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Industrial and terrestrial carbon leakage under climate policy fragmentation

Mikel González-Eguino*[a,b], Iñigo Capellán-Pérez[b], Iñaki Arto[a],
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One of the main concerns in international climate negotiations is policy fragmentation, which could increase the carbon emissions of non-participating countries. Until very recently the carbon leakage literature has focused mainly on "industrial" carbon leakage through various channels, such as the induced changes in the prices of fossil fuels. But there is another potential channel that has received little attention so far: the carbon leakage triggered by land use changes, referred to as "terrestrial" carbon leakage. This paper explores the magnitudes of these two forms of leakage in a situation where CO_2 emissions in all sectors, including from land use change, are taxed equally. We explore the implications of different fragmentation scenarios using the GCAM integrated assessment model. Our results show that total carbon leakage is at its highest when the biggest developing regions do not participate, but its rate decreases with the size of the coalition. We also show that under different fragmentation scenarios terrestrial carbon leakage may be the dominant type of leakage up to 2050, due to deforestation in non-participating regions. The implications of shifting food and bioenergy production to non-participating regions are also analyzed.

Key words: Climate change, Energy, Carbon leakage, Industrial carbon leakage, Terrestrial carbon leakage, bio-energy.

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1. Introduction

The objective of stabilizing climate "at a level that would prevent dangerous anthropogenic interference with the climate system" (UNFCCC, 1992) has been translated into the long-held target of keeping concentrations of greenhouse gases (GHG) below 450 ppm CO_2-equivalent, which in turn is likely to limit global average temperature rise to 2 degrees Celsius (°C) above the pre-industrial level. According to the Intergovernmental Panel on Climate Change (IPCC, 2014), this target will require global GHG emissions to be severely reduced by 2050 and be close to zero by the end of the century.

Global climate change constitutes one of the greatest collective action problems in human history. Because GHGs mix uniformly in the upper atmosphere we are dealing with a pure global public good and, therefore, a multi-national response is required. To address the risks of climate change effectively, efforts that engage most countries (at least the "major emitters") will need to be undertaken. The Kyoto Protocol (UN, 1998), effective from 2005 to 2012, was the first attempt by the international community to curb GHG emissions through a legally binding international agreement. However, it failed to achieve a decisive breakthrough in international climate policy (Prins et al., 2010; Schiermeier, 2012). One of the lessons from the Kyoto Protocol is that a fragmented climate regime, with different countries joining the coalition with different objectives and timings, may be a more realistic scenario which may pave the way for a global regime in the long run (Hof et al., 2009). Consequently, the United Nations Framework Convention on Climate Change (UNFCCC) process has shifted from a top-down legally binding climate policy architecture towards a bottom-up approach in which countries decide individually on emission reduction targets (the so-called "voluntary pledges").

At the Conference of Parties held in Warsaw in November 2013 (COP 19), decision 1/CP.19 led to all Parties being invited to initiate or intensify domestic preparations for their intended nationally determined contributions (INDCs) towards the achievement of the climate stabilization objective. INDCs have been communicated in advance of COP 21 and it is hoped that the 2015 Agreement will spur the efforts of the international community to achieve the goals of the UNFCCC to prevent dangerous climate change, and will replace the Kyoto Protocol from 2020 onwards.

The European Union (EU) was one of the first regions to reach an internal decision on an INDC target. On 23 October 2014 it agreed on a domestic GHG reduction target of at least 40% compared to 1990 levels and a target of at least 27% for renewable energy and energy savings by 2030 (EC, 2014). A few weeks later, on 11 November 2014, China and the United States of America (US) jointly announced their respective post-2020 actions on climate change. According to the Joint-Agreement (WH, 2014), the US intends to achieve an economy-wide target of reducing its emissions by 26–28% below its 2005 level in 2025 and China intends CO_2 emissions to peak around 2030 and to increase the share of non-fossil fuels in primary energy consumption to around 20% by 2030. Therefore, climate action is expected to remain fragmented for a long time with a variety of regional/national climate policy agendas being pursued in different parts of the world.

One of the main concerns about fragmented climate regimes is carbon leakage. A fragmented climate regime is characterized by different climate policies across regions and sectors and this may lead to relocation of production to regions with less stringent mitigation rules, leading to higher emissions in those regions and, therefore, to carbon leakage. Until very recently the carbon leakage literature has focused mainly on "industrial" carbon leakage (ICL). There are three main channels that may lead to

ICL[1]: (1) the fossil fuel price channel, where reductions in global fossil fuel energy prices due to a fall in their energy demand in climate-constrained regions trigger higher fossil fuel demand and CO_2 emissions in non-participating regions; (2) the competitiveness channel, where carbon-constrained industrial products loose international market shares to the benefit of unconstrained competitors; and (3) the technology-dissemination channel, where carbon-saving technological innovations induced by climate policy in climate-constrained regions spill over to regions with less stringent climate policy. Integrated Assessment Models (IAMs) have focused primarily on the fossil fuel channel (Otto et al., 2014), whereas Computable General Equilibrium models (Hourcade et al., 2006) are a better tool to incorporate the other two mechanisms. In this paper we use an IAM and therefore we focus exclusively on the fuel price channel when measuring ICL.

But there is another type of carbon leakage that has received little attention so far: the carbon leakage triggered by land use changes, which we refer to as "terrestrial" carbon leakage (TCL). TCL can arise, for instance, when a regional carbon tax is applied not only to industrial but also to terrestrial carbon emissions and, as a consequence, market forces drive these regions to re-locate the production of food and/or bioenergy to regions with less stringent terrestrial carbon mitigation rules. Wise et al. (2009), Calvin et al. (2010), Calvin et al. (2014), Kuik (2014) and Otto et al. (2015) are examples of an emerging subset of this literature focusing on the TCL associated with carbon mitigation policies. However, to the best of our knowledge, no previous study has carried out an analysis where the magnitudes of the two forms of leakage (ICL and TCL) are included. This might be related to the fact that few models incorporate both dimensions in the same framework (see the Supplementary Materials in Otto et al., 2014). This article uses the GCAM model, an IAM that links energy and land-use systems, to fill that gap.

The type of mitigation strategy in this study is the so-called Universal Carbon Tax (UCT) regime in which CO_2 emissions in all sectors, including land use change, are taxed equally. This is in contrast with most of the literature, which considers the Fossil Fuel and Industry Carbon Tax (FFICT) regime, in which the carbon tax is applied only to fossil fuel and industrial emissions. Wise et al. (2009) show that if correcting measures are not implemented an FFICT regime leads to a large, most probably unsustainable change in land-use due to a huge increase in bio-energy[2] production. A UCT regime would constitute an "idealized implementation" scenario. But, as noted by Clarke et al. (2014), the mitigation scenarios used in the new literature consider more realistic implementations, the two most prominent of which are "fragmented action" (mitigation is not undertaken "where" it is less expensive) and "delayed participation" (mitigation is not undertaken "when" it is less expensive). Our scenarios include both of these deviations because developing and developed countries will start reducing emissions at different stages and the two groups will have different carbon prices.

The paper is organized as follows. Section 2 provides an overview of the GCAM model with a focus on those aspects that are of particular interest for the study. Section 3 present the different scenarios of fragmented climate regimes considered in the paper. Section 4 discusses the key findings of the study in terms of environmental effectiveness (Subsect. 4.1), effects on energy systems (Subsect. 4.2), effects on

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[1] Calvin et al. (2009) and Kriegel et al. (2014) offer a thorough discussion and quantification of the different channels by which carbon price differentials lead to changes in carbon emissions outside the regions taking domestic mitigation action and Antimiani et al. (2013) assess alternative solutions to this type of carbon leakage.
[2] In fact, bioenergy in combination with carbon capture and storage (BECCS) plays a crucial role in temperature stabilization scenarios (<2ºC) due to its capacity to contribute to negative emissions (Clarke et al., 2009; Edenhofer et al., 2010).

land use (Subsect. 4.3), effects on climate (Subsect. 4.4) and effects on mitigation costs (Subsect. 4.5). Finally, Sect. 5 draws conclusions.

2. Methods

2.1 Overview

The analysis in this paper uses the Global Change Assessment Model (GCAM 4.0), an IAM that links the world's energy, agriculture and land use systems with a climate model. GCAM, which traces its origin to a model developed by Edmonds and Really (1985) and was previously known as MiniCAM (see Edmonds et al., 1997), is a community model developed at the Joint Global Change Research Institute of the University of Maryland[3] (Calvin et al., 2011). GCAM was one of the four models chosen by the Intergovernmental Panel on Climate Change (IPCC) to create the Representative Concentration Pathways (RCPs) for the IPCC's Fifth Assessment Report (see Thomson et al., 2011).

GCAM is a dynamic recursive economic partial equilibrium[4] model driven by assumptions about population size and labor productivity that determines gross domestic production (GDP) in 32 geopolitical regions (see Table A1 in the Appendix) operating in 5-year time steps from 1990 to 2100. The model can be run with any combination of climate and non-climate policies in relation to a reference scenario and pre-set carbon price and mitigation costs. GCAM tracks emissions and atmospheric concentrations of GHGs, carbonaceous aerosols, sulfur dioxide, and reactive gases and provides estimates of the associated climate impacts. An important feature of the GCAM architecture is that the GCAM terrestrial carbon cycle model is embedded within the agriculture-land-use system model. Thus, all land uses and land covers, including non-commercial land, are fully integrated into the economic modeling in GCAM. This coverage makes GCAM capable of modeling policies that jointly cover carbon in all activities in energy, agriculture, forestry, and other land uses. For more details, see (Calvin et al., 2011).

2.2. The energy and land use systems

GCAM contains detailed representations of technology options for each of its economic components with technology choice determined by market probabilistic competition (Clarke and Edmonds, 1993). The model produces outputs that include energy and agricultural prices and land use allocation. The model can track not only fossil fuel and industrial emissions but also emissions associated with land use change (LUC).

The GCAM energy system includes primary energy resource production, energy transformation to final fuels, and the use of final energy forms to deliver energy services such as passenger kilometers in transport or space conditioning for buildings. GCAM distinguishes between two different types of resources: depletable and renewable. Depletable resources include fossil fuels and uranium; renewable resources include wind, geothermal energy, municipal and industrial waste (for waste-to-energy), and rooftop areas for solar photovoltaic equipment. All resources are characterized by cumulative supply curves, i.e. upward-sloping supply-cost curves that represent the idea that the marginal monetary cost of resource utilization increases with deployment. Carbon capture and storage (CCS) technology is available for application to large, point-source emission facilities. These include electric power generation,

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[3] Detailed information can be found at http://www.globalchange.umd.edu/models/gcam/
[4] GCAM establishes market-clearing prices for all energy, agriculture and land markets simultaneously but has no explicit markets for labor and capital and no constraints such as balance of payments.

hydrogen production, cement manufacturing and large industrial facilities. Complete documentation on all the technologies in the energy system is provided in Clarke et al. (2009).

The agriculture and land use component[5] is fully integrated into (i.e. solved simultaneously with) the GCAM economic and energy system components. Data for the agriculture and land use parts of the model comprise 151 sub-regions in terms of land use, based on a division of the extant agro-ecological zones (AEZs). Land is allocated between the various uses based on expected profitability, which in turn depends on the productivity of the land-based product (e.g. mass of harvestable product per hectare), product price, and non-land costs of production (labor, fertilizer, etc.). The productivity of land-based products is subject to change over time based on future estimates of crop productivity change. This increase in productivity is exogenously[6] set, adopted from projections from the FAO (Bruinsma, 2003). GCAM includes several different commercial and non-commercial land uses including ten crop categories[7], six animal categories[8], three bioenergy categories (see below), forests, pasture, grassland, shrubs, desert, tundra, and urban land. All agricultural crops, other land products, and animal products are globally traded within GCAM.

Bioenergy in GCAM is classified into three categories: traditional bioenergy, bioenergy from waste products, and purpose-grown bioenergy (Luckow et al., 2010). Traditional bioenergy comprises straw, dung, fuel wood, and other energy forms that are utilized in an unrefined state in the traditional sector of an economy. Traditional bioenergy use, although significant in developing regions, is a relatively small component of global energy and, as regional incomes increase over the century, it becomes less economically competitive. Bioenergy from waste products is a by-product of another activity. The amount of potential waste that is converted to bioenergy is based on the price of bioenergy. However, the bioenergy price does not affect production of the crop from which the waste is derived. Purpose-grown third-generation bioenergy refers to crops whose primary purpose is the provision of energy. The amount produced in this category depends on profitability with respect to other land-use options. The productivity of those crops is based on region-specific climate and soil characteristics and varies by a factor of around three across the GCAM regions. GCAM considers also the possibility of using bioenergy in the production of electric power and in combination with CCS technologies.

3. Scenarios

In this section we present the scenarios of different fragmentation regimes. As mentioned in the introductory section, the UNFCCC process has shifted from a top-down legally binding climate policy architecture to a bottom-up approach in which all Parties have been invited to decide their INDCs for the achievement of the climate stabilization objective. In this context, the EU has most clearly expressed its ambition by aiming for an emission reduction of 80% by 2050 and undertaking to respect that target even if no international agreement is reached[9]. China's long term commitment is less clear, but it has announced a commitment to "achieve the peaking of CO_2 emissions around 2030". Consequently, we

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[5] A full description of the agriculture and land use module in GCAM can be found in Kyle (2011) and Wise and Calvin (2011).

[6] GCAM assumes exogenous crop productivity improvements along the century, although the implications of different climate change scenarios have been explored recently (Kyle et al., 2014).

[7] The ten crop categories are Corn, Rice, Wheat, Other Grains, Sugar, Root Tuber, Palm Fruit, Fiber Crops, Oil Crops and Other Crops.

[8] The six animal product categories are Beef, Dairy, Pork, Poultry, Sheep, Goat and Others.

[9] The US announced on 12 November 2014 that would reduce its annual emission of GHGs by 26–28% below its 2005 level in 2025. This is not as clear as the EU's announcement but it seems to be consistent with the pledge made by the US Government in 2010 to reduce annual emissions by 83% by 2050 compared with 2005.

consider as a plausible outcome one in which the regions from the developed world taking part in the international climate regime follow the EU's commitments (to reduce emissions by 80% in 2050) and the regions from the developing world taking part in the international climate regime follow China's commitments (emissions peaking in 2030).

With respect to long-term climate policy we assume that, despite its fragmentation, the international climate regime will be guided by the principles provided by the "common but differentiated convergence" (CDC) approach. This is interpreted by Höhne et al. (2006) to mean that per capita emissions will have to converge to an equal per-capita emissions level[10] by 2100. For a detailed representation of the implications of emission reduction in emission per capita in each scenario see Fig. A3 in the Appendix.

Table 1 presents the scenarios that we use for our analysis. In the reference scenario (REF) we look at the possible evolution of GHG emissions in the absence of climate policies. The other six scenarios (Scenarios FR1-FR6) consider different possibilities of engagement of regions in the international climate regime. In choosing the groups of regions that take part in these scenarios of fragmented climate action we assume that all or part of the regions in the developed world may consider engaging in climate action even if developing regions do not engage, that some regions in the developing world will engage in climate action only if developed regions also engage in climate action and that some regions, for reasons which may include poverty or high dependency of their economies on fossil fuel resources, will never engage in climate action.

As Table 1 shows, if only developed regions take part in the international climate regime, the share of global carbon emissions covered by each of the fragmented scenarios in 2050 ranges from 7% (FR1) to 28% (FR3). If developing regions take part, the share ranges from 54% (FR4) to 88% (FR6).

All the scenarios apply a UCT regime in the participating regions. This means that both industrial and terrestrial emissions are subject to the same tax. Also it is important to mention that along the convergence process in per capita emissions to 2100 there will be a North–South divide regarding the timing and the emission reduction objectives, which will lead to two UCT regimes operating simultaneously, one for developed countries and another for developing countries.

Table 1: Scenarios

Scenarios	Participating Regions	Share of global total CO_2 emissions regulated by 2050
REF	None	0.0%
FR1	EU-27	7.1%
FR2	EU-27 + US	19.4%
FR3	Developed	28.4%
FR4	Developed + China	53.8%
FR5	Developed + BASIC	70.5%
FR6	All countries, except Africa + Russia + Middle East	88.0%

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[10] The convergence level is set at 0.5 tons of CO_2 per capita, the maximum per-capita emission level that would be required in GCAM to meet the 2°C stabilization target if every region in the world cooperates under a uniform climate regime.

4. Results

4.1 Carbon leakage and emissions

In this section we present the results for carbon leakage (ICL and TCL) associated with each of the fragmented climate policy scenarios. The carbon leakage rate is measured as the increase in carbon emissions outside the regions taking domestic mitigation action divided by the reduction in the emissions of those regions. Thus, if the emissions in participating and non-participating regions in each FRX fragmented climate regime are represented as E^{FRX} and E_{NP}^{FRX}, respectively, and the emissions in participating and non-participating regions in the reference scenario as E^{REF} and E_{NP}^{REF}, respectively, the leakage rate is given by:

$$\text{Leakage Rate (\%)} = 100 * \frac{\left(E_{NP}^{FRX} - E_{NP}^{REF}\right)}{\left(E_{P}^{REF} - E_{P}^{FRX}\right)}$$

Note that a sufficiently long time-frame in the order of decades has to be considered if the aim is to properly account for variations in carbon emissions due to land-use change.[11] Therefore, in order to capture a meaningful measure of TCL, the results for carbon leakage are presented in cumulative terms from 2020 (when the international climate regime enters into force) up to 2050 and to 2100.

Figure 1 shows the cumulative carbon leakage rate for the different fragmentation scenarios from 2020 to 2050 (left) and from 2020 to 2100 (right), distinguishing between ICL and TCL. Several conclusions follow. First, the cumulative leakage rates for ICL in this study are consistent with those in the literature[12] (see Böhringer et al., 2012). Second, it is found that in both time periods the total carbon
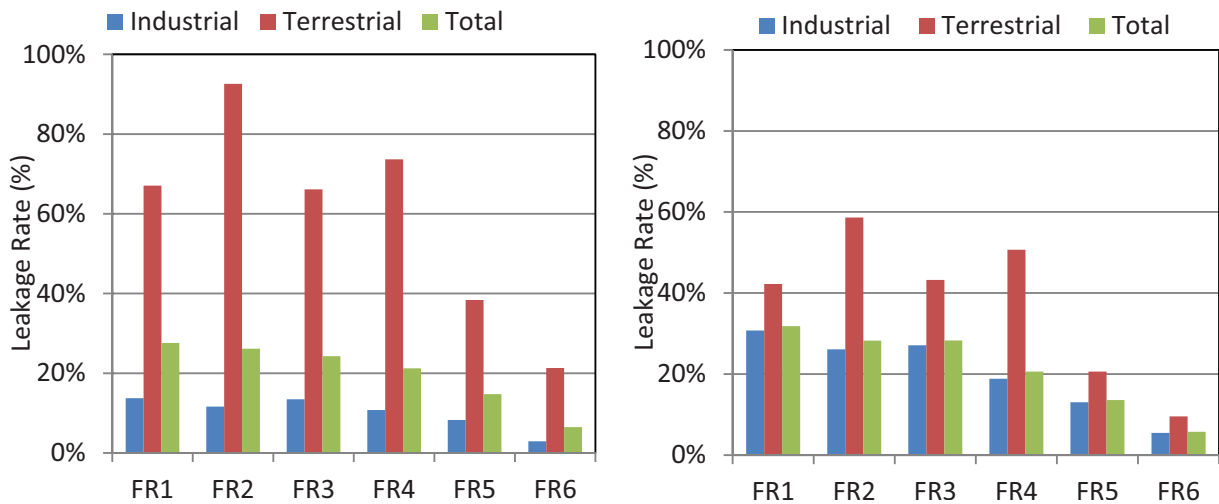

Figure 1: Global carbon leakage rate (%) for 2020−2050 (left) and 2020−2100 (right) by scenario.

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[11] All the carbon that is stored in a forest converted to cropland is released at once, but it takes decades for afforestation to build up all the carbon storage potential in the new forests (Nilsson 1995).

[12] Notice that the results of GCAM can only be compared with those of similar models, i.e. with partial equilibrium models.

leakage rate decreases with the size of the coalition implementing the international climate regime. In fact, the highest total leakage rate in the period 2020–2050 is in scenario FR1 (28%) and the lowest in the scenario FR6 (6%). Third, the ICL rate is much lower than the TCL rate. In the period 2020–2050 the ICL rate ranges from 3% to 14% and the TCL rate ranges from 21% to 93%. Fourth, the ICL rate dominates in the long run, where the rates for total leakage and ICL almost coincide.

Figure 2 shows the cumulative carbon leakage in absolute terms associated with the different fragmentation scenarios from 2020 to 2050 (left) and from 2020 to 2100 (right). In the first period we find that cumulative carbon leakage is in the range from 22 $GtCO_2$ to 98 $GtCO_2$ and that the highest values occur in scenarios FR3, FR4 and FR5. As expected, the relationship between leakage (in absolute terms) and the size of the coalition implementing the climate regime shows an inverted-U shape: it takes low values when the size is small (FR1), the values increase as the size grows to FR2-FR3, but once the coalition reaches a certain critical level (close to that for FR4) further increases in the size of the coalition (to FR5-FR6) reduce the potential for emissions to "leak" due to the reduced size of the non-participating regions. This pattern can also be observed in the period 2020–2100, with the only difference being that the amount of leakage is much higher in this case for every scenario. Note also that when a new region joins the climate coalition it starts reducing its emissions according to its reduction target, but by contrast all the regions outside the coalition increase their emissions. This effect can be observed in Fig. A4 in the Appendix, where regional disaggregation of carbon leakage is presented for each of the scenarios.

When comparing the TCL and the ICL effects, in absolute terms, TCL dominates during the period 2020–2050. However, if the longer period 2020–2100 is considered, the situation is inverted and the ICL effect dominates. This is due to the fact that emissions related to land-use change take place mainly between 2020 and 2030 (when mitigation policies start to be implemented in the developed and developing regions, respectively), but then start to decline. This will be examined in detail in Subsect. 5.3.

Figure 3 shows the trend in emissions associated with the energy and land-use systems. The left hand side of Fig. 3 shows that global emissions associated with the energy system increase monotonically over time
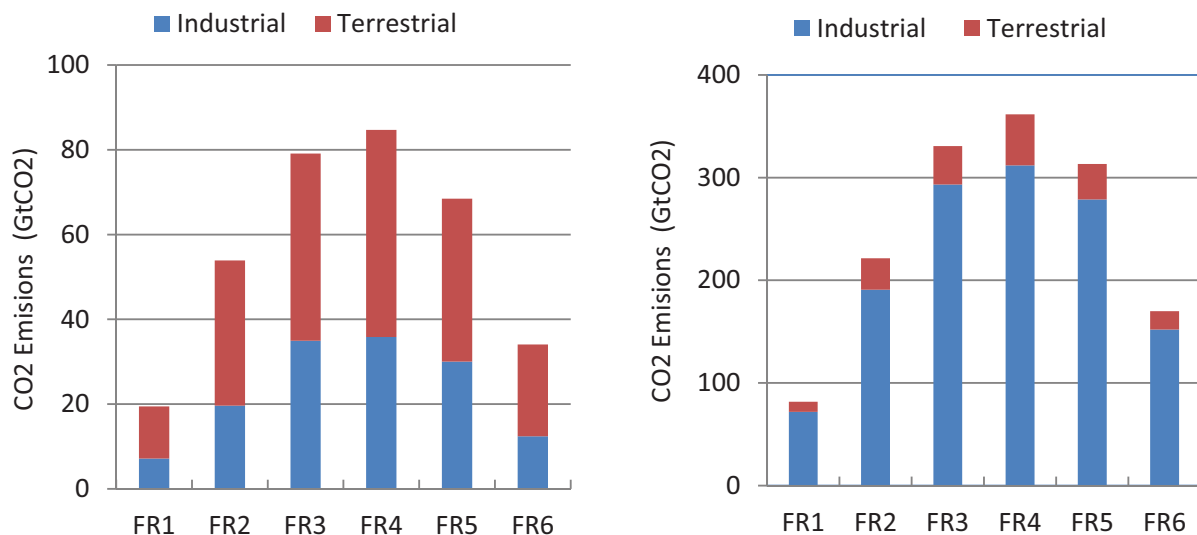

Figure 2: Global carbon leakage (GtCO$_2$) for 2020−2050 (left) and 2020−2100 (right) by scenario.

not only for the REF scenario but also for scenarios FR1, FR2 and FR3, where only developed regions take part in the international climate regime. For global emissions arising from the energy system to fall it is necessary that developing regions join the coalition (scenarios FR4, FR5 and FR6). However, global emissions from the energy system rise again around 2050 if the only developing regions joining the international climate regime are the so-called BASIC countries (scenarios FR4 and FR5). The right hand side of Fig. 3 shows that in the REF scenario emissions associated with land-used change decrease from +8 $GtCO_2$ in 2010 to −0.5 $GtCO_2$ in 2100, whereas in the rest of the scenarios afforestation drives emissions associated to negative values (from −0.5 $GtCO_2$ in FR1 to −9.6 $GtCO_2$ in FR6) before 2050 and they converge to values closer to those of the REF scenario by the end of the century.

Finally, Table 2 shows the mitigation rates in 2050 by scenario and regions. The shaded area represents those regions that are in the climate coalition in each of the fragmented scenarios. It can be seen that in those regions outside the grey area (non-participant regions) emissions are always higher in any fragmented scenario than in the REF scenario, due to the presence of carbon leakage. It can also be seen that the different marginal abatement cost of each country affect mitigation efforts. For example, China with an objective of a maximum increase of 140% of total CO_2 emission by 2050 (FR4) is tighten only to 103% when other developing countries enter the coalition (FR6), since China´s marginal abatement costs are higher. By contrary, the EU can relax slightly its objective by 2050 (FR1), when the US enters the coalition (FR2). Table 2 also shows that there are important differences between scenarios in terms of the global emission reduction effort. Therefore, it is better to be cautious when comparing the effect of these scenarios in terms of mitigation costs or climate change control achievement, as shown in the following sub-sections.
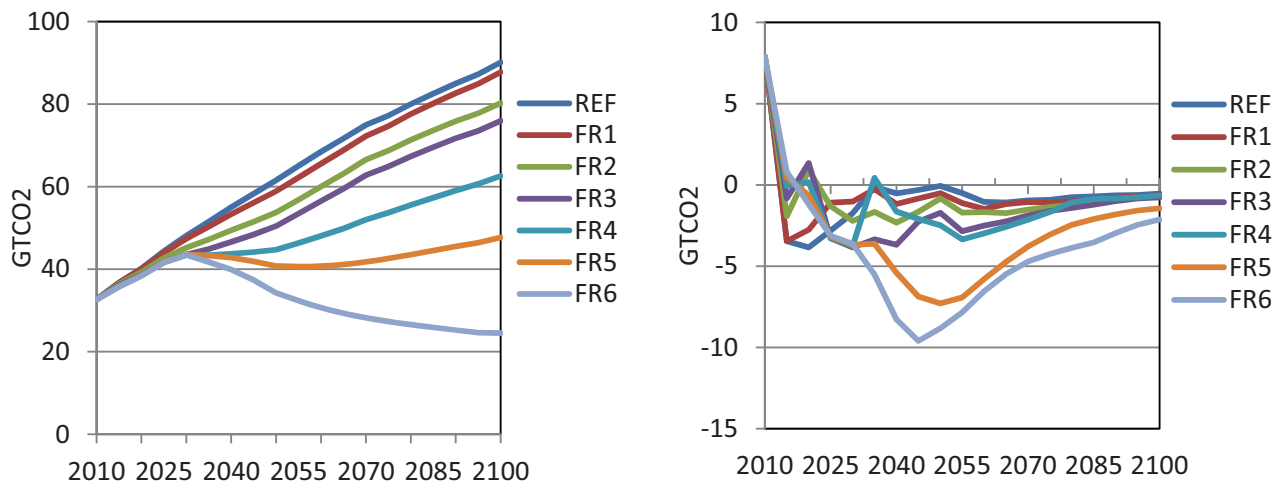

Figure 3: Global emissions by scenario (GtCO₂): energy system (left) and land-use changes (right).

Table 2: Mitigation rates (%) by 2050 (compared to 1990)

	REF	FR1	FR2	FR3	FR4	FR5	FR6
EU27	1%	-80%	-78%	-79%	-79%	-78%	-78%
USA	49%	51%	-88%	-90%	-91%	-92%	-92%
Other Developed	70%	75%	82%	-75%	-76%	-77%	-78%
China	288%	292%	298%	307%	140%	138%	103%
Brazil+ India+ S.Africa	365%	369%	383%	398%	407%	117%	101%
ROW	189%	192%	202%	214%	221%	226%	85%
Russia, ME and Africa	84%	87%	93%	100%	104%	103%	102%
Global	131%	121%	100%	86%	63%	38%	12%

4.2 Effects on the global energy system

This section analyses the changes in the global energy system which are important to understand the driving forces behind the carbon leakage effects. Figure 4 shows the global primary[13] energy mix in 2050. As the size of the climate coalition increases the share of fossil fuel in total primary energy demand decreases from 82% in the REF scenario to 76% in scenario FR3. This reduction in demand for fossil fuels causes a drop in the price of fossil fuels[14] by 2050 (cf. Fig. 6). Even though the change in the fossil fuel price index is limited[15] for every scenario, ranging from 17.5% in REF to 15.5% in FR6, we find that the bigger the size of the coalition the lower the increase in the fossil fuel price index.
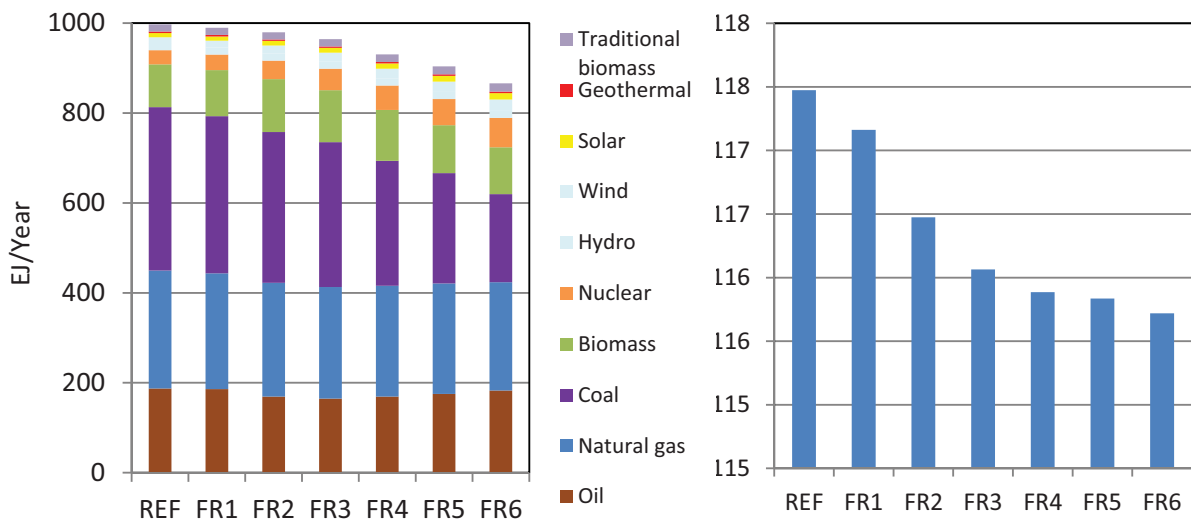

Figure 4: Energy System: A) Global primary energy in 2050 (EJ/year, direct equivalent) and B) Global Fossil Fuel Price Index in 2050 (2010=100).

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[13] In direct equivalent terms.

[14] The Index of Fossil Fuel includes the global price variation of crude oil, natural gas and coal. Each element is weighted according to the proportion of energy (EJ) in the primary energy mix.

[15] This is due to the supply-cost curves implemented in GCAM from Rogner (1997), characterized by large amount of resources at relatively low and stable extraction cost (Capellán-Pérez et al., 2014).

According to the results reported in Figs. 5 and 6 it may seem that fragmentation of the international climate regime does not have a substantial impact on demand for (and therefore the price of) fossil fuels. However, one should also consider other effects in the energy system that would take place simultaneously. First, climate policies will induce improvements in energy efficiency that will be translated into reductions in global energy consumption. Thus, Fig. 5 shows a 13% reduction in the consumption of primary energy by 2050 between the REF and the FR6 scenario. Second, the inclusion in this model of CCS technologies allows for some amount of fossil fuels to be used also in the participating regions. Figure A5 in the Appendix also shows that a substantial part of the global electricity mix in 2050 is still covered by fossil fuel with CCS technology (up to 12%). The greatest expansion due to mitigation policies is in nuclear power (up to 31%). The figure also shows that biomass does not have a prominent role in the energy system and the use of biomass with CCS is marginal in all the scenarios along the century.[16] This expansion of biomass is explored further in the next sub-section.

4.3 Effects on the global land-use system

The main channels for TCL are the deforestation and/or afforestation that take place in response to fragmentation of the climate regime. As stated in the introductory section, all the scenarios used in this paper are implemented following a UCT approach. When participating regions put an explicit value on terrestrial carbon emissions, they have an incentive to trade products from land with low carbon density storage (e.g. crop land) for products from land with high carbon density storage (e.g. forest). This triggers afforestation in participating countries and deforestation in non-participating countries. Clearing mature forests immediately releases many years of accumulated carbon but it will take decades for afforested areas to store that amount of carbon (Nilsson, 1995). This means there may be temporarily an increase in land-use change related emissions even if the forest area remains globally stable.

The biggest absolute variation takes place within the land given over to forests. Figure 5a tracks the trend in the global area given over to total forest land (managed and unmanaged). In the REF scenario
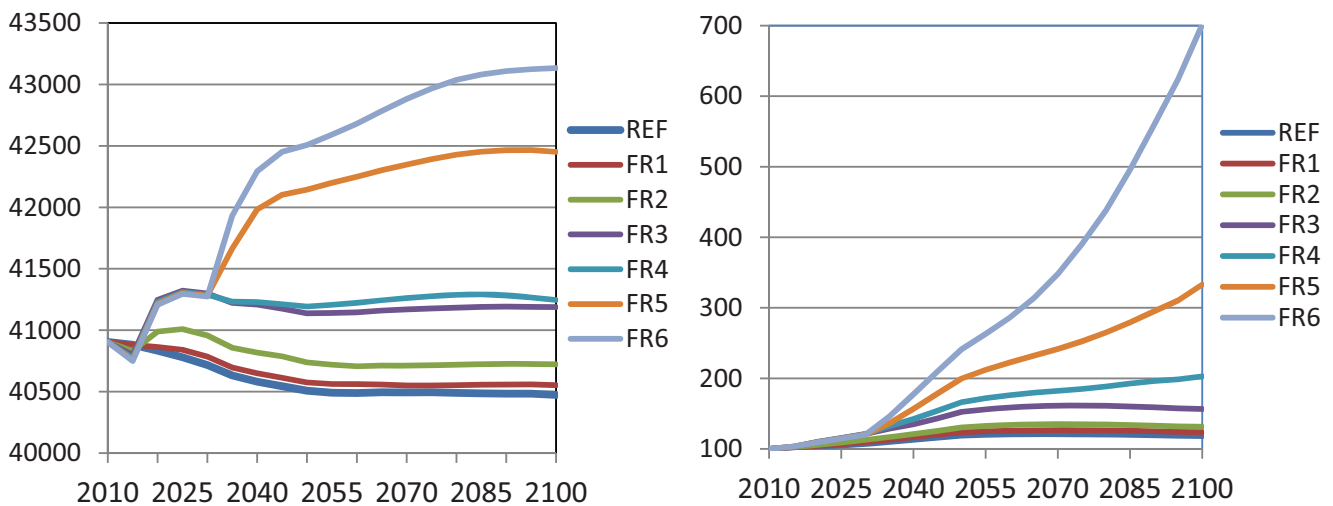

Figure 5: Land-use System: A) Trend in global forest area by scenario compared (Mkm^2). B) Global Food Price index by scenario (Base 2010=100).

[16] This is also true for all the scenarios in 2100.

there is a slight decrease in the area of forest over time due to an increasing area for food/biofuel production. However, the introduction of (fragmented) climate policy leads to an increase in the global forest area. It is even possible to see the "jumps" in afforestation in the year in which regions start their mitigation efforts (2020 for developed countries and 2030 for developing countries). Globally, the total forest area increases with the increase in the size of the coalition from +0.2% to +4.9% by 2050.

Table 3 shows the global land-shift under different scenarios by 2050 for crops, biomass and forest area, as the rest of the land uses remains nearly unchanged (see also Figs. A6 and A7 in the Appendix). Afforestation in participating regions occurs at the expense of shifting food and bioenergy production to non-participating regions. By 2050 the forest area in participating regions increases between 10% and 25%, whereas in non-participating regions the land dedicated to bioenergy increases between 15% and 40% and the land dedicated to crops increases between 4% and 40% depending on the scenario.

Table 3: Change in the land area in 2050 (compared to REF)

	FR1	FR2	FR3	FR4	FR5	FR6
Crops						
Participating	-35.9%	-34.5%	-37.8%	-30.4%	-23.4%	-15.0%
Non-participating	4.0%	9.4%	18.4%	25.9%	38.2%	39.6%
Global	1.4%	2.3%	2.6%	4.9%	3.5%	1.3%
Bioenergy						
Participating	-38.4%	-22.8%	-23.1%	-15.4%	-21.5%	-20.9%
Non-participating	12.5%	34.3%	42.1%	41.5%	21.6%	15.6%
Global	3.1%	15.4%	9.4%	5.9%	-8.1%	-11.1%
Forest						
Participating	23.0%	17.6%	10.5%	10.2%	10.8%	8.7%
Non-participating	-0.9%	-1.9%	-2.5%	-2.9%	-2.0%	-0.6%
Global	0.2%	0.6%	1.6%	1.7%	4.0%	4.9%

An important effect associated to a UCT regime is the increase in the price of food because of the pricing of terrestrial carbon emissions (see also Calvin et al., 2014). Moreover, climate policy fragmentation forces a shift of the production of biomass/food to those regions that are outside the climate coalition, which implies that production is not undertaken in those places where productivity is highest. Thus, fragmentation will intensify the increase in the price of food globally. The impact on the global food price index[17] is shown in Fig. 5b. The higher the mitigation target (and the level of afforestation in participating regions) the greater the increase in the price of food. In 2050 the price of food could increase by a factor of 2 in FR5 and 2.5 in FR6. By 2100, prices increase by a factor of 3 in FR5 and 7 in FR6. The greatest increases are in the prices of animal products such as beef and poultry.

4.4 Effect on the climate system and mitigation costs

This section shows the implication of fragmentation for the climate system. Figure 6a shows the different carbon prices associated with each scenario depending on whether each region is participating or not in

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[17] The Food Price Index includes the global price variation of the ten crops and six animal categories included in the GCAM model.
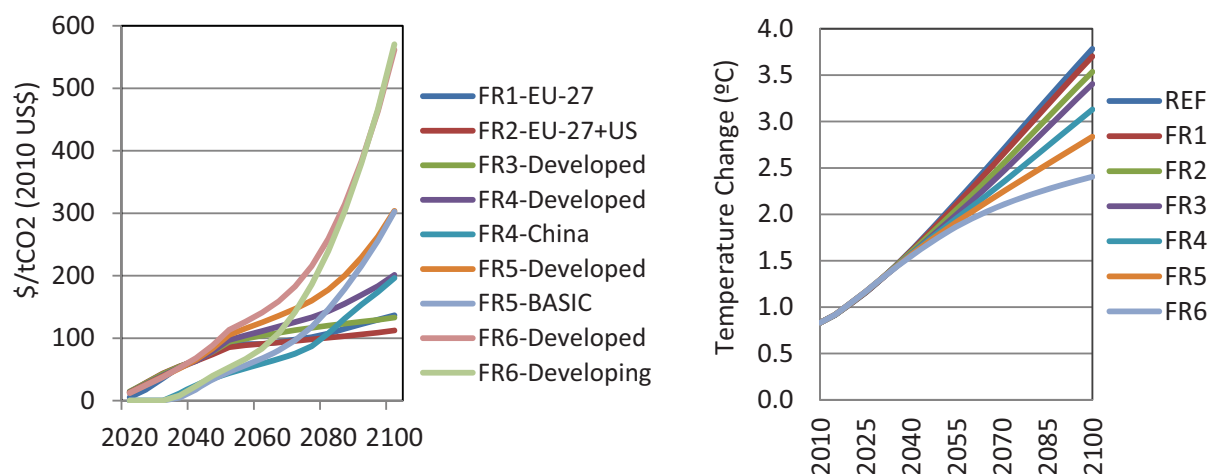
Figure 6: Climate System: A) CO_2 prices by regions ($/tCO^2$ US$2010) and B) Global temperature change by scenario, 2010−2100 (°C).

the international climate regime.[18] An increasing mitigation effort of participating countries means an increasing carbon price. Figure 6b shows the temperature change for each of the scenarios. Consistently with emission reduction targets, increases in average temperature in 2100 are very different. In the REF scenario the temperature in 2100 increases to 3.8°C above preindustrial level, whereas in FR1, FR2 and FR3, due to the fact that developing regions do not take part in the international climate regime, it is only slightly below that level (3.7, 3.5 and 3.4°C, respectively). Even in scenario FR6, where only Russia, the Middle East and Africa are outside the international climate regime, the increase in the mean global temperature (2.4°C) exceeds the threshold of 2°C.

Finally, the regional cost of mitigation can also be observed in Table 4, which measures the policy cost by 2100 in terms of GDP. The regions outside the climate coalition have no mitigation target, so the policy cost in terms of GDP is 0%. However, regions that are in the climate coalition in each of the fragmented scenarios have a policy cost. The total policy cost increases from 0.13% of global GDP in FR1 to 0.44% in FR3 and 2.49% in FR6. Also, note that the participation of the US in the coalition reduces the mitigation cost for the EU. In other situations, such as the case of China when other BASIC countries join the coalition, mitigation costs increase. This effect depends on how the mitigation options with the lowest costs are distributed among the regions, since the market will allocate more mitigation effort to these regions.

Table 4: Policy cost by regions in 2100 (% of GDP)

	FR1	FR2	FR3	FR4	FR5	FR6
EU27	0.90%	0.50%	0.50%	0.55%	0.70%	1.17%
USA	0.00%	1.01%	1.02%	1.21%	1.41%	1.82%
Other Developed	0.00%	0.00%	0.94%	1.14%	1.38%	1.90%

[18] Note that in FR4, FR5 and FR6 there are two "bubbles", one for developing regions in the climate regime and the other for developed regions in the climate regime. This means that in those cases there will be two different converging prices.

China	0.00%	0.00%	0.00%	1.73%	2.07%	3.08%
Brazil+ India+ S.Africa	0.00%	0.00%	0.00%	0.00%	3.29%	4.29%
RoW	0.00%	0.00%	0.00%	0.00%	0.00%	3.83%
Russia, ME and Africa	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Total	0.13%	0.30%	0.44%	0.82%	1.31%	2.49%

5. Concluding remarks

As of early November 147 countries, both developed and developing countries have submitted their national post-2020 climate action commitments, known as INDCs, and these commitments will form the foundation of a future international climate agreement. As a consequence of the bottom-up approach adopted since Copenhagen in which regions decide individually on voluntary pledges, the resulting agreement will be in the nature of a fragmented climate regime. Fragmented climate policy regimes are prone to carbon leakage defined as the situation that may occur if, for reasons of costs related to climate policies, economies were to transfer carbon-intensive production to regions which have laxer constraints on GHG emissions.

While most studies in the literature have examined the concept of industrial leakage, the phenomenon can also occur in the terrestrial system. This study analyses the magnitudes of the two types of leakage (ICL and TCL) implementing a UCT regime (CO_2 emissions in all sectors, including land use change, are taxed equally) under different fragmentation scenarios. For this analysis, we use the GCAM model that links the world's energy, land use and agriculture systems with the climate system. Overall, the main scope of this paper is to examine the implications in terms of ICL and TCL of more realistic scenarios for the international climate regime where mitigation action is fragmented and delayed. The simplifying assumption used to build the future scenarios of fragmented and delayed climate action is that developed regions taking part in the international climate regime will unilaterally commit to reduce emissions by 80% in 2050 (in line with the EU's INDC and consistent with its energy roadmap) and the emissions from developing regions taking part in the international climate regime will peak in 2030 (in line with China's INDC). With respect to long-term climate policy we assume that, despite its fragmentation, the international climate regime will lead to equal per-capita emissions level by 2100. The study also includes an assessment of the effects of the fragmented climate regimes on energy systems, land use, climate and mitigation costs.

We derive four main findings from our study. First, we show that carbon leakage in absolute terms takes the highest values (between 20 and 80 cumulative $GtCO_2$ by 2050) when the biggest developing regions do not take part in the international climate regime. Second, the carbon leakage rate decreases with the size of the climate coalition (between 5% and 25% by 2050). Third, TCL turns out to be the dominant type of leakage up to 2050, due to deforestation in non-participating regions, but ICL takes over during the second half of the century. Fourth, fragmented scenarios where only developed countries take part in the international climate regime lead to a range of average estimates of temperature changes above 3.4ºC. Even in the more optimistic scenarios where only Russia, the Middle East and Africa are outside the international climate regime, coordinated climate action has the capability of limiting the forecast temperature rise to around 2.4 ºC by 2100, exceeding the threshold of 2ºC.

Two main caveats apply to the analysis. First, this paper examines an idealized UCT regime, leaving aside the difficulties associated with its implementation. Second, the effect of climate on yields and vegetation is not included and, although it is beyond the scope of this paper, this issue is one of the improvements of the modeling approach that is currently being discussed by the IAM and GCAM communities (Page et al., 2013).

Finally, we point out future research directions. Even though we have already commented some preliminary results regarding the effect of the fragmented climate regime on the price of food, more research effort should be devoted to disentangle what part of that increase is the result of the implementation of a UCT regime and what part is due to the fragmented nature of the climate regime. Another possible future research direction would be to extend the analysis to consider the introduction of biodiversity-sensitive forest preservation incentives in the international climate regime, since it has been observed that one important implication of a UCT-type instrument in a fragmented climate policy scenario is that it leads to deforestation in non-participating countries.

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Appendix

Table A1: Regional disaggregation of GCAM 4.0 and classifications

Developed Regions	Developing Regions	Non-Participants
Argentina	Brazil	Africa_Eastern
Australia_NZ	Central America and	Africa_Northern
Canada	Central Asia	Africa_Southern
EU-12	China	Africa_Western
EU-15	Colombia	Middle East
Europe_Non_EU	Europe_Eastern	Russia
European Free Trade	India	
Japan	Indonesia	
Mexico	Pakistan	
South Korea	South Africa	
Taiwan	South America_Northern	
USA	South America_Southern	
	South Asia	
	Southeast Asia	

Source: Own elaboration

Figure A2: Emissions per capita by regions and scenarios, 2010–2100 (tCO₂)

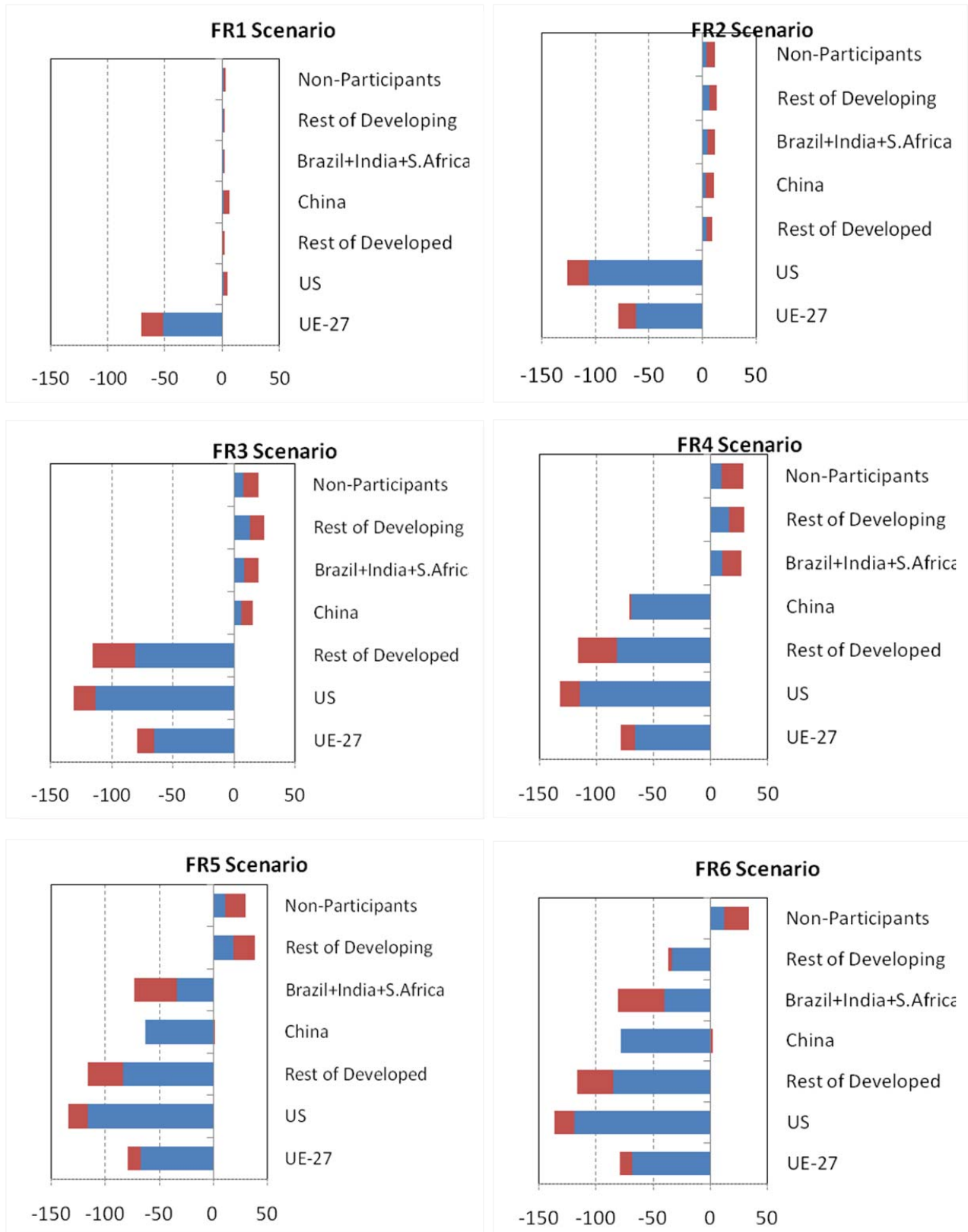*Figure A3: Carbon leakage by regions and scenarios, 2010–2050 (GtCO₂)*

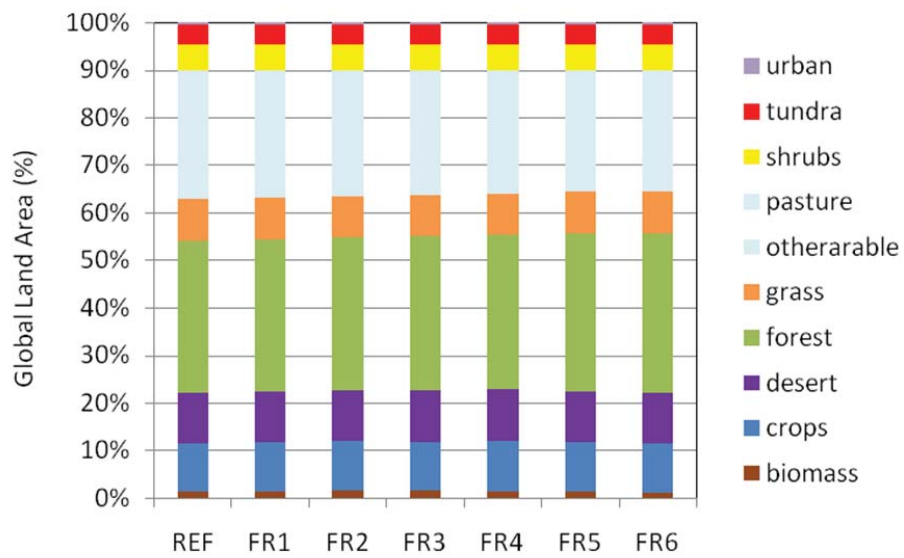*Figure A4: Global land use area in 2050 by scenario (%)*

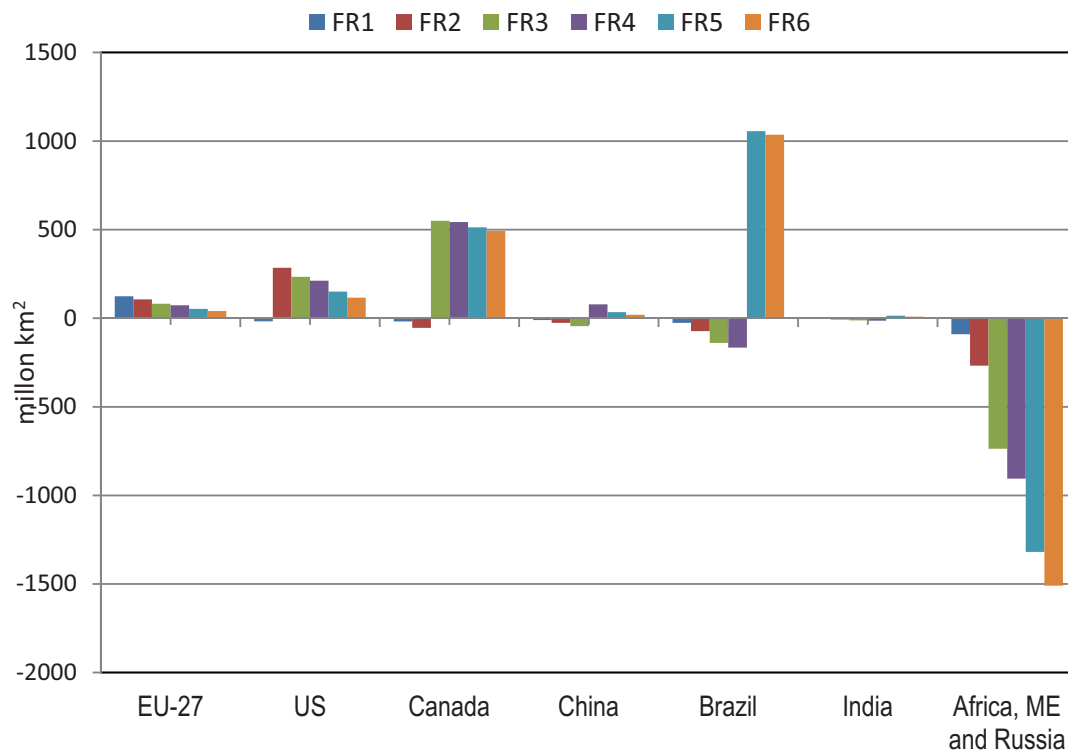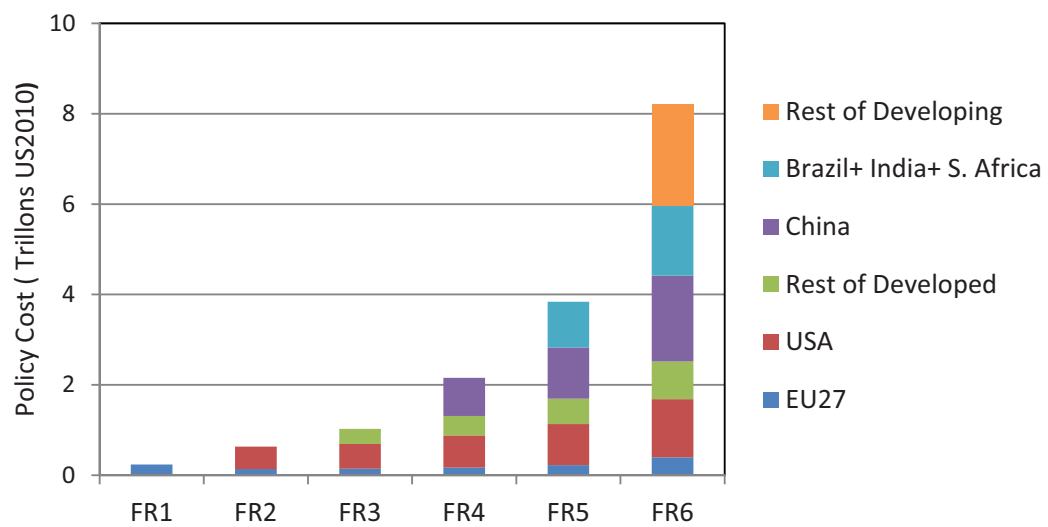*Figure A5: Change in forest area by regions in 2050 compared to REF (in million km²)*

Figure A6: Policy costs for the different scenarios in 2100 (Trillion 2010$)

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