Cost comparison of climate change mitigation options

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Abstract

The global community has reaffirmed its commitment to reduce greenhouse emissions to control the expected increase in the global average temperature. Thus, many governments and private sectors are interested in the cost-efficiency of frequently discussed mitigation methods – forest and pasture carbon sequestration (FPCS) subsidy, carbon tax, and biofuels – and their impacts on the global economy. We modified our new developed computable general equilibrium for the analysis. We simulate different rates to observe their mitigation potentials. Our results suggest that there is a trade-off between cost-efficiency and emission reduction between policies, where tax can achieve larger emission reductions under the same rate of FPCS but with higher economic costs. Likewise, combining tax and an equivalent subsidy has a larger reduction potential due to the synergistic effects, but food prices increase dramatically. Biofuels proved to be costlier than FPCS or tax.

Keywords: climate change, food price, mitigation policies, sequestration subsidy, carbon tax

JEL codes: Q15, R52, Q54.

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1. Introduction

The global community, in the 2015 Paris Agreement of the United Nations Framework Convention on Climate Change (UNFCCC), pledged its commitment to reduce GHGs emissions. The agreement, in which about 150 countries are involved, seeks to hold the global average temperature increase below 2°C above preindustrial levels (i.e. average temperature during 1850-1900)[1-5]. This implies ambitious emission reduction targets with actions in many areas of the economy, such as agriculture, energy and transport industries, which are major anthropogenic emission sources[6-8]. The summary report by the Secretariat of the UNFCCC [9] synthetizes estimates for the contribution of the parties that have to be achieved by 2025 and 2030. These calculations are based on the Intergovernmental Panel on Climate Change (IPCC) mitigation scenarios which cover the so-called Kyoto gases (i.e. CO_2 and non-CO_2 emissions). In order to achieve the goal of the Paris Agreement, annual global emissions should be about 3.3GtCO_2e lower in 2030[5,9], and about 50% reduction in GHGs by 2100[10].

At the national level, many mitigation strategies can be adopted. There are many options for reducing GHG emissions including greater reliance on renewable or low carbon electricity, improved fuel economy in transportation, more efficient buildings and energy delivery systems. With respect to agriculture, Levin, et al. [11] discussed three possible actions that are commonly mentioned in the literature: forest carbon sequestration, biofuel expansion and carbon pricing[10,12,13]. Each of these has different effects on the global economy and environment.

Forestry helps to reduce GHGs emissions by capturing atmospheric CO_2 in its biomass and land through photosynthesis[14-16]. This natural process is called forest carbon sequestration [FCS]. According to Noble, et al. [17], forest biomass has accumulated about 284 gigatonnes of carbon [GtC] with an overall gross terrestrial uptake of 2.4 GtC/yr. In addition, a substantial body of evidence suggests that this method is relatively less expensive than other types of mitigation[16,18-22], bringing the attention of policy makers in the last quarter century [14,23-25].

Biofuels appear to offer a cleaner, greener and in general more sustainable alternative to fossil fuels[26,27]. Biofuels have become a focal point for many transport industries that are seeking to cooperate in this effort, including the international aviation sector [4]. This is partially because biofuels can achieve multiple goals such as: (1) improving the security of energy supply[28], (2) reducing GHG emissions[29], and (3) developing business opportunities in the agricultural and rural sectors[30]. Thus, governments have promoted the use of biofuels through different subsidy and regulatory policies. The European Union (EU) has implemented the Renewable Energy Directives (RED). These mandates require Member states to achieve goals in terms of shares in total energy consumption and in transportation[31]. In the US, 36 billion gallons ethanol equivalent of biofuels must be consumed annually by 2022 as directed by the Energy Independence and Security Act (EISA) of 2007[32]. The EU commission and US Federal Aviation Administration have also biofuel production targets for the upcoming years [4,33,34].

Taxing carbon emissions is also recognized by economists and international organizations as a highly efficient market-based method[35]. This instrument encourages producers and consumers to move away from carbon intensive activities, commodities and technologies towards cleaner options[24]. Another advantage is that, in a perfectly competitive world, emissions are reduced in places with high current emission intensity or potential for mitigation in the least expensive manner. In order to motivate global reductions in emissions, an equal carbon tax to all nations and economic sectors is generally proposed. Agriculture also would be included[2].

Notwithstanding, each of these popular methods can bring some side-effects. Aggressive forest carbon sequestration policies can become a threat for food security due to land competition between forest, pasture and agriculture. This competition can bring about huge food price rises, especially in developing economies where food takes a larger share in national income[36-38]. Biofuel also raises concerns as a competitor with food production since first-generation biofuels use agricultural feedstocks such as grains, sugar crops, and oilseeds[39,40]. In addition, biofuels are relatively expensive, which makes its implementation in the industry somewhat difficult[41]. A global carbon tax affects significantly countries with high rate of carbon emissions intensity[2,42]. This could affect the livestock, transportation, and energy sectors and lower household consumption and real income[36].

This study aims to improve our understanding of climate change mitigation policies by addressing these important questions: What is the cost for the global economy of implementing alternative climate change mitigating policies to reduce global emissions? What are the impacts in terms of welfare, food security, and prices? Which method is more cost-efficient for each region? Is there a linear relationship between the mitigation method and its impacts? (i.e. doubling the tax/subsidy/biofuel expansion doubles the emission reduction?) What are the environmental and economic impacts of implementing a combination of emissions tax and carbon sequestration subsidy (tax-subsidy) regime versus the implementation of each regime (either a tax or a carbon sequestration subsidy) in isolation?

To accomplish the objective of this paper, we made use of our new version of a well-known computable general equilibrium (CGE) model to calculate the economic and environmental impacts of climate change mitigation entitled GTAP-BIO-FCS. We modified and expanded our first version used in Pena-Levano et al.[37] to include carbon sequestration from pasture land [PCS]. This permits us to provide further insights and evaluate indirect land use change [iLUC]. This model is quite well suited for the economic analysis of climate change policies including carbon sequestration subsidy to pasture and forest (FPCS), carbon tax, and biofuels. We defined four policies: (i) A FPCS subsidy [in $/tCO_2e$], (ii) a global uniform tax on GHGs [in $/tCO_2e$], (iii) a global uniform carbon tax and an equivalent FPCS subsidy, and (iv) expansion of biofuels. For cases (i)-(iii) we simulated tax and/or subsidy rates from 5$/tCO_2e$ to 80$/tCO_2e$ to achieve different global GHG emissions reductions targets. For the biofuel case, the US, EU, and Brazil biofuels were increased accord to their targets explained in the next section. Finally, we compared the cost-efficiency [in $/tCO_2e$] of each mitigation policy and their global impacts on welfare and food.

We chose this range [5 – 80$/tCO_2e$] to evaluate how the cost-efficiency of each mitigation method (except biofuels) can vary according to the emission reduction target. Specifically, we chose 80$/tCO_2e$ as our highest tax and/or subsidy rate because this rate achieves the 50% emission reduction by 2100 proposed in the IPCC 'mitigation scenario' [RCP 4.5][10]. Hence, our research intends to contribute to the literature because (1) It shows the economic and environmental impacts of relevant climate change mitigation methods, (2) It compares the cost-efficiency of each method at a global scale, (3) It also provides the importance of implementing these alternative methods simultaneously versus in isolation, (4) It evaluates the relationship between cost-efficiency and emission reduction, and (5) It gives important feedback regarding the distribution of welfare effects.

2. Methodology

2.1 The economic computable general equilibrium [CGE] model: GTAP-BIO-FCS model

Computable general equilibrium [CGE] models are recognized to be suitable for policy analysis including environmental issues such as climate change[43,44]. The Global Trade Analysis Project [GTAP] model is a well-known CGE model which associates consumption, production, and trade in a multi-regional and multi-sectorial framework assuming perfect competition and constant returns to scale[45]. To estimate the economic and environmental impacts of alternative climate change mitigation policies, we use a special version of this model which takes into account FCS, PCS, biofuels and carbon taxes as explicit mitigation instruments.

This new model is entitled GTAP-BIO-FCS and is documented in Pena-Levano, et al. [46]. The core data used is the GTAP v7 database, which represents the global economy in 2004. It divides the world into 19 regions which includes 43 industries and 48 commodities. It considers the so-called Kyoto GHGs [CO_2 and non-CO_2 gases] and associates them with their emission sources in the demand and production sides, including emissions from agricultural activities. It separates annual carbon sequestration associated with forestry biomass from carbon stored in forestry land. It includes biofuels and their by-products such as distillers' dried grains with solubles [DDGS] and vegetable oil meals. The model also calculates welfare (in $US of equivalent variation [EV]) and decomposes the sources of welfare variation. In addition, in this study we extend our first version GTAP-BIO-FCS model to include carbon sequestration from pastureland, which is described in the next sub-section.

2.2 Modifications to the first version of the GTAP-BIO-FCS model to include pasture carbon sequestration

The first version of the model [GTAP-BIO-FCS v.1] was used in Pena Levano, et al. [36] to evaluate the impact of FCS subsidies on food security. Regional FCS supplies are based on the Global Timber Model (GTM) developed Sohngen and Mendelsohn [47] and calibrated by Golub, et al. [25]. Thus, the GTAP-BIO-FCS v.1 takes into account the 'gross gains' in annual FCS when we convert non-forest to forest land.

Nevertheless, because these values are 'gross FCS', it does not recognize which source of land (i.e. crop or pasture) is converted to forest, missing the fact that non-forest land can also generate soil carbon sequestration. For the case of cropland, several studies show evidence of the carbon sequestration potential from several crops [i.e., corn and sorghum][48] and agricultural management practices (i.e., crop rotation, organic plantation, etc.)[49-51]. Nevertheless, there is a wide range of soil carbon sequestration estimates [0.4-1.2 $GtCO_2/yr$] depending on the type of crop plant and location[52,53]. Some studies argue that, in the long-term, soils might become saturated with carbon reaching an equilibrium with the atmosphere and thus, agricultural cropland may cease to be a sink[54]. Powlson, et al. [55] also states that adding organic materials whilst increasing soil organic carbon, overall it does not constitute additional sequestration from atmospheric carbon to land. In addition, if the land-management on agricultural practices is reversed, then the carbon accumulated is lost at a rapid rate[56]. Considering this debate and the fact that our model is used for analysis of long-time horizons, we assume no annual projected soil carbon sequestration from cropland, and that gross FCS seems appropriate for cropland-to-forest conversion.

The case is different for pasture-to-forest-conversion. Grassland has on average much higher sequestration potential than cropland. Several studies argue that grazing land can remove even one-fifth of the annual CO_2 released into the atmosphere[57]. Hence, its contribution in carbon sequestration [CS] is not negligible. Converting pasture-to-forest has two effects in terms of CS: (i) we gain CS from forest, but (ii) we lose the CS by pastureland. Thus, considering only gross FCS would mean that we assume the same quantity in carbon sequestered for both cases (pasture-to-forest and cropland-to-forest) which is not appropriate. Annual sequestration of pasture land is not zero.

For this reason, we improved our model by implementing a value for the PCS. However, the original modeling framework does not provide a supply curve for PCS. Thus, in order to obtain an approximation, we first look into the relationship of PCS-FCS for each region at the AEZ level from the AEZ-EF model developed by Plevin, et al. [58]. In this way, we know how much PCS is lost in a given area considering the quantity gained from FCS. Then, we use the FCS-PCS ratio and multiply it by the original gross FCS values [from the GTAP-BIO-FCS model] to obtain the PCS values. In this way, we obtain an approximation of the PCS values for each region at AEZ level. We assume the rate of sequestration is identical for pasture land used by the two ruminant livestock industries [beef and dairy cattle]. This second version of the model is referred simply as GTAP-BIO-FCS from this point.

2.3 Scenarios and assumptions

We use a simple comparative approach to isolate the effects of each mitigation policy from other major factors such as population growth, capital accumulation, income changes, and intertemporal discounting, which can interact with economic and climate variables in a dynamic modeling framework and have a wide range of estimates. These types of interactions are important subjects, but they are not the focal point of this study.

The following experiments are implemented in the model:

1. Subsidy on pasture and forest carbon sequestration (***Subsidy*** scenario): This experiment provides a subsidy on carbon sequestered by forestry and pasture land [in $/t$CO_2$e] to achieve global net GHG emission reductions. We iterate subsidy rates from 5$/t$CO_2$e to 80$/tCO_2e [in increments of 5$/t$CO_2$e] to observe the additional requirements of forest and pasture, their contribution to the mitigation efforts and the impacts on food prices.

Thus, the FPCS subsidy seeks to motivate forest cover and pastureland expansion. Its implementation in the GTAP-BIO-FCS model is through subsidies on forest inputs (i.e., forest land and self-use forest biomass use) and subsidy to pasture land. In this scenario, we impose no expansion of biofuels to isolate the effects of the subsidy policy. For this reason, we also do not include any climate change impacts on agricultural or forest land productivity. This latter isolation assumption is also implemented in the other scenarios.

2. Tax regime for GHG reduction (Tax *scenario)*: This experiment implements a global uniform carbon tax [under the same range of the ***Subsidy*** scenario] to achieve reduction in emissions from consumption, production and endowments. For this scenario, we also impose no expansion of biofuels to isolate the effects of the carbon tax.

3. Biofuel expansion (***Biofuel*** scenario): By using a biofuel mandate modeled with an implicit subsidy and revenue neutral policy, we encourage first-generation biofuel expansion in three major economies: the European Union, Brazil and United States. Specifically, we increase corn ethanol and soybean biodiesel in US, European rapeseed biodiesel, and Brazilian sugarcane ethanol. We start with expanding corn ethanol production from its 3.41 billion gallons [BG] in 2004 to 15 billion gallons [BG] which is the US RFS mandated for 2015[59]. US soybean biodiesel is raised by +0.81BG while Brazilian sugarcane ethanol is increased by +3 BG. These were the values corresponding to previous analysis to calculate indirect land use changes (iLUC) for the California Air Resource Board (CARB). For EU rapeseed biodiesel, we increased production to 3.61 BG, which is the annual production for EU biodiesel in 2016[60]. We then vary the initial expansions by 25%, 50% and 75%, and then from 125%, to 300% [by increments of 25%, as displayed in Supp. Table 1].

4. Carbon Tax – Sequestration Subsidy (TS *scenario)*: This experiment implements a global uniform carbon tax and an equivalent sequestration subsidy to the global economy with similar rates as the other two previous experiments. We considered this scenario to illustrate the interactive effect of combining both mitigation methods.

Note that for scenarios (1), (2) and (4), we have similar rates to reduce net global GHG emissions. Nevertheless, for biofuels, we implement smaller expansions. This is because, considering that biofuels are only a small sector of the economy, and it is not the intention of biofuel producer regions to make biofuels responsible for ambitious emission reduction targets (such as 10% or over). Thus, we implement a smaller shock. Nevertheless, if either FCS or carbon tax are less expensive than biofuel under these circumstances, in which biofuel has the advantage of having a smaller shock, this would illustrate that implementing a bigger shock for biofuels would just make biofuels more expensive but not change the conclusion.

2.4 Cost calculation

We use three approaches in order to compare the cost-efficiency of each mitigation type:

I. Unitary welfare cost (UWC)*:* This is defined as the cost for the regional welfare of reducing GHG emissions (in $/tCO_2e$). Mathematically, it is formulated as:

$$UWC_r^m = \frac{\Delta EV_r^m}{\Delta EMIT_r^m}$$

where ΔEV_r^m represents the regional welfare variation (in millions $USD of Equivalent Variation [EV]) of implementing mitigation alternative *m* (*m*=sequestration subsidy, carbon tax, biofuel policy), and $\Delta EMIT_r^m$ indicates the net emission reduction (in millions of tons of CO_2-equivalent). The value of $\Delta EMIT_r^m$ is determined endogenously in the model as a result of the subsidy rate.

II. Unitary production cost (UEC): This index represents the cost in terms of reduction in real income due to lower net GHG emissions (also in $/tCO_2e$). This is formulated as follows:

$$UEC_r^m = \frac{\Delta GDP_r^m}{\Delta EMIT_r^m}$$

where ΔGDP_r^m is the change in real GDP (in millions of $USD) for region *r*.

II. Unitary direct cost (UDC): In this method, we track the costs in terms of required tax or subsidy per unit of emission reduction, as outlined in the following (for the detailed mathematical formulation, please see Supp. Annex 2):

- For the *sequestration subsidy*, its cost is defined as the subsidy to increase CS by pasture and forest.
- For *carbon taxes*, its cost is based on the tax required to reduce gross emissions.
- For *biofuels*, its cost is the subsidy to biofuel production to decrease net emissions (including direct cost and iLUC impact)
- For the *tax/subsidy*, its cost is based on the tax/subsidy rate required to reduce net emissions.

3. 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 variables to highlight the global impacts of the three mitigation methods. In some instances, because we only increased production of biofuels in US, EU, and Brazil, we pay particular attention on these regions.

3.1 Emission reduction of each scenario in isolation

Sequestration Subsidy - We simulated decreases in net global emission to illustrate the effects of implementing a sequestration subsidy as the only mitigation method. This subsidy is the same for all global regions and is provided as an incentive for forest inputs (biomass and land) and pastureland. Considering that there are no other incentives in other sectors of the economy, FPCS subsidy is the main cause of the net emission reduction.

This policy encourages forest expansion across the globe at expense of agricultural land. Although pasture also sequesters carbon, forest has a higher carbon sequestration [CS] intensity which motivates afforestation (fig. 1). Nevertheless, at high subsidy rates [70-80$/tCO_2e$], pastureland stops decreasing due to the attractiveness of the subsidy, and forest takes away land mainly from crop production. Places with vast current forest and high FCS intensity take advantage of this incentive. Thus, the contribution in emission reduction is heterogeneous. Regions such as the US, China, India, Brazil & South America, and Sub-Saharan Africa sequester most of the carbon globally.

Our FPCS annual curve follows a similar pattern compared to previous research developed by Sohngen [61], where the sequestration subsidy increases carbon sequestration at a decreasing rate (fig. 1). Nevertheless, our curve comes from CGE simulations (which includes feedbacks effects from the economy such as international trade effects) and also takes into account PCS. Our simulations suggest that at about15$/tCO_2e$ (equivalent to a revenue per hectare of $64.2 per year), there is about 30% increase in sequestration (which leads to 5% global emission reduction). This important insight shows that even under low subsidy payments, there is motivation to afforest. This is consistent with the conclusions obtained under the experimental study conducted by Jayachandran, et al. [62]. In their research, they implemented a subsidy-payment program paid to Ugandan forest-owners for 2 years which motivated them to avoid deforestation.

Considering that land is a valuable scarce resource, the land competition with agriculture makes the sequestration subsidy less effective at higher rates. Thus, at 80$/tCO_2e$, sequestration from forest and pasture reaches a limit in expansion (+50%). This means that sequestration alone can reduce only 11% of the total emissions.

Tax on emissions – The uniform tax is applied to all source of emissions across the world. As expected, because their global GHG releases, ruminants [beef and dairy cattle], electricity and transport sectors are three major players in the mitigation effort[38,63]. Their role varies depending on the tax rate (fig. 2). At 10$/tCO_2e$, electricity and ruminant livestock provide together about two thirds of the GHG emission reduction. Transport sector has approximately a 6% share. At 80$/tCO2e, ruminant sector participation is much lower (about 16%) while electricity share is larger (42%). This is partially attributed to the fact that the electricity sector is globally a major sector of the economy, thus its potential for emission reduction plays a larger role with high taxes. In contrast, the livestock sector is much smaller compared to this industry, which provides a limit in its mitigation effort. Hence, as the tax rate increases, livestock industry share decreases, while electricity (and also transport) shares in the emission reduction becomes larger. The share of these industries reaches an equilibrium at high tax values ($60/tCO_2e$ and over).

The carbon tax and sequestration subsidy impacts differ by region. With the carbon tax, regions with large mitigation potential and high carbon-intensive sectors are more heavily penalized (i.e. China, Russia, South Asia to cite a few). With the sequestration subsidy, regions with vast forest (i.e. Latin America) provide most of the reduction. However, an important aspect is illustrated here, under the same tax/subsidy rate, the tax on emissions reduces more drastically the net emissions compared to the subsidy on sequestration. This is mainly because the tax is applied to many sectors of the economy while the subsidy is only devoted to pasture and forestry.

Biofuel expansion – We increase biofuels in regions with significant production in 2004 according to goals established (in BG). In order to motivate this expansion, a subsidy is paid for biofuel producers assuming tax neutrality (i.e. no changes in government tax revenue). The expansion in biofuel helps to mitigate climate change to a certain extent (fig. 3). There are two forces that determine its emission reductions. On one hand, first-generation biofuels motivate substitution from fossil fuels, which decreases emissions. However, because there is land movement into harvested area for biofuel feedstocks, there is a loss in carbon sequestration from forest and pastureland (i.e. indirect land use change [iLUC]).

Under moderate expansions of first-generation biofuels, the net emission reduction is largely positive due to the large substitution of fossil fuels and small land conversion. Nevertheless, larger biofuel expansions reduce its benefits due to sequestration losses provoked due to ILUC which can decrease the benefits of substituting fossil fuels, as pointed out by Searchinger, et al. [64]

3.2 Impacts on food prices of each method in isolation

Sequestration Subsidy – Afforestation due to the large revenues from sequestration subsidies comes with a cost for the economy. Expanding (mainly) forest globally moves land away mainly from agriculture. There is an overall decrease in crop harvested area and pastureland which leads to increase in prices for food commodities [37,38].

We present a composite index for changes in prices for rice and ruminant sectors [fig. 4], and for crops that can serve as biofuel stocks (i.e. coarse grains, oilseeds and sugar) [Supp. Fig. 2]. The ruminant-rice ratio shows that the price index increases at a decreasing rate for regions with vast forest cover and sequestration intensity (Brazil, Central America, Sub-Saharan Africa). These economies suffer dramatic boosts in food prices. This is because, high sequestration rates subsidize pasture land which alleviates partially the increase in prices for these commodities. For the other economies and other commodities, the behavioral relationship between prices and sequestration rate is linear (R^2>90%).

Food consumption decreases also the most in the places with vast forest but at a lower rate than prices. Likewise, because pasture land receives part of the subsidy, livestock product prices increases but at a lower rate than the other crops.

In terms of output, there is an overall reduction in agricultural commodities for most regions. Livestock is especially affected in South America (including Brazil) due to the afforestation. In contrast, the European Union is one of the few regions that did not decrease food production, mainly because it does not expand significantly its forest.

Tax on emissions – The reduction in gross GHGs due to the tax drives decreases in outputs in carbon intensive sectors. Energy sectors (i.e. coal, oil, gas, oil products, and electricity) are heavily penalized. Their production decreases everywhere, especially in emerging economies (i.e. China, India, East Asia, among others). Electricity prices go up in most countries (i.e. USA, EU, China, India, Russia, Sub-Saharan Africa).

The emission tax changes the distribution of the harvested area. Paddy rice is more heavily penalized because its land releases methane. This moves away some land from rice to other crops. Thus, rice prices increase by almost double compared to the other crops. Similar behavior is seen for ruminants (i.e. beef and dairy cattle) who emit methane and nitrous oxide through enteric fermentation and manure decomposition[65-67].

Observing our price index for rice and ruminant sectors, there is a linear relationship between the price increase and the tax regime (R^2>90% for most regions). The slope of the price increase depends on the regional carbon intensity of the sector, in which carbon-intensive regions have larger slopes. We observe that the effect in prices for rice and ruminant sectors [fig. 4] is almost ten times compared to other crops [Supp. Fig. 2] for any rate within our simulation range.

The carbon tax and sequestration subsidy policies affect economic sectors differently. For the cases of sequestration subsidy, the land competition affects mainly forestry, livestock and crop sectors, driving up food prices and land rent. This affects especially regions that take advantage of the subsidy. Carbon taxes on emissions penalize less crops, but affect more other carbon-intensive industries such as energy sectors and ruminants. Overall, ruminant sectors are more affected than electricity under the same tax/subsidy rate as observed in figure 4. This illustrates that there exists a trade-off: taxing emissions can reduce more rapidly net emissions but at higher price increases than subsidizing sequestration.

Biofuel **-** The biofuel expansion has several consequences:

(i) It requires more agricultural feedstock. Thus, US production of coarse grains (mainly corn) increases to supply the raw material for the corn ethanol. US private domestic food consumption of coarse grains then decreases, which reduces exports to satisfy food demand. A similar situation happens for production of US soybeans, EU rapeseed and Brazilian sugar crops. In our base scenario, previously described, the competition between food and biofuel increases prices of the agricultural commodities that are used as raw materials by 1-3% in the cases of these three regions. For other crops, the food prices increases are less than 1%.

(ii) There is an increase in biofuel byproducts, US vegetable oil from soy, European vegetable oil from rapeseed.

(iii) There are two effects for livestock. The direct (positive) effect is the additional biofuel feedstock through co-products such as DDGS. The indirect (negative) effect is the reduction of crop feedstock. The net effect in our base case is mixed: For US and EU the effects offset each other; for Brazil, the indirect effect is larger (i.e. about one percent decrease in livestock products).

3.3 Cost-efficiency comparison of the emission tax and FPCS subsidy versus biofuel expansion

We use three different approaches to evaluate the effect of each method in isolation. Each of these approaches were previously described in section 2.4 [i.e., UWC, UEC and UDC] and are presented in table 1. For the comparison of the three mitigation alternatives, we chose a specific target. For the tax and subsidy cases, we chose the scenario that reduces net emissions by 10% while biofuel is expanded according to our main scenario.

Sequestration Subsidy **-** In terms of welfare costs, the average cost for society to mitigate climate change using this policy as the only mitigation method is about \$26/tCO_2e. The EV variation calculation includes costs in allocative efficiency, terms of trade, technical efficiency, among others. Tracing a simple linear regression [Supp. Fig. 1], we find a high negative correlation between FCS intensity (in tCO_2e sequestered by a \$1 value of forest) and cost-efficiency. This means that regions with high FCS intensity are more cost-efficient. This is because for regions located in Latin America and Sub-Saharan Africa, \$1 of forest value sequesters large amounts of CO_2. The GDP approach provides similar results.

Tax on emissions – In terms of cost-efficiency, regions with relatively low cost of imposing this tax are China, India, South America (including Brazil), South East Asia, South Asia, Russia and Sub-Saharan Africa. This is because these are places with large mitigation potential where it is relatively cheaper to cut emissions.

Biofuel expansion – In terms of cost-efficiency, the welfare loss for these three economies is higher (in \$EV/tCO_2e) than under the sequestration subsidy. Interestingly, for the EU, the decrease in emissions due to the biodiesel policy (-14 MtCO_2e) is larger than when implementing a sequestration subsidy (-10MtCO_2e) although it represents also a much higher cost. Because the land devoted to harvested area is moved towards biofuel feedstocks for the US, EU and Brazil, this reduces crop exports. Thus, Asian regions and Russia take advantage and benefit from this action. This leads to improvements in terms of trade (and technical progress) which are reflected in positive values for EV for these regions. The GDP cost comparison provides a similar interpretation. For the direct cost approach (which combines the subsidy paid to biofuel producers and taxed to private consumers), US would incur in a unit cost of 230 \$/tCO_2e (for ethanol) and 440\$/tCO_2e (for biodiesel) to achieve its target. For the EU, implementing the biodiesel expansion costs 908\$/tCO_2e, whereas for Brazil sugarcane ethanol is 168\$/tCO_2e.

Comparing taxes and subsidy versus biofuels we find that, in terms of direct costs, paying taxes on emissions is relatively cheap (about or lower than the average) for emerging economies with large mitigation potential. Biofuels, on the other hand, are more attractive (i.e. specifically ethanol) than imposing a carbon tax for the US (even considering iLUC), but it is less preferred than a FCS subsidy. For the EU, imposing a tax regime seems to be more cost-efficient than the other two alternatives, and although increasing biodiesel can provide higher net emission reductions than FCS, its cost is at least twice as high. For Brazil, the difference between implementing FCS subsidy and a tax regime is relatively small. Overall, comparing the three mitigation alternatives, it is not surprising that an emissions tax seems more attractive for emerging economies, except in few regions where FCS is relatively cheaper (i.e., Central and South America, Middle East and North Africa). Biofuels are more costly to be implemented alone when compared to the other two methods for all regions, despite the fact that biofuel had a smaller shock.

3.4 The tax-subsidy scenario: Emission reduction and effect on food prices

Emission reduction in the TS scenario - We simulated tax on emissions for all industries while providing simultaneously an equivalent sequestration subsidy for pasture and forest. This scenario shows that combining both policies provide higher emission reduction than each mitigation method in isolation demonstrating the synergistic effect of both methods (fig. 9). Thus, at 80$/tCO$_2$e, the RPC4.5 goal of reducing 50% net emissions is achieved. This is about half of the value that would be required if we would only impose a tax to reduce net emissions [i.e. in our *tax* scenario the rate was 150$/tCO$_2$e]. Our findings are consistent with previous evaluations of the forest role in climate change mitigation. For example, Nordhaus [68] concludes that implementing forest sequestration in the mitigation effort could decrease the carbon price by about 50% for the RCP4.5 goal [i.e. limit the global temperature increase below 2°C]. Likewise, Nordhaus [68] indicated that under an '*optimal carbon*' abatement policy, forestry could sequester about the 30% of the global emission abatement over the century. Our simulation shows that FPCS can contribute about 21% share in the mitigation at 80$/tCO$_2$e, considering our CGE model takes into account global interactions.

This combined policy shows important insights. (1) The net emission reduction is not linear with respect to the tax-subsidy rate (fig. 5). (2) the FPCS share decreases for high TS rates (fig. 1). (3) The TS regime motivates forest expansion at the expense mainly from cropland. (4) Pastureland is reduced at a decreasing rate because although ruminants' emissions are taxed, there is revenue from pasture carbon sequestration. (5) Combining both policies can achieve larger emission reductions (fig. 9) at any given rate compared to each policy in isolation.

Price changes in the TS scenario – As observed in fig. 6, the tax-subsidy provokes substantial increases in food prices, in particular for rice and ruminant sectors. Because this policy is a combination of two mitigation alternatives, the price increase is a weighted average of both methods where the weight is the sectorial contribution in the emission reduction. Thus, it can be observed that the dominant factor is the carbon tax: the effect on prices by the TS scenario is similar to the tax scenario, being slightly lower for places that take advantage of the sequestration subsidy such as Central America. For this reason, the price increase across the world have overall a linear relationship with the tax-subsidy rate. Likewise, there is much higher emission reduction compared to the FPCS subsidy but the penalty in prices is dramatic.

3.5 The effect on welfare

Sequestration Subsidy – Carbon sequestration from forest and pasture decreases welfare for all regions due to the fact that land is taken away mainly from cropland. Nevertheless, the EV decrease is lower in places that take advantage of the subsidy due to their high sequestration intensity such as

Sub-Saharan Africa and Brazil [fig. 7]. Likewise, the EV losses have a linear relationship with the subsidy (with an R-square higher than 90% for most regions).

Tax – The tax on emissions to all industries affect regions depending on their carbon emission intensity. Overall, emerging economies are the most affected compared to the developed regions (especially Japan and EU who receive benefits due to favorable terms of trade). On the other hand, because the tax affects simultaneously and differently to many sectors there is no linear relationship between EV and carbon taxes.

TS – As expected, the TS decreases welfare for all regions but not at a linear rate due to the impact of the policy in many industries of the economy. Interestingly, the losses are higher than implementing the sequestration subsidy alone but lower than imposing only a tax regime for places with vast forest. For other economies, the TS policy has even worse effects on welfare than implementing taxes or sequestration subsidy alone. This provides an important insight, the sequestration subsidy helps to alleviate EV losses only for economies with high sequestration potential. Otherwise it worsens the situation.

3.6 Cost-efficiency comparison

For this case, we compare the global welfare cost average of the three methods (subsidy, tax and tax-subsidy) in terms of equivalent variation by emission reduction [in \$EV/tCO_2e]. At smaller rates, it is observed in fig. 8 that tax on emissions is the most efficient, until a certain value (which was determined in this exercise to be about \$55/tCO_2e). Above this value, the subsidy becomes more cost-efficient. Nevertheless, the tax reaches higher net emission reductions than subsidy at higher rates (fig. 9).

The tax-subsidy regime has a social cost that is between the tax and subsidy costs. This result is due to the fact that this policy can be seen as a weighted average of the other two methods in isolation. In addition, the synergy of both policies permits achievement of higher emission reductions (fig. 9). Similar results are provided using GDP as the representative cost.

4. Conclusions and final remarks

The global community has reaffirmed recently its commitment to reduce GHGs emissions to control the expected increase in the global average temperature. This implies ambitious emission reduction targets with actions in many areas of the economy, such as agriculture, forestry, energy and the industry. Thus, governments and private sectors are interested in the cost-efficiency of frequently discussed mitigation policies –sequestration subsidy, carbon tax, biofuel expansion – and their impacts on the global economy. We use our new developed computable general equilibrium named GTAP-BIO-FCS for the task. This model incorporates these mitigation methods making it suitable for climate change policy analysis.

For the sequestration subsidy and the carbon tax, we simulate a range of rates to observe their potential in achieving emission reductions using each instrument in isolation. For biofuels, we expand production in regions that had significant biofuel production in recent years.

Our results suggest that:

- Carbon sequestration helps to reduce the cost of implementing an emission tax in the economy, but its contribution approaches a limit.
- At high rates, carbon sequestration is more cost-effective. Tax is lower cost at low rates.
- Comparing emission reductions, the carbon tax requires a lower tax rate to reach a reduction target compared to the high subsidy on sequestration for the same target. This demonstrates a trade-off between cost-efficiency and emission reduction between the two policies.

- The effect of combining tax and an equivalent subsidy on price is overall a weighted average of the effect of the tax and the FPCS subsidy on isolation. However, its emission reduction potential is larger due to their synergistic effect.
- The tax-subsidy regime has a social cost that is between the tax and subsidy costs, thus its welfare cost lies between the values of the tax and subsidy.
- Biofuels proved to be costlier than the other two mitigation methods in all regions despite having a smaller shock.

Thus, our study illustrates that the distribution of the costs of the alternative mitigation methods is a complex issue, where the burden goes to different sectors and regions depending on the instrument implemented. Likewise, the net effects on welfare depends on the cost of reallocating resources and the change in terms-of-trade.

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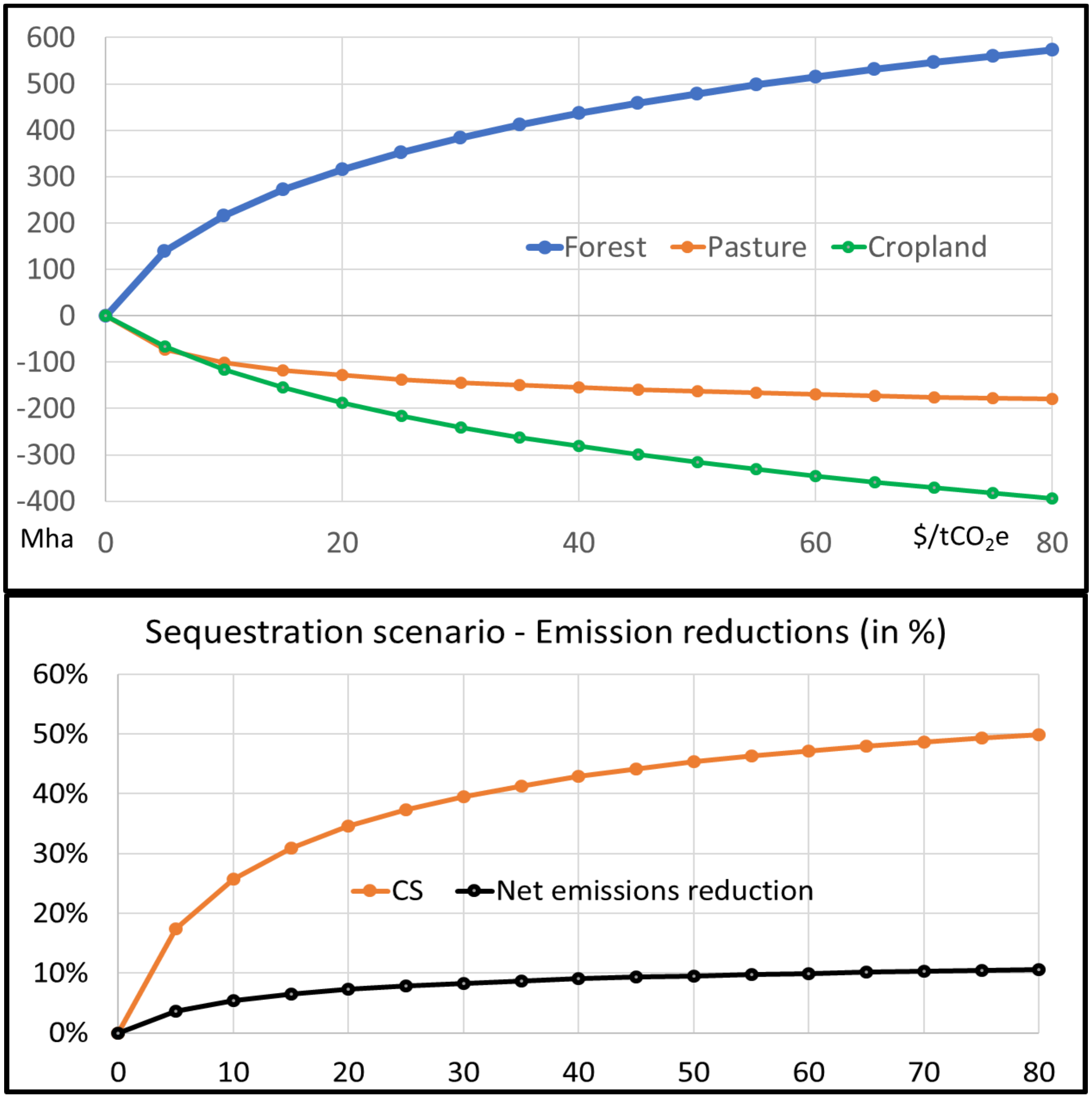


Figure 1. Land use change (in Mha) [top] and emission reduction (in %) [bottom] – *Sequestration Subsidy* scenario

This graph shows the changes in global land use [top] (in Mha) and emission reduction [bottom] (in %) for different subsidy rates [from 0 to 80$/t$CO_2$e]

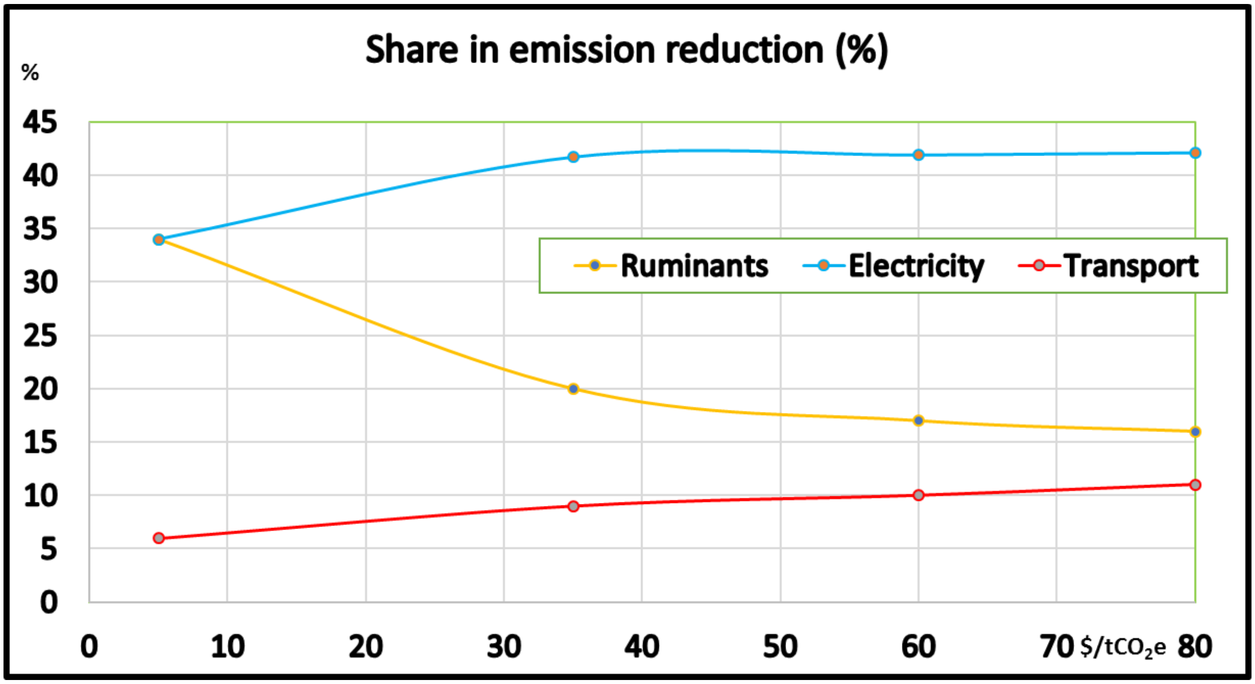


Figure 2. Shares in the global emission reduction of three industries– *Tax* scenario

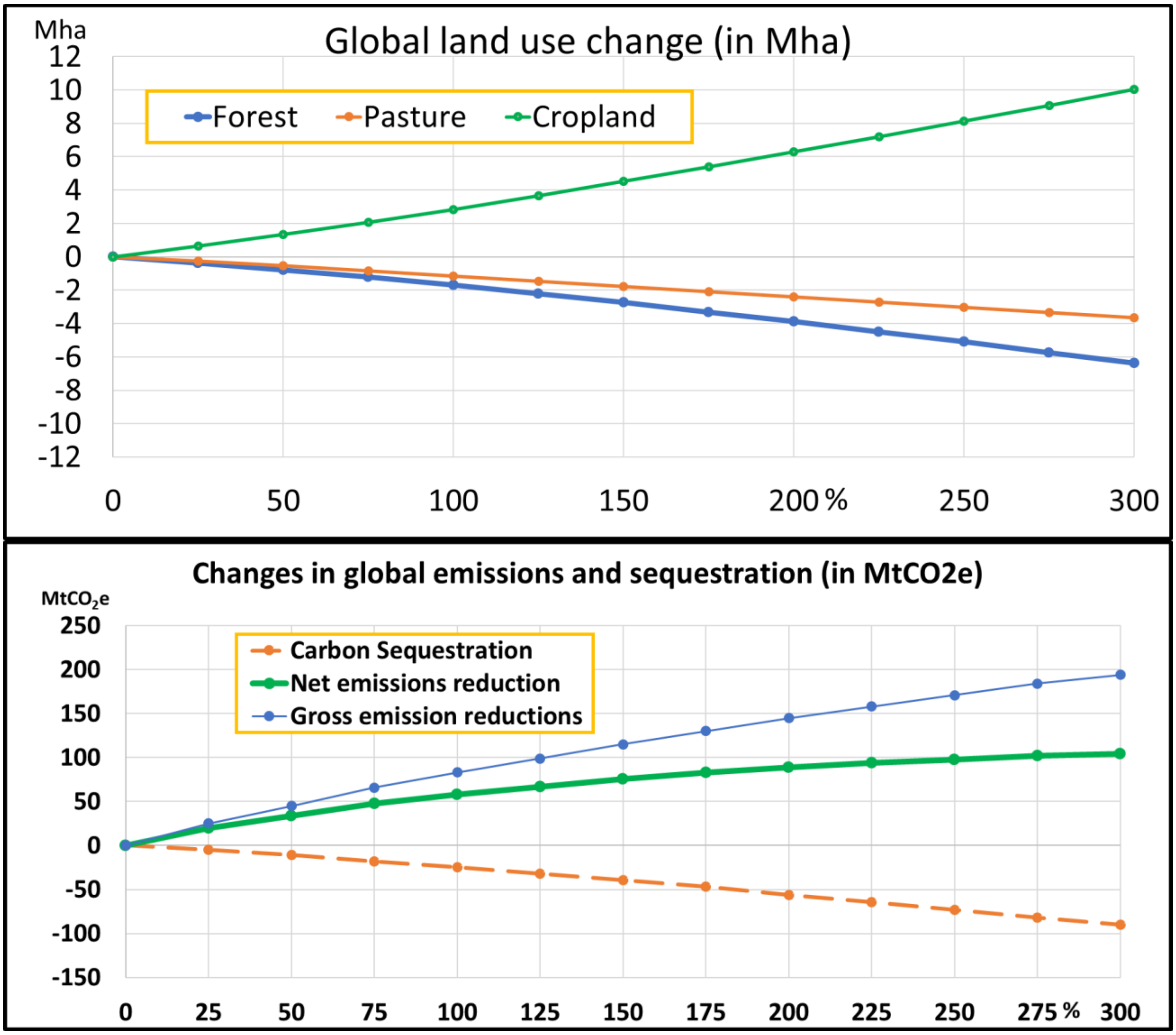


Figure 3. Land use change (in Mha) [top] and emission reduction (in $MtCO_2e$) [bottom] – *Biofuel* scenario

This graph shows the changes in land use (top) and emission reduction (bottom) for different biofuel expansions (as % of variation from the main biofuel scenario)

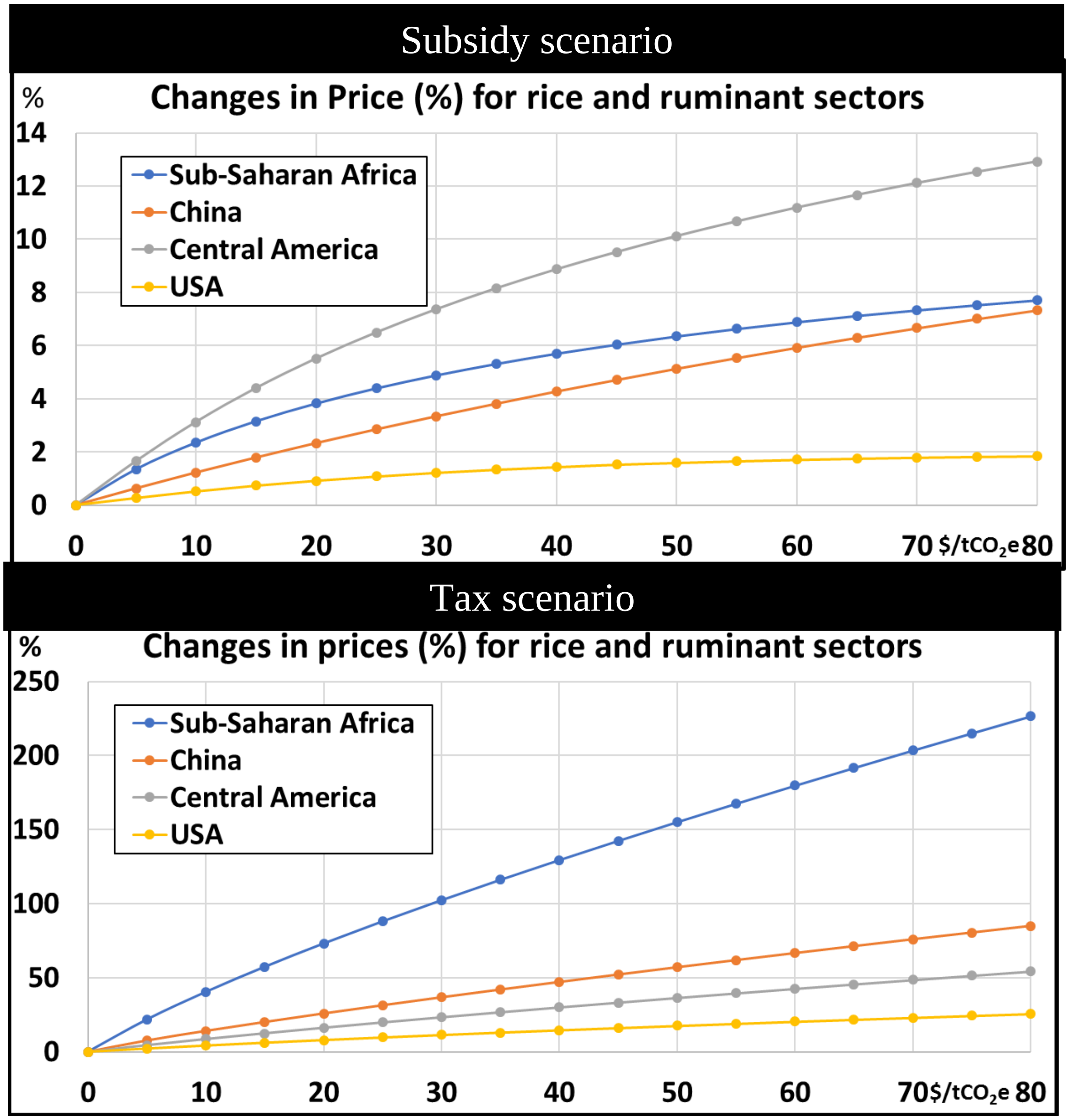


Figure 4. Changes in prices for rice and ruminant sectors (in %) for the *sequestration subsidy* [top] and *tax* [bottom] scenario

This graph illustrates the changes in prices for food commodities. This price index is a composite from rice and ruminant sectors for selected regions.

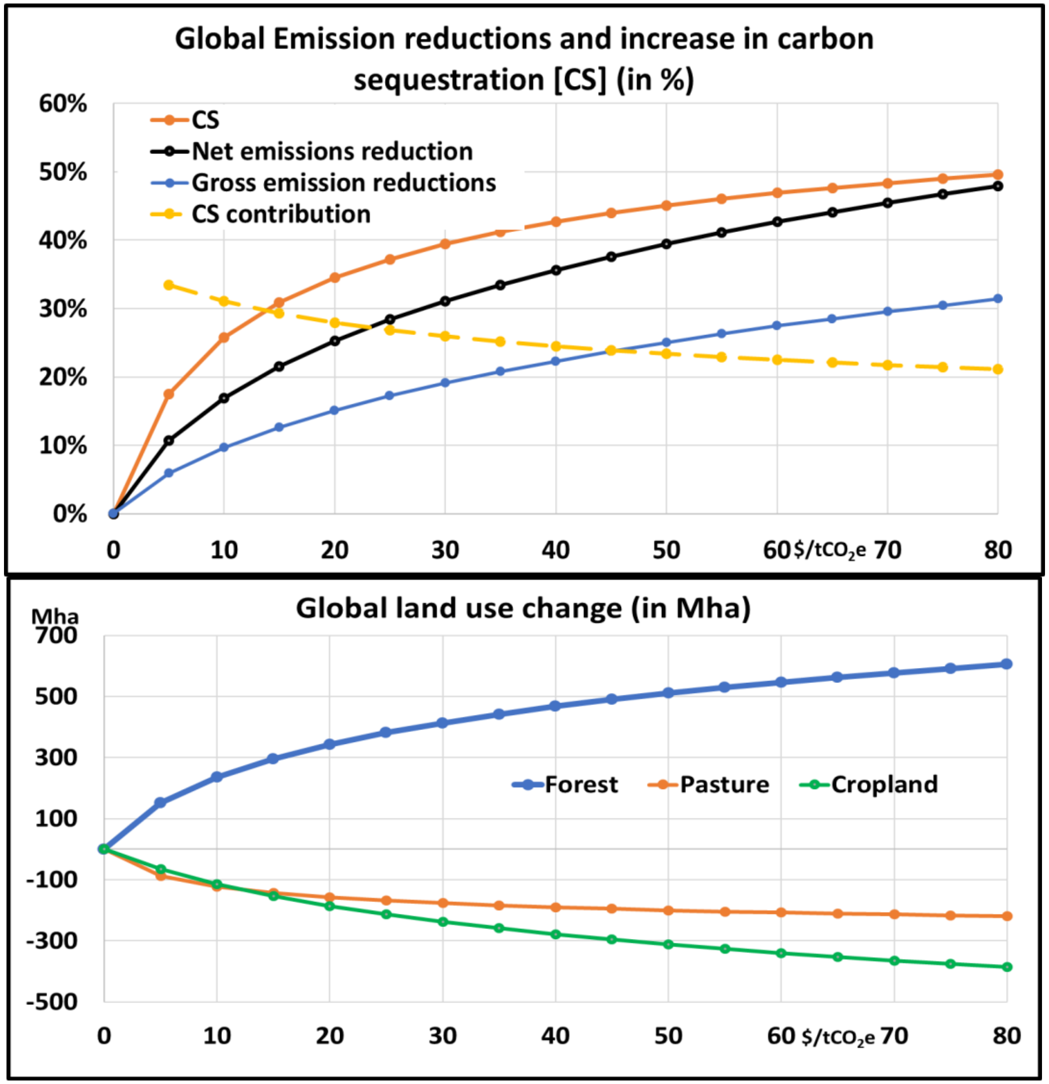


Figure 5. Emission reduction (in %) [top] and Global land use change (in Mha) [bottom]– *TS* scenario

This graph shows the changes in land use (bottom) and emission reduction (top) for different subsidy rates [from 0 to 80$/$tCO_2e$]

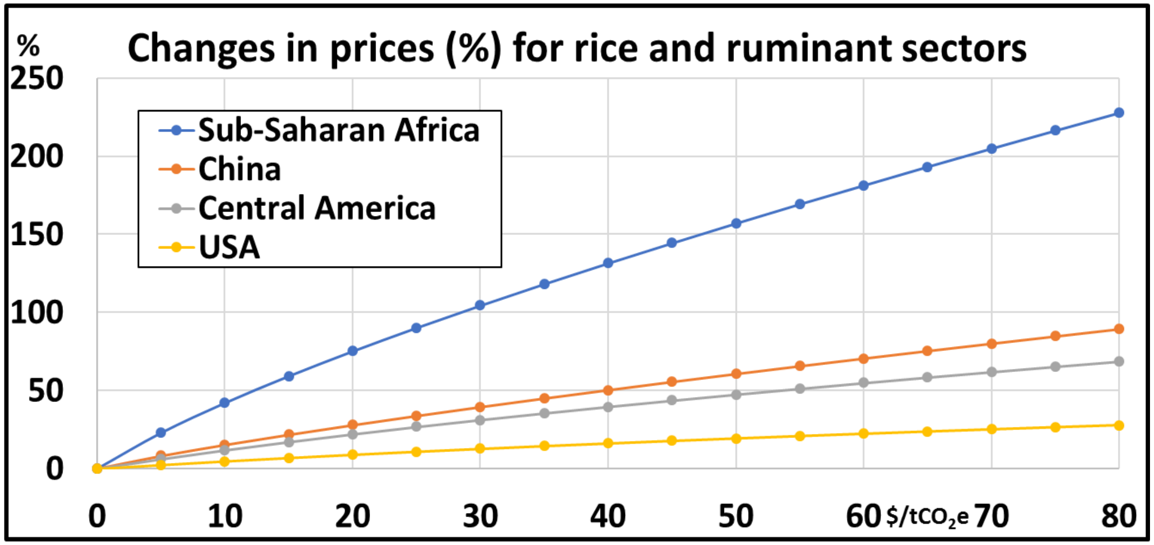


Figure 6. Changes in prices for rice and ruminant sectors (in %) for the *TS* scenario

This graph illustrates the changes in prices for food commodities. This price index is a composite from rice and ruminant sectors for selected regions.

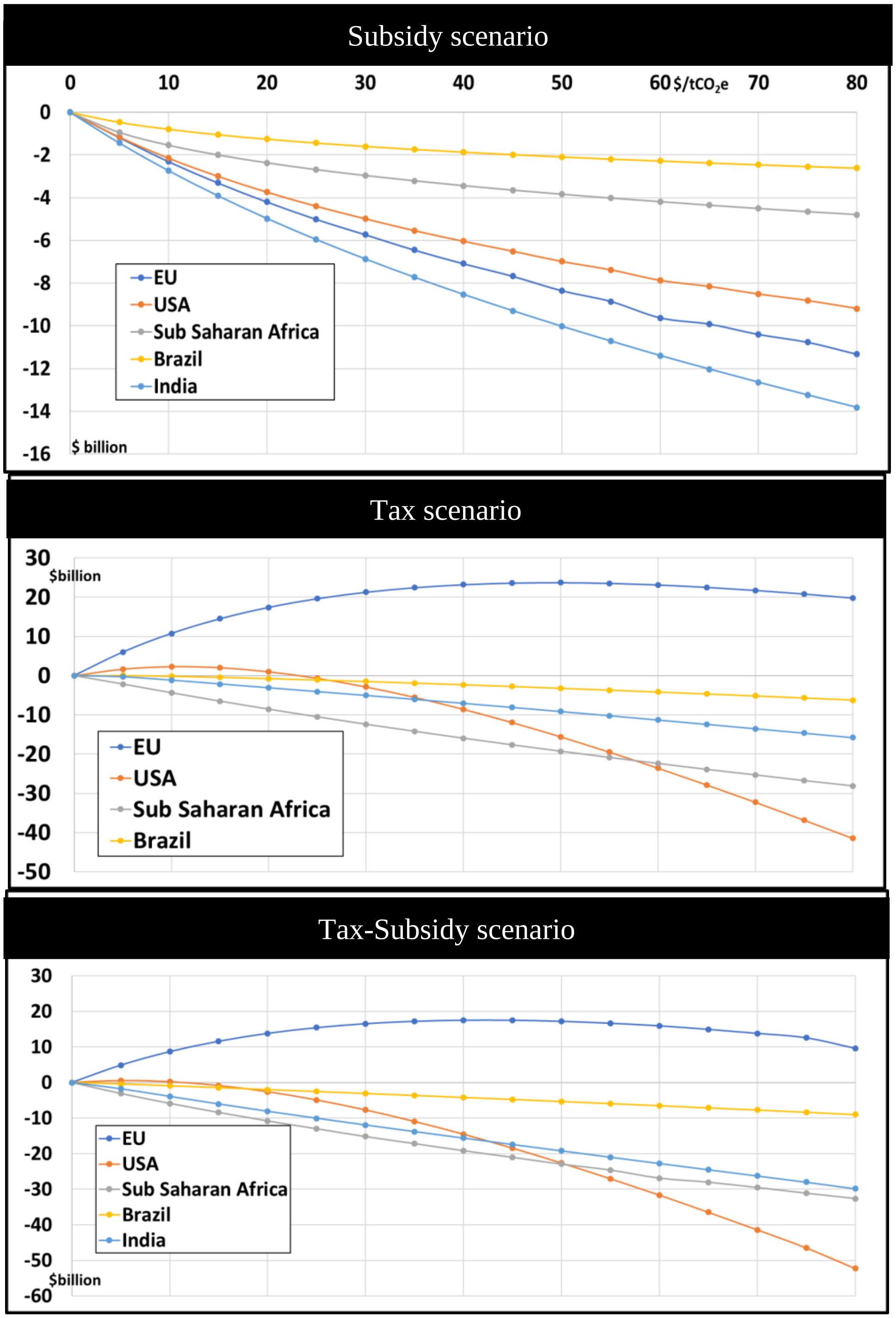


Figure 7. Changes in welfare (in $billion) for the sequestration [top], tax [middle] and TS [bottom] scenarios

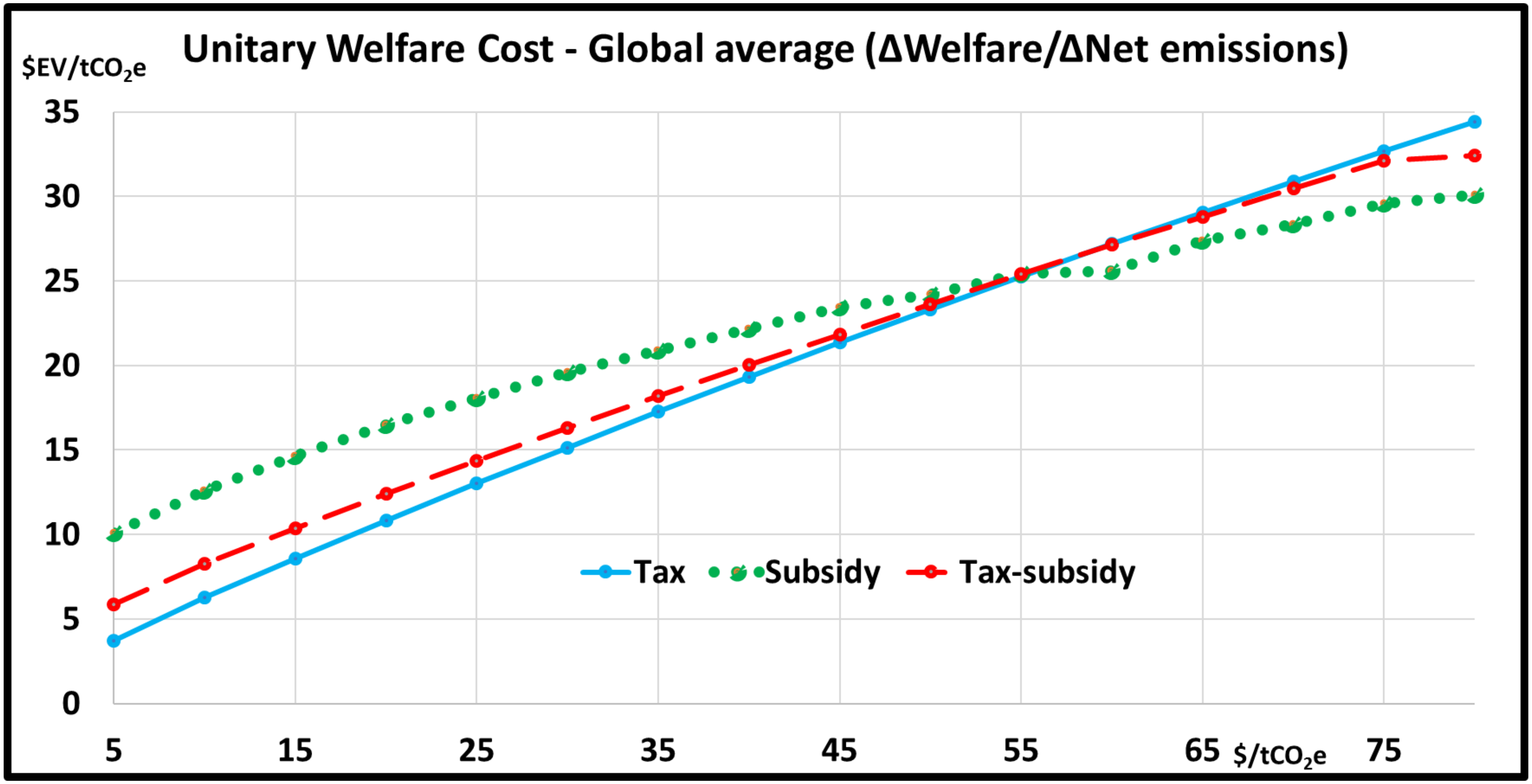


Figure 8. Cost-efficiency comparison (in terms of changes in welfare per unit of emission [$EV/tCO₂e]) for each scenario

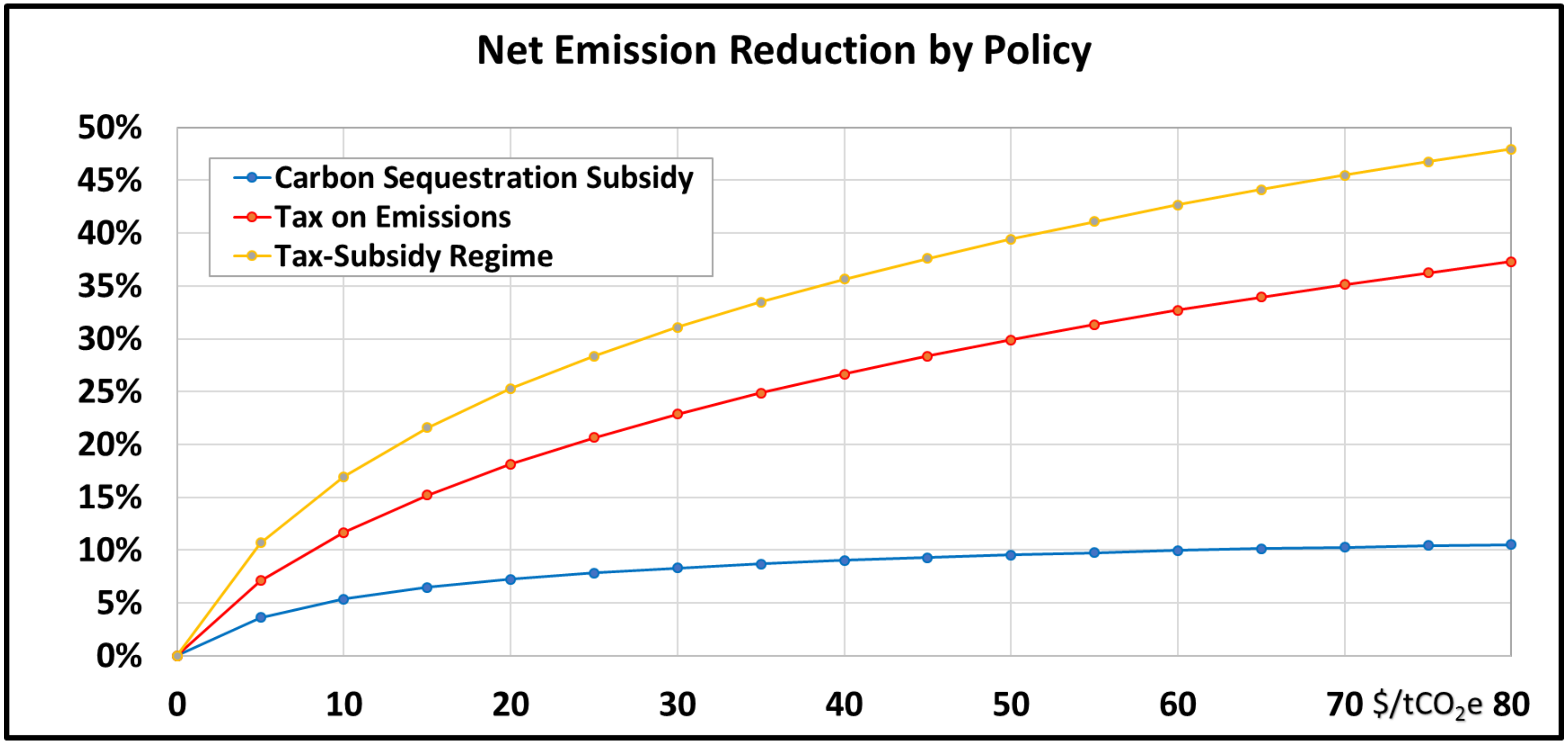


Figure 9. Net global emission reduction for each scenario

Table 1. Cost-efficiency comparison by climate change alternative method

	ΔEV/ΔNet Emission [Mill$/MtCO₂e]			ΔGDP/ΔNet Emission [Mill$/MtCO2e]			Unitary direct cost	
	CS Subsidy	Biofuel	Tax	CS Subsidy	Biofuel	Tax	CS Subsidy	Tax
USA	16	210	-8	21	307	11	108	203
EU	914	1470	-46	635	1608	-14	426	199
Brazil	7	274	1	12	281	5	52	68
Canada	23	-119	13	29	12	8	682	125
Japan	97	327	-116	60	67	6	170	342
China	57	71	7	52	10	7	206	68
India	30	212	2	30	78	4	89	39
Central America	21	-1062	54	21	-416	36	68	161
South America	9	-633	8	14	-19	3	70	52
East Asia	38	305	-25	25	64	9	85	194
Malaysia & Indonesia	41	30	16	47	7	5	136	136
South East Asia	23	186	1	50	41	5	165	72
South Asia	44	485	3	37	68	5	140	62
Russia	-357	-469	11	156	-63	-1	845	72
Central Europe	350	-10	16	457	-6	15	240	103
Other European countries	1540	-2088	333	509	75	27	714	258
Middle East & North Africa	182	-973	202	61	2	21	128	303
Sub-Saharan Africa	15	-373	12	17	-28	5	214	39
Oceania	-3	24	0	7	5	5	286	120
GLOBAL	**26**	**883**	**5**	**26**	**882**	**5**	**108**	**203**

Note: For the case of Biofuels, because the calculation of the unitary cost is only for three regions in which US has two different types of biofuels, they are not reflected in the chart.

Supplementary Annex 1

Biofuel Scenarios

Supp. Table 1. Biofuel scenarios (increase in billion gallons [BG])

	US	US	EU	Brazil
	Corn Ethanol	**Soy Biodiesel**	**Rapeseed biodiesel**	**Sugar ethanol**
Baseline	3.41	0.02	0.42	3.99
Main Scenario (100%)	+11.59	+0.81	+3.19	+3.00
25%	+2.90	+0.20	+0.80	+0.75
50%	+5.80	+0.41	+1.60	+1.50
75%	+8.69	+0.61	+2.39	+2.25
100%	+11.59	+0.81	+3.19	+3.00
125%	+14.49	+1.01	+3.99	+3.75
150%	+17.39	+1.22	+4.79	+4.50
175%	+20.28	+1.42	+5.59	+5.25
200%	+23.18	+1.62	+6.39	+6.00
225%	+26.08	+1.83	+7.18	+6.75
250%	+28.98	+2.03	+7.98	+7.50
275%	+31.87	+2.23	+8.78	+8.25
300%	+34.77	+2.44	+9.58	+9.00

This table shows the increase in biofuel for each region-biofuel type. The biofuel expansion is presented in changes (in billion gallons) from the baseline scenario. Our 'main expansion' scenario represents our initial increase [which is equivalent to 100%] (e.g., in order to obtain 15BG for US ethanol, we increase US ethanol production by +11.59BG). Here, the *25% scenario* represents 25% of the increase in our main scenario (e.g., 25% of +11.59BG, which is about +2.90BG of US ethanol), similar logic for the other scenarios.

Supplementary Annex 2

Unitary direct costs formulation

This section explains the mathematical formulation for the calculation of the unitary direct cost (UDC) for each mitigation method.

II.A Sequestration Subsidy

The cost-efficiency UDC_r^{CS} [in \$/tCO_2e] is defined as the average subsidy cost of increasing 1% of carbon sequestration by forest and pasture. Thus:

$$UDC_r^{CS} = \frac{SS_r}{\Delta\%CS_r}$$

where SS_r is the sequestration subsidy (in \$/tCO_2e) provided for carbon sequestration, and $\Delta\%CS_r$ is the net percentage increase in annual regional carbon stored, which is calculated endogenously as a result of the subsidy rate.

II.B Carbon tax

For the tax on GHG emissions, the cost efficiency UDC_r^{TAX} [also in \$/tCO_2e] is the average cost in implementing a carbon tax in order to reduce by 1% the regional gross emissions (from both consumption and production). This is formulated as:

$$UDC_r^{TAX} = \frac{CTAX_r}{\Delta\%GE_r}$$

Here, $CTAX_r$ is the imposed carbon tax. $\Delta\%GE_r$ refers, as before, to the percentage change in gross emissions in region *r*, obtained as a result of the tax on emissions.

II.C Biofuel expansion

Finally, the cost-efficiency UDC_r^{BF} [in \$/tCO_2e] refers to the average subsidy devoted to biofuel in order to decrease 1% of regional net emissions (including iLUC effects). Mathematically:

$$UDC_r^{BF} = \frac{BS_r}{\Delta\%EMIT_r^{BF}}$$

where BS_r is the biofuel subsidy cost (i.e. in million \$USD, burden to consumers and producers), and $\Delta\%EMIT_r^{BF}$ is the percentage increase in annual net GHG emissions [in MtCO_2e]. BS_r is obtained endogenously in the model, according to the regional biofuel production goals defined earlier.

II.D Carbon tax and sequestration subsidy

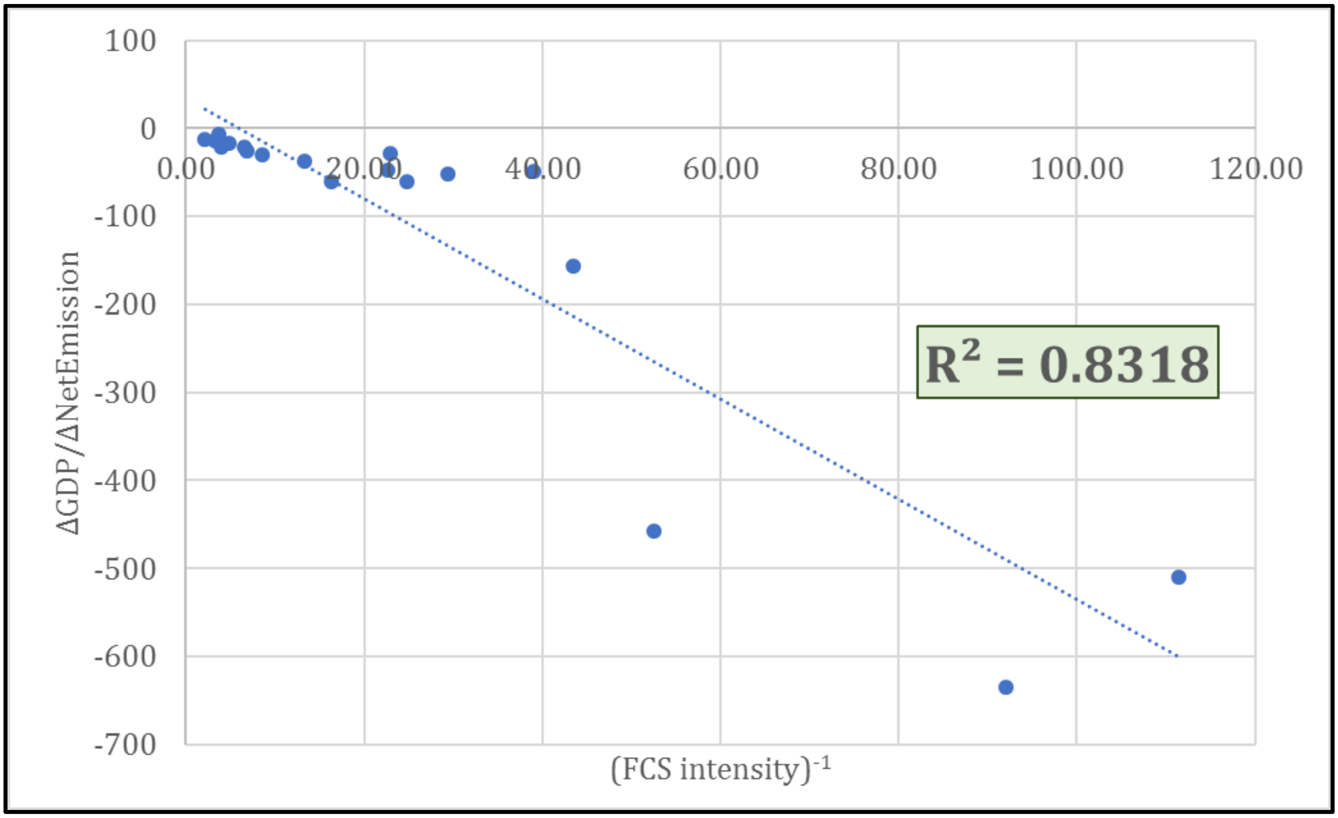
For the tax-subsidy regime, the cost efficiency UDC_r^{TS} is the average cost in implementing a tax-subsidy to reduce by 1% the regional net emissions. The cost is calculated as:

$$UDC_r^{TS} = \frac{CTAX_r}{\Delta\%EMIT_r}$$

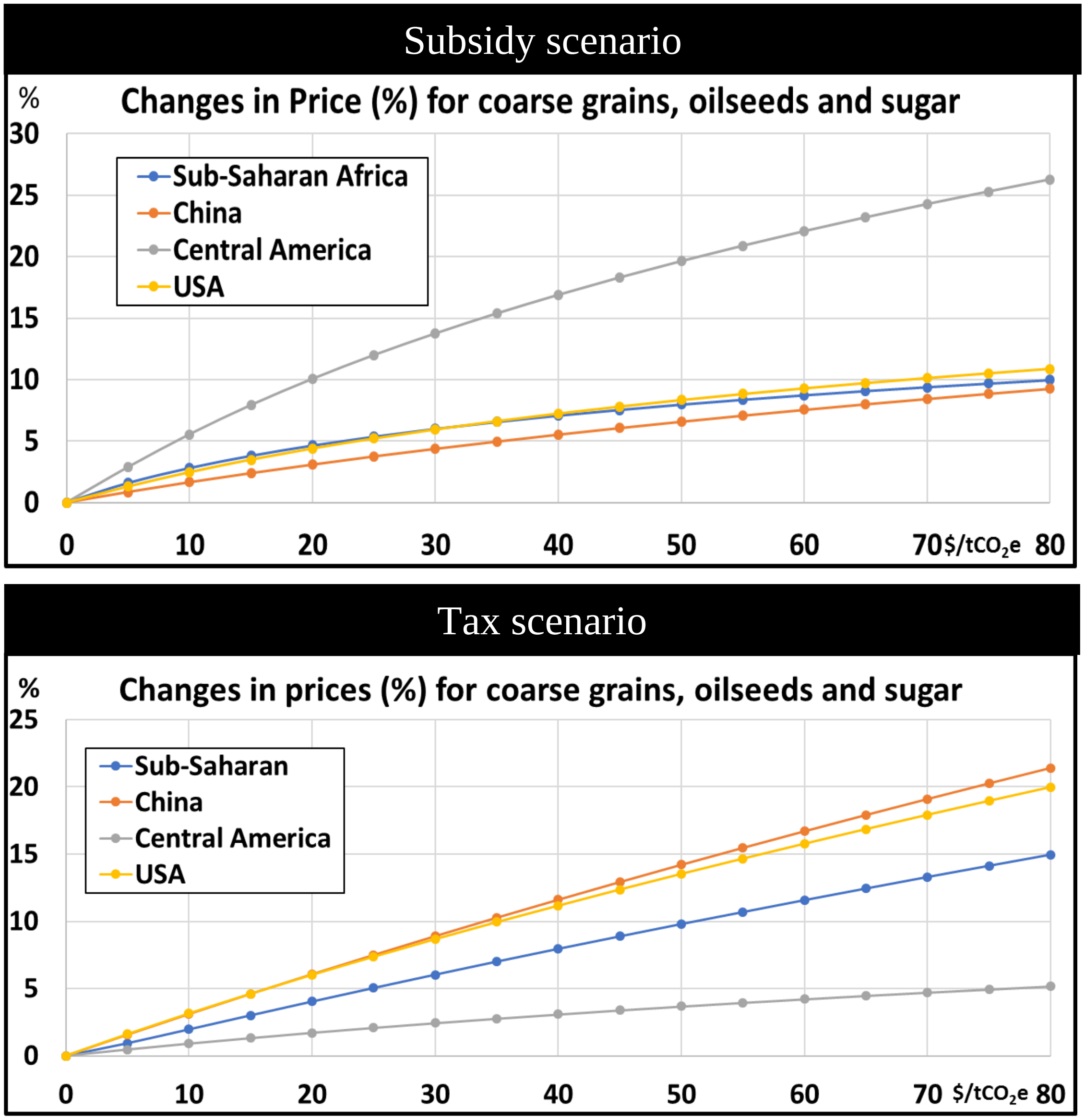
Here, $CTAX_r$ is the imposed carbon tax. $\Delta\%EMIT_r$ refers, as before, to the percentage change in net emissions in region *r*.

Supplementary Annex 3

Supplementary figures for social costs of each mitigation method



Supp. figure 1. Relationship between GDP cost and forest carbon sequestration intensity



Supp. figure 2. Changes in prices (%) for coarse grains, oilseeds and sugar for selected regions – FPCS Subsidy [top] and Carbon tax [bottom] scenarios