0	-17.4
South East Asia	-49.3	56.0	-34.7	-20.0	-13.7	-2.5	121.4	-37.1	-78.9	-20.0
South Asia	-26.5	-5.6	-19.3	-33.2	-18.6	-17.8	27.0	-30.4	-46.2	-28.4
Russia	-87.9	-31.9	-4.3	18.7	-26.2	-14.5	37.6	-52.1	-54.0	-31.3
Other Central Europe	8.2	-4.3	-28.9	12.9	-30.9	-5.3	59.6	-30.6	-26.2	-16.6
Other European countries	191.7	20.3	31.3	61.3	-6.5	19.5	5.7	1.3	27.8	9.5
Middle East & North Africa	44.2	-8.6	-4.9	6.2	-22.9	-3.2	24.3	-16.3	-21.8	-17.7
Sub-Saharan Africa	-70.8	-65.5	-32.4	-57.1	-37.5	-49.0	111.7	-73.8	-66.5	-53.4
Oceania	182.8	-23.6	-17.6	-31.2	-2.0	-39.6	30.0	-36.6	0.5	-0.9

Table 10. Changes in output (%) for scenario 2 (tax regime/incentive and crop yield shocks)

Region	Paddy Rice	Wheat	Coarse Grains	Oilseed	Sugarcane	Other Ag. Products	Forestry	Dairy	Ruminants	Non Ruminants
United States	413.1	210.6	285.9	367.2	332.6	220.8	-4.8	69.3	115.6	32.0
European Union	186.3	215.9	279.8	267.9	131.5	121.5	10.8	64.2	119.7	56.7
Brazil	515.9	379.9	419.5	498.6	479.6	385.5	1443.2	253.9	878.5	105.5
Canada	1.8	190.5	341.5	303.2	673.5	197.7	10.0	79.6	156.5	52.3
Japan	213.5	173.8	181.9	227.4	156.3	158.8	10.2	83.5	119.8	40.4
China	438.7	162.6	252.8	239.9	92.5	193.1	207.5	153.7	522.7	80.3
India	1012.8	176.6	263.7	454.8	329.9	248.2	-32.5	40.0	696.6	25.8
Central America	490.8	210.4	240.7	425.4	246.2	236.8	185.2	140.2	271.2	67.0
South America	750.2	319.8	399.2	501.0	329.6	460.2	1632.5	156.1	359.2	74.4
East Asia	353.6	284.2	240.3	355.9	-6.1	218.3	405.3	142.6	221.3	78.4
Malaysia & Indonesia	632.2	-27.4	298.9	713.6	418.8	256.4	20.2	106.0	817.0	51.2
South East Asia	477.5	160.2	227.0	394.7	146.0	166.7	10.0	209.8	1271.9	61.6
South Asia	448.2	132.0	171.4	255.8	106.7	156.9	-24.5	69.7	621.5	59.9
Russia	562.1	150.4	60.8	214.1	123.5	71.1	38.1	197.0	223.7	45.3
Other Central Europe	122.2	122.0	112.1	177.8	101.1	87.1	-18.6	102.8	131.7	81.3
Other European countries	126.7	147.8	94.1	213.7	107.7	110.8	10.8	48.1	90.2	22.3
Middle East & North Africa	128.4	131.6	106.0	171.7	56.8	97.1	2.9	53.9	117.2	32.0
Sub-Saharan Africa	427.4	244.6	428.2	533.4	164.3	267.9	524.0	790.4	621.9	108.5
Oceania	293.6	186.1	254.2	343.7	81.1	267.4	29.0	90.2	190.3	37.1

Table 11. Changes in the price index for private consumption expenditure (%) and GDP price index (%) per scenario

Region	Only tax regime (Scenario 1)		Tax + Carbon Yield (Scenario 2)	
	Price index for private consumption	GDP price index	Price index for private consumption	GDP price index
United States	4.6	3.0	4.1	2.2
European Union	7.2	4.7	8.8	4.7
Brazil	15.5	6.3	21.5	7.0
Canada	6.0	2.9	6.7	3.8
Japan	4.2	2.4	5.7	1.6
China	31.0	13.1	55.4	21.5
India	34.2	22.1	97.1	57.8
Central America	11.4	7.0	18.1	10.3
South America	13.6	8.5	25.1	15.3
East Asia	10.7	5.5	19.8	7.2
Malaysia & Indonesia	34.3	13.7	67.2	24.0
South East Asia	19.8	12.2	27.9	18.0
South Asia	31.1	21.7	74.0	50.7
Russia	45.0	16.4	53.0	19.0
Other Central Europe	26.2	21.4	42.3	40.7
Other European countries	6.0	3.8	6.4	2.9
Middle East & North Africa	19.3	7.5	33.5	14.5
Sub-Saharan Africa	46.4	31.5	86.7	53.0
Oceania	8.4	8.0	12.0	12.2

Table 12. Changes in GDP (%) per scenario

Region	Only tax regime (Scenario 1)	Tax + Carbon Yield (Scenario 2)
United States	-2.0	-2.8
European Union	-2.6	-4.0
Brazil	-7.8	-12.3
Canada	-4.6	-5.8
Japan	-1.1	-1.7
China	-16.0	-20.5
India	-12.9	-23.9
Central America	-4.1	-6.8
South America	-8.8	-13.9
East Asia	-4.8	-7.0
Malaysia & Indonesia	-9.5	-15.6
South East Asia	-7.2	-9.5
South Asia	-9.4	-17.6
Russia	-22.9	-24.5
Other Central Europe	-18.6	-26.0
Other European countries	-1.4	-1.8
Middle East & North Africa	-7.5	-10.7
Sub-Saharan Africa	-19.7	-28.8
Oceania	-4.5	-6.7

Table 13. Changes in Equivalent Variation (EV) in $US billions per scenario

Region	Only tax regime (Scenario 1)	Tax + Carbon Yield (Scenario 2)
United States	-202.6	-263.6
European Union	-195.1	-318.3
Brazil	-39.9	-62.8
Canada	-26.1	-25.4
Japan	-54.1	-97.8
China	-225.5	-291.7
India	-61.4	-122.1
Central America	-41.3	-67.8
South America	-56.5	-93.5
East Asia	-37.0	-69.2
Malaysia & Indonesia	-25.1	-41.2
South East Asia	-30.7	-32.9
South Asia	-15.5	-28.3
Russia	-71.9	-77.8
Other Central Europe	-48.7	-58.8
Other European countries	-8.0	-11.5
Middle East & North Africa	-84.5	-113.6
Sub-Saharan Africa	-66.2	-99.1
Oceania	-5.6	-6.3
GLOBAL CHANGE	**-1295.7**	**-1881.5**

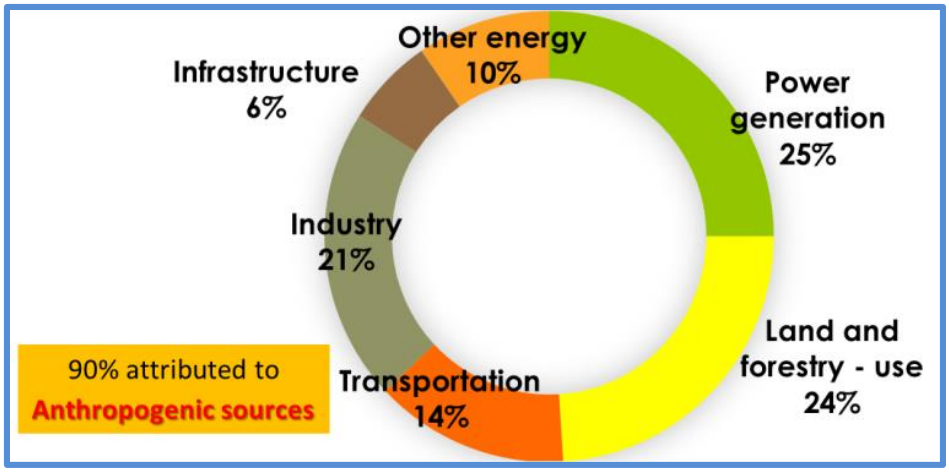

Figure 1. Direct greenhouse gas emissions (% of contribution) by economic sectors
Source: Adapted from IPCC report, 2014, modified by the authors in order to describe only direct emissions.

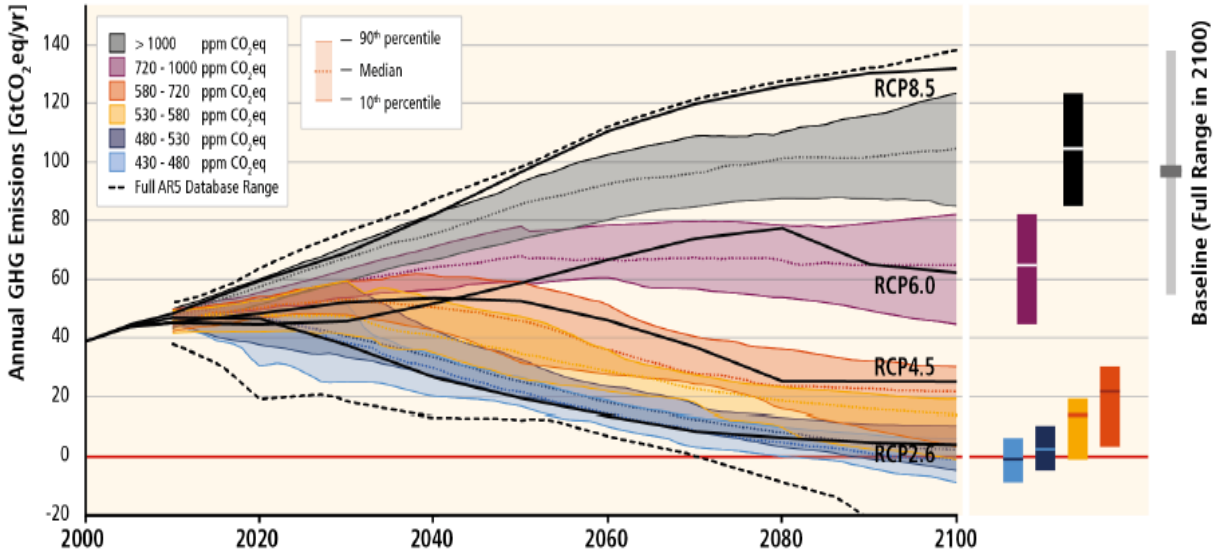

Figure 2. GHG Emission pathways between 2000-2100 for all the AR5 scenarios
Source: IPCC WGIII (2014) AR5. Modified by the authors

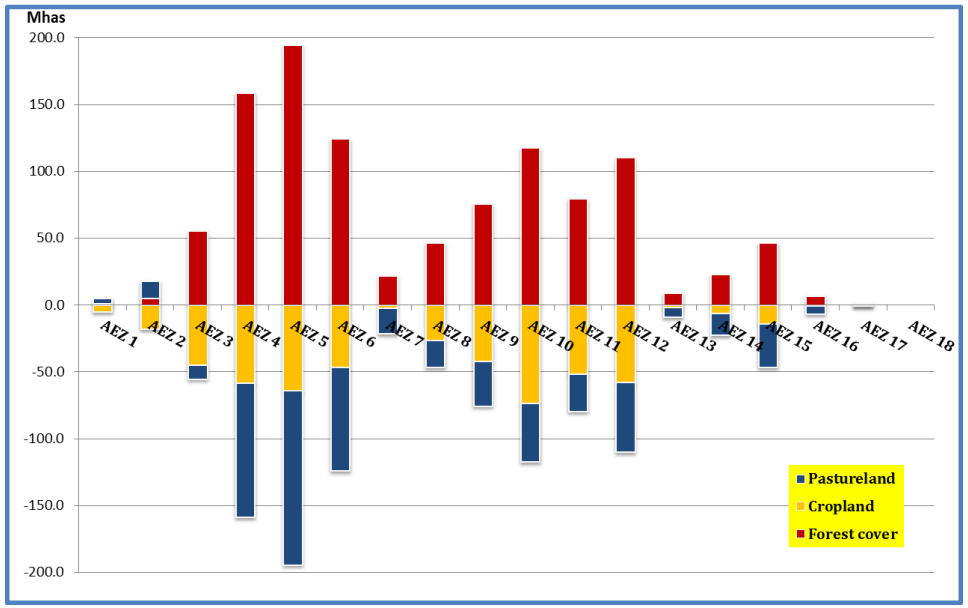

Figure 3a. Changes in land cover per AEZ (in millions of hectares from the baseline) for scenario 1

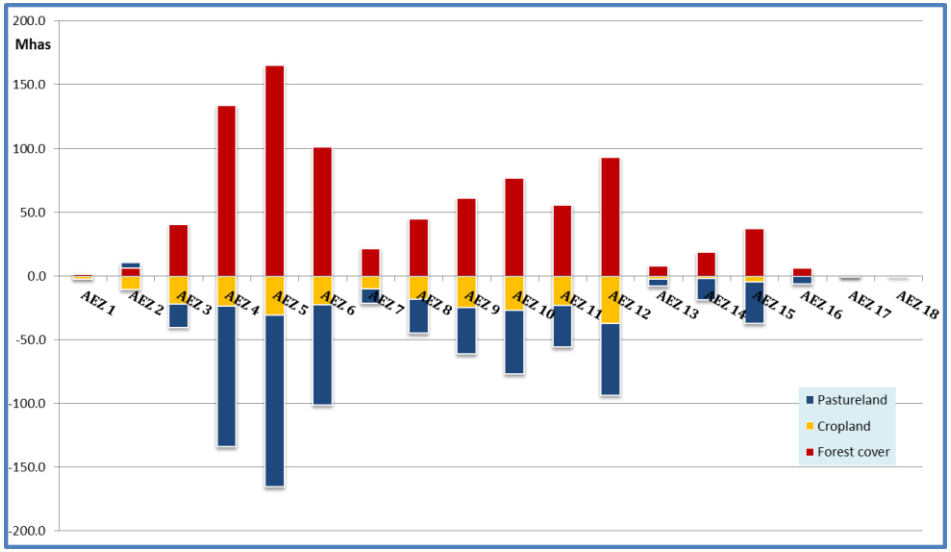

Figure 3b. Changes in land cover per AEZ (in millions of hectares from the baseline) for scenario 2

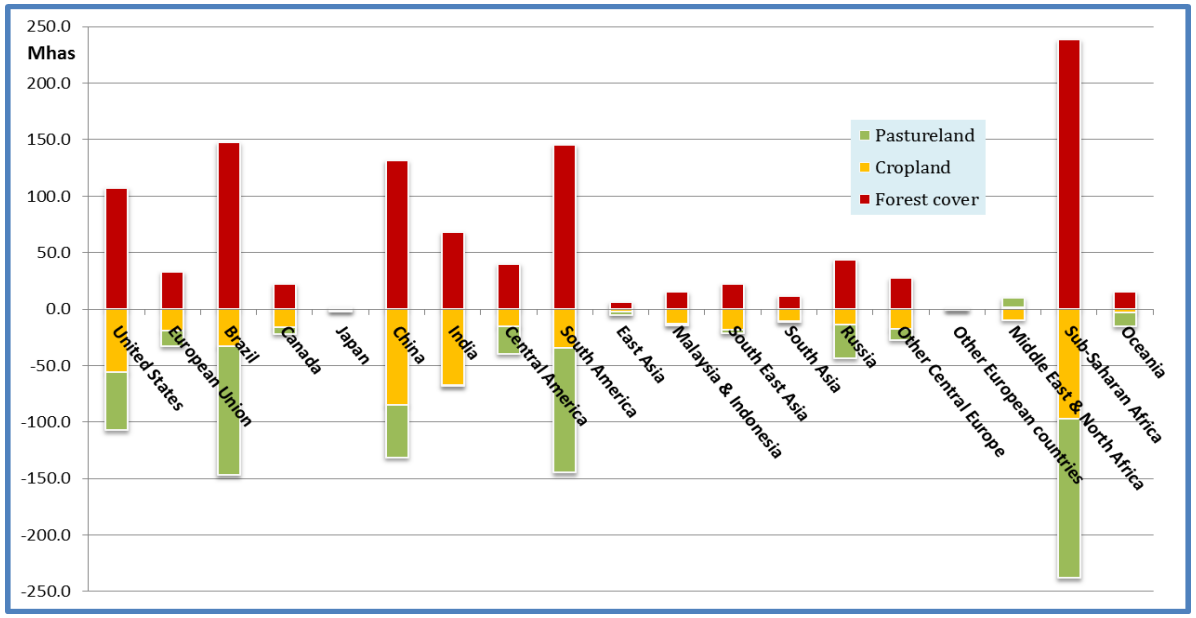

Figure 4.a Changes in land cover per region (in millions of hectares from the baseline) for scenario 1

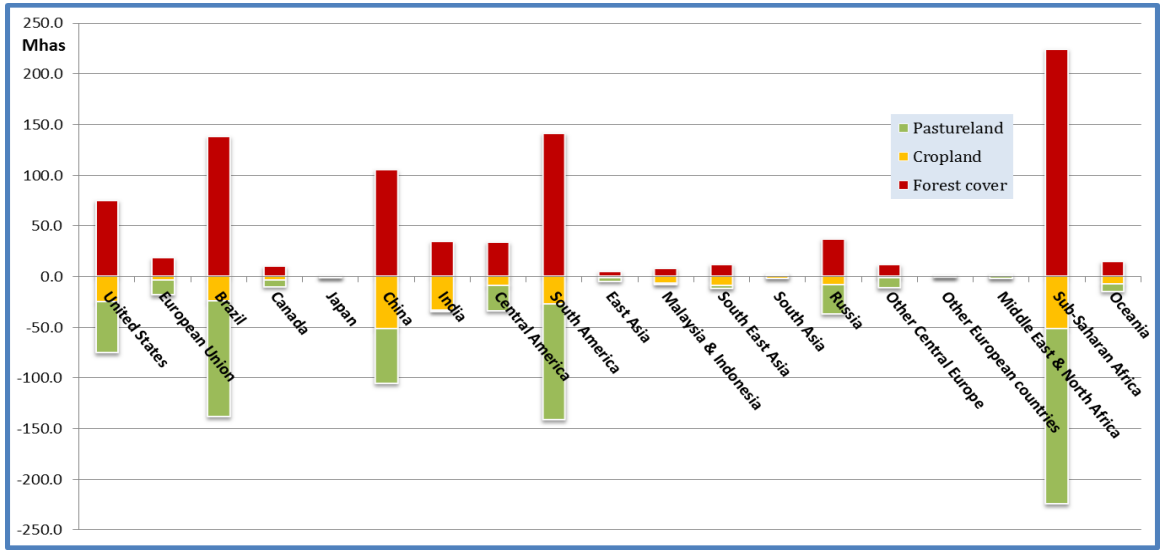

Figure4.b Changes in land cover per region (in millions of hectares from the baseline) for scenario 2

ANNEX A

Annex A1. The modification of the GTAP-AEZ-GHG model

The following formulation is added into the model:

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

where $y_{Z,C}^{RG}$, $Q_{Z,C}^{RG}$, $A_{Z,C}^{RG}$ are the productivity (in tons/ha), production (in tons) and harvested area (in hectares) of crop ***C*** at the agro-ecological zone ***Z*** and region ***RG***. The production and harvested area come from the database of the model.

Posteriorly, we difference 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 ($y_{Z,C}^{RG}$) is equivalent to our crop productivity changes (i.e. $\boldsymbol{S_{Z,G}^{RG}}$). Thus, the model becomes able to incorporate our crop yields shocks to evaluate the period 2000-2100.

Annex A2. Climate change impacts on agricultural productivity

GTAP-AEZ-GHG crops (G)	AGMIP crops (C)
Paddy rice (pdr)	Paddy rice
Wheat (wht)	Wheat
Cereal grains (gro)	Maize, millet
Oilseeds (osd)	Rapeseed, soybean
Sugarcane and sugar beet (c_b)	Sugarcane, sugar beet
Other agricultural products (ocp)	