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The Kyoto Agreement:
Regional and Sectoral Contributions to the Carbon Leakage

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Abstract

Carbon emissions abatement in a group of countries can result in increased emissions in non-abating countries. This effect has been referred to as carbon leakage. The Kyoto Agreement calls for a number of industrialized countries to limit their emissions while other countries have no abatement commitments. This paper assesses the sectoral determinants of the leakage in a static multi-sector, multi-regional computable general equilibrium model. In baseline estimates based on our model, the Kyoto Agreement leads to the carbon leakage rate of 10 percent. A decomposition technique is applied which attributes increases in carbon emissions by non-participating countries to specific sectors in the abating countries. This information is important for the debate on the tax exemptions for certain industries in the participating countries as it provides information for the most- and least- leakage contributing sectors of the economy. In absolute terms, carbon restrictions on chemical, iron and steel industries are the major sources of the leakage of the carbon emissions into the developing world. In relative terms, these industries along with mining, non-ferrous metal industry, and non-metallic mineral industry have the highest ratio of induced leakage to their sectoral carbon emissions. Additional calculations indicate the need for caution in the carbon tax design. For example, exemptions of any sector from a carbon tax are not justified because they lower welfare in a region. At a region-specific level, actions by the European Union and the USA are mainly responsible for the leakage of carbon. Different regions have a different ratio of induced leakage to their share of abatement. Europe and Japan have a larger relative contribution to the leakage than the USA. The emissions are primarily transferred into China, the Middle East region, and South Africa. The degree of sectoral and regional data disaggregation, and international capital mobility do not change the leakage rate significantly. As has been noted in other studies, fossil-fuel supply elasticity and trade substitution elasticity are crucial determinants for projecting the total world emissions of CO_2.

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1 Introduction

Expanding economic activities can impose potentially irreversible environmental damage at local and global levels. A major example is "the greenhouse effect". This term refers to the effect of rising atmospheric concentrations of carbon dioxide and other gases emitted from burning of fossil fuels and other human activity. According to different models (see, for example, Bruce *et al* (1996) for a review), the greenhouse effect will cause significant global warming by the middle of the next century in the absence of policy intervention. In 1992 the United Nations Framework Convention on Climate Change (UNFCCC) was ratified by 154 countries. According to 1997 Kyoto Protocol, these countries agreed to limit greenhouse emissions. The Protocol calls for industrialized countries[1] to limit their emissions by the first part of the 21-st century. Developing countries have not committed themselves to reduce their greenhouse emissions because they have made minor contributions to global carbon dioxide concentrations. Unilateral carbon emissions abatement by a subset of countries has raised serious doubts about its environmental efficiency. Abatement activities of the industrialized countries might result in a movement of carbon emissions into the regions with no restrictions. This effect has been called *leakage*.

The main purpose of this paper is to estimate the region- and sector-specific contributions to the carbon leakage resulting from the Kyoto Agreement. As far as we know, this is the first study which assesses the leakage induced by a particular Annex B region. Information about the most- and least- leakage contributing sectors of the economy is important for the debate on a carbon tax design. An optimal carbon taxation attains a desirable global carbon reduction target at minimum cost. The first-best solution would apply a carbon tax in every country with a structure based on marginal abatement costs. The Kyoto Agreement, where some countries are exempt from abatement, leads to the second-best solution. The optimal tax rate must include additional costs as a result of the carbon leakage. The results of our study can be used as a

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[1] The countries are listed in the agreement in the Annex B, so they are called Annex B or Annex I countries. They include most OECD countries. For a full list of the Annex B countries, see Appendix 1.

starting point for the problem of optimal taxation in the second-best setting. We do not address this very challenging problem in the current paper. Another complicating issue of carbon tax design is sectoral exemptions from environmental regulations which for various reasons are applied in many countries. In this paper we address an important question how sectoral exemptions affect the carbon leakage and regional welfare.

The leakage rate is defined as the ratio of total increased carbon emissions by the non-Annex B countries to total emissions abatement by the Annex B country. This means that if the leakage rate is 40%, then a decrease in carbon emissions by Annex B countries by 100 million tons would lead to an increase in carbon emissions by non-Annex B countries by 40 million tons. As a result, the total decrease in the world carbon emissions would be 60 instead of 100 million tons.

It is important to estimate the magnitude of the carbon leakage. If the leakage rate is high (close to 100%), then the decrease in carbon emissions by the Annex B countries assigned by the Kyoto Protocol has no effect on global emissions. An assessment of the leakage is a challenging task because of complex interactions between energy and non-energy markets. There are several potential sources for the carbon leakage (Felder and Rutherford (1993), Burniaux and Martins (2000), Kverndokk *et al* (2000)).

The first one is due to the change in a demand on global fossil-fuel markets. Carbon abatement commitments may decrease the demand in the Annex B countries. This may lead to lower international prices for fossil fuels and increase in the fossil-fuel demand and emissions in the non-Annex B countries. The change in the non-Annex B energy demand depends on the fossil-fuel prices and substitution possibilities. Different fossil fuels have different carbon content[2]. The Kyoto agreement might cause a fall in the price of oil relative to the price of coal. Based on a new price ratio, a non-Annex B country might substitute a relatively less carbon-intensive oil for carbon-intensive coal. Thus, the change in the fossil-fuel demand may even lead to a negative leakage. The magnitude of the leakage depends on the supply response by fossil-fuel producers. The decision about the

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[2] The ratio of carbon in coal:oil:gas is 1:0.75:0.57.

rate of fossil-fuel extraction is an important determinant for the international price, and, therefore, for the carbon leakage.

The second major reason for the leakage comes from the higher costs of energy-intensive products in the Annex B countries. Carbon abatements might cause a shift of production to the non-Annex B countries due to the change in the competitiveness of the energy-intensive industries. It will lead to a positive carbon leakage. Also, the changes in terms of trade and regional income (for example, a change in oil revenue greatly affects an oil-exporting country's income) may cause positive or negative leakage.

The existing models give very different and sometimes even negative estimates for the leakage rate (Felder, Rutherford (1993)). However, most studies have found that the rate is about 5-35 percent. As reported by the Energy Modeling Forum (EMF (2000)), the current models have the following magnitudes for the leakage rate: 8% (G-Cubed), 9% (GTEM), 11% (Gemini-E3), 14% (WorldScan), 26% (MS-MRT), 34% (MERGE4). Also, OECD (Burniaux, Martins, (2000)) has reported that their leakage estimate with the GREEN model is 5%. These estimates are reported for the scenario where carbon emission permits are non-tradable between countries. According to the existing models, permit trading decreases the carbon leakage rate approximately by half.

The goal of this paper is not to provide yet one more estimate for the leakage rate but to decompose the contributions to the leakage at regional and sectoral levels. The existing models evaluate an increase in the emissions in a particular non-abating region. The novelty of this paper is that it investigates the origin of the leakage, i.e., what sector in what abating region causes the increase in emissions in a particular non-abating region. An important implication of the study is whether leakage effects justify sectoral exemptions from carbon taxation.

The basis for the research is a static large-scale computable general equilibrium (CGE) model of the world economy. The model is build on the GTAP-EG dataset (Rutherford and Paltsev (2000)), which combines the energy and economic data for 45 regions, 23 goods (5 of which are energy goods), and 5 primary factors. To assess the economic implications of the Kyoto Protocol, we apply a decomposition procedure described by Harrison *et al* (1999). Their procedure is used for decomposing CGE models' simulation results with respect to exogenous shocks. The change in any endogenous variable is equal to the sum of the contributions to this change attributed to the exogenous variable. The contributions that make up the decomposition are defined as integrals. They depend on the path by which the exogenous variables move from their pre-simulation to post-simulation values.

Bohringer and Rutherford (2000) applied the procedure to study the effect of implementation of Kyoto agreement on welfare. They calculate a cross-country matrix for monetary transfer payments which would have to be assigned on a bilateral basis. Our paper develops the decomposition technique further and focuses on region- and sector-specific effects of carbon limits by a particular Annex B country on carbon emissions of a particular country of the world. As such, the total economic impact is split into contributions from its own policy changes and those from other regions.

Key findings of this paper can be summarized as follows. The leakage rate is 10.5% for the baseline values of the model. The economic sectors in which the carbon tax contributes the most to the leakage are the chemical industry (it contributes 2.1% to the total 10.5% leakage, or a 20% share), the iron and steel industry (16%), and final demand (15%). Some sectors, like final demand, transport, dwellings, or services, have high contributions because of their large size. Therefore, we introduced two ratios for assessing relative contributions. The leakage-emissions ratio (LE) relates emissions increase in the non-Annex B countries due to a carbon tax in a particular region or sector to total carbon emissions in that region or sector. Accordingly, the leakage-abatement ratio (LA) shows how leakage induced by a particular sector or region is related to abatement in that sector or region. Adjustment for total emissions and the magnitude of abatement shows that mining and the non-ferrous metal industry make relatively high contributions to the leakage along with the iron and steel, and chemical industries.

The leakage can be reduced if carbon abatement is imposed upon those sectors which will not move to another country to pollute. Indeed, our model shows that the exemptions in the chemical, the iron and steel, and the non-ferrous metal industries reduce the leakage. However, sectoral exemptions from carbon regulations are not justified. Holding the Annex B emissions constant, exemptions for some sectors imply increased tax rates for others and a decrease in regional welfare.

The regions whose actions lead to the largest induced leakage are the European Union (36-51% of the contribution to carbon leakage based on different scenarios), the USA (28-34%), and Japan (13-18%). The regions have very different ratios of the induced leakage to their emissions abatement. In the baseline estimate, the USA share of the total emissions abatement equals 54% and the share of the induced leakage is 29%, while for the European Union these numbers are 26% and 41%, respectively. This result is influenced by a pattern of a global trade. It shows that, in relative terms, mitigation activities by the USA do not affect global carbon emissions as strongly as actions by Europe, Japan, Australia, and New Zealand. In fact, LE and LA ratios are the highest for Australia and New Zealand.

The regions where the emissions will rise the most due to the implementation of the Kyoto Agreement are China (24-32% of the total increase) and the Middle East countries (24-30%). The relations between the following regions are the major contributors to the leakage: USA-Middle East, Europe-South Africa, Japan-China, and USA-China. A consideration of the sector specific carbon taxes in the Annex B regions leads to the following results. China will be affected the most by the tax on the iron and steel sector in Japan, then by the tax on the chemical industry in the USA, and by the tax on the chemical industry in the European Union.

It is usually proposed that the carbon tax should be levied on fossil fuels according to their carbon content. Our calculations show that, in absolute terms, the tax on oil has almost the same contribution (41.8%) to the leakage as the tax on coal (42.4%). Carbon tax on gas contributes 15.8%. As such, the ratio of the leakage contribution for taxes on coal:oil:gas is 1:0.99:0.37. However, the ratio adjusted for the total emissions from a particular fossil fuel (LE ratio) is 1:0.69:0.47, which is close to the relative carbon content of the fossil fuels.

We tested our results with respect to different values of fossil-fuel supply elasticity and Armington elasticity. Changing the fossil-fuel supply elasticity from 0.5 to 20 leads to the decrease in the leakage rate from 15 to 5 percent. A change in Armington elasticity of substitution between domestic and imported goods from 1 to 8, and a corresponding change in the substitution elasticity between imported goods from 4 to 16 results in the increase in the leakage from 7 to 15 percent. Our model shows that the degree of the international capital mobility is not a very influential determinant of the leakage rate. Eliminating restrictions on capital movements increases the leakage rate approximately by 15 percent.

It is also found that the degree of a sectoral disaggregation in the model does not greatly affect the results. However, the differences are bigger in the case of the regional disaggregation. A representation of electricity in the model changes the sectoral decomposition. The leakage rate is not changed much with a disaggregation, and turns out to be about 10% for the values assumed in the model.

The remainder of the paper is organized in the following way. Section 2 describes the GTAP-EG model and data. The decomposition procedure which attributes increase in the carbon emissions in the non-Annex B countries to a sector-specific tax in an abating region is outlined in section 3. Section 4 discusses the results of decomposing the carbon emissions leakage at a region- and sector-specific level. A sensitivity analysis with respect to the different values of fossil-fuel supply elasticity and Armington elasticity is performed. Then different scenarios regarding the level of aggregation and international capital mobility are considered. Section 5 concludes.

2 The GTAP-EG Model

The model employed in this paper is based on the GTAP-EG dataset (Rutherford and Paltsev (2000)). The world is divided into regions. Each region incorporates markets for non-energy goods, C, electricity, E, and non-electric energy, N. Non-electric energy includes: oil, gas and coal. Crude oil may be produced domestically or imported, and it is then refined prior to delivery as an input to production and final demand. Electricity is not traded and is produced using coal, oil, gas or non-fossil inputs. Final energy products are supplied as inputs both to production and to final demand.

Consumption in each region is associated with utility maximization by a representative agent subject to a budget constraint. The agent supplies primary factors (capital, K, labor, L, and energy resources, R) to non-energy and energy sectors. Factor income of each representative agent is then allocated to the purchase of energy (E and N), non-energy goods (C), and investment (I). Regions are connected with the global economy through trade in energy and non-energy goods. Energy trade involves primarily crude oil and coal which can be exported or imported in international markets.

The flows are implemented in the model in the following way. In the model there are three types of produced commodities, fossil-fuel, non-fossil fuel commodities, and electricity. The model assumes that goods produced in different regions are qualitatively distinct (Armington (1969)). This implies that trade in goods is represented as flows between pairs of countries rather than from individual countries and an integrated global market. Every bilateral trade flow requires its own transportation services. Primary factors in each region include labor, capital and fossil-fuel resources. Labor is mobile within domestic borders but cannot move between regions. Capital can be global or region-specific. Natural resources are sector-specific.

In the GTAP-EG model, an economy in region r consists of three production blocks. The block Y_{ir} is related to production, where fossil-fuel production has a different structure from other production sectors. A production block for Armington supply, A_{ir}, represents an aggregation between domestic and import varieties and across imports from different trading partners. Armington supply is used then for private consumption and as an intermediate input to production. A production block yt describes the provision of international transport services. In each region the representative agent (described by a block RA_r) depicts a collective decision process for allocating income to households and to a government.

Regions may apply domestic carbon taxes. Carbon tax revenue is collected by the representative agent in each region. Within this model, the carbon tax policy is equivalent to an emission permit system where the permit price coincides with the carbon tax. There are also taxes on output, ty, intermediate inputs, ti, consumption, tc, export, tx, and import, tm. Figure 1 depicts the structure of the model.

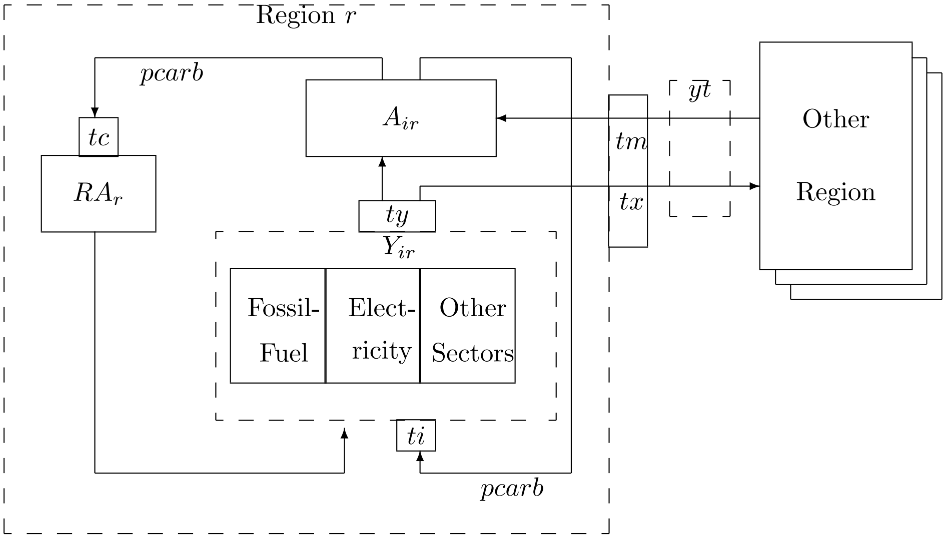


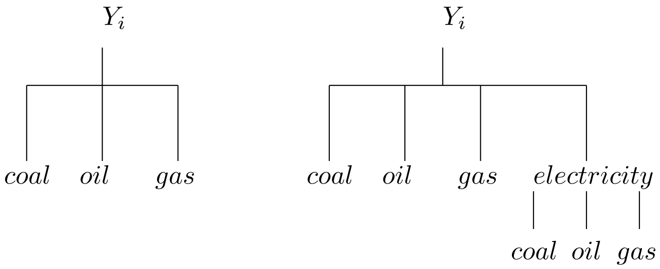
Fig. 1. Structure of the GTAP-EG model.

Fossil fuel production activities include extraction of crude, gas, and coal. Production has the structure shown in Figure A.1 in Appendix 2, where a value to the right of the arc represents an elasticity. Fossil fuel output ($y(xe)$, where xe is one type of exhaustible energy: crude, gas, coal) is produced as an aggregate of a resource input ($pr(xe)$) and a non-resource input composite. The non-resource input for the production is a fixed - coefficient (Leontief) composite of labor (pl) and the Armington aggregation ($pa(i)$) of domestic and imported intermediate input from a production sector i. The elasticity of substitution between pa and pl equals zero ($id:0$), which characterizes a Leontief composite. The elasticity of substitution ($s:esub\_es$) between the resource input and the non-resource input composite depends on the value share of resource inputs in fossil fuel supply.

Non-fossil fuel production (including electricity and refining) has a different structure. Figure A.2 illustrates the nesting and typical elasticities employed in production sectors other than fossil fuels. Output is produced with fixed-coefficient (Leontief) inputs of intermediate non-energy goods and an energy-primary factor composite. The energy-primary factor composite is a constant-elasticity of substitution (CES) function with elasticity = 0.5. Primary factor inputs of labor and capital are aggregated through a Cobb-Douglas production function ($va : 1$). The energy composite is a CES function of electricity versus other energy inputs, coal versus liquid fuels, and oil versus gas.

Armington aggregation activity generates intermediate demand for production and final demand for consumption as a mix of domestic and imported goods as imperfect substitutes. We assume that the domestic-imports elasticity of substitution (d) equals to four, while the elasticity of substitution among import sources (m) equals to eight. Imports from every region require transportation services (pt) which are implemented as shown in Figure A.3 for region S. The international transport services are assumed to be a Cobb-Douglas composite of goods provided in the domestic markets in each region. Final demand has the structure shown in Figure A.4. Utility in each country is a constant elasticity aggregate of non-energy consumption and energy. The non-energy composite is in turn a Cobb-Douglas aggregate of different goods while final energy is a Cobb-Douglas aggregate of electricity, oil, gas, and coal.

The difference between the model used here and the basic GTAP-EG model (Rutherford, Paltsev (2000)) is the special treatment of electricity production. In the core model, production sectors which use electricity as an intermediate input are not affected by carbon taxes levied on electricity. They pay taxes on direct usage of fossil fuels but not on carbon emissions from electricity use, as is shown in Fig. 2.a. In this case, the electricity sector is represented in the same way as any other non-fossil fuel sector. However, in order to more fully account for the carbon which is emitted in the certain industry, carbon which is emitted by electricity when it is used as an intermediate input in that industry should also be accounted for. The result of this change in representation of electricity is the structure of non-fossil fuel production shown in Fig 2.b. In terms of Fig. A.2., the electricity production block is added to the nest ($e : 0.1$), instead of $pa(ele)$.



a) Core Model b) Modified Model

Fig. 2. Electricity in the GTAP-EG model

As has already been noted, the full GTAP-EG dataset has 45 regions and 23 sectors. Regions and sectors for the full GTAP-EG dataset are presented in Appendix 3. In this paper, calculations for different aggregations of the full dataset have been made. For the sake of compactness, most of the results in this paper are reported for the dataset (called a *base* dataset), which is obtained from the full GTAP-EG by aggregating into 13 regions and 23 sectors. Regions and sectors for the base dataset are listed in Appendix 5. We also provide the main results for disaggregated data. They are reported in Appendices 6 and 7.

3 A Decomposition Method

General equilibrium analysis is extremely valuable because it can account for interrelated and balanced transactions between all regions and sectors in the world economy. The resulting change in the endogenous variable of interest (such as welfare, carbon emissions, etc.) depends on many direct and indirect mechanisms. As various partial effects, which may work in opposite directions, contribute to the overall effect, it is sometimes very difficult to explain in depth the aggregate policy outcome. Therefore, procedures which allow the decomposition of simulation results with respect to exogenous shocks are very helpful for understanding the importance of a particular policy instrument on overall change in an endogenous variable.

In this paper, a method described by Harrison *et al* (1999) is used for the decomposition of a change in carbon emissions in the non-Annex B regions due to the restrictions in specific sectors of the Annex B. We denote carbon emissions in a non-Annex B region s as Z^s. The emissions might change because of the change in exogenous policy instruments, such as a carbon tax X in a sector i of the Annex B region b. Based on certain values of the instrument variable, X_{ib}, the GTAP-EG model gives a numerical value for Z^s, so it can be expressed as a function

$$Z^s = F(X_{ib}) \tag{1}$$

A change in the carbon taxes X_{ib} leads to an aggregate change in the outcome for the non-Annex B region's carbon emissions from Z^s to Z^{s*}. The objective of the analysis is to create a consistent decomposition of the aggregate change ΔZ^s = Z^s - Z^{s*} into the changes due to a particular sector-specific carbon tax in a particular Annex B region, such that

$$\Delta Z^s = \sum_{ib} \Delta Z^s_{ib} \tag{2}$$

where ΔZ^s_{ib} is the change in the carbon emissions in a region s due to the change in the carbon tax X_{ib} in a sector i of a region b. When F is non-linear, the total change in Z^s is path-dependent, i.e., the decomposition is sensitive to the ordering of changes in the policy instruments X_{ib}. We assume that the policy instruments are introduced simultaneously. Therefore, the change in the carbon tax X_{ib} can be represented as

$$\Delta X_{ib} = X^1_{ib} - X^0_{ib} \tag{3}$$

where X^1_{ib} is the final value and X^0_{ib} is the starting value of the policy instrument. The path between these two points can be constructed as follows.

$$X_{ib} = X^0_{ib} + t\Delta X_{ib} \tag{4}$$

where t is a scalar which parameterizes the change in X_{ib}. When $t = 0$, X_{ib} is at its starting value. When $t = 1$, the carbon tax is at its final value.

For a given value of t we can write

$$\frac{\partial Z^s}{\partial t} = \sum_{ib} \frac{\partial F}{\partial X_{ib}} \frac{\partial X_{ib}}{\partial t} = \sum_{ib} \frac{\partial F}{\partial X_{ib}} \Delta X_{ib} \tag{5}$$

Then the total change in Z^s is given by the following expression.

$$\Delta Z^s = \int_{t=0}^{t=1} \frac{\partial Z^s}{\partial t} dt = \int_{t=0}^{t=1} \left(\sum_{ib} \frac{\partial F}{\partial X_{ib}} \Delta X_{ib} \right) dt = \sum_{ib} \left[\Delta X_{ib} \int_{t=0}^{t=1} \frac{\partial F}{\partial X_{ib}} dt \right] = \sum_{ib} \Delta Z_{ib}^s \tag{6}$$

Equation (6) gives us the method of calculating the decomposition which is applied in this paper. That is, we start with calculating the partial derivatives $\partial F / \partial X_{ib}$ for a particular t, then integrate the derivatives over the whole range of t, then multiply the result by the change in the policy instrument ΔX_{ib}, and sum over all policy instruments.

The method is applied in the following way. First, the Business-As-Usual (BAU) scenario is considered. There are no limits on carbon emission in this case. It is important to choose an appropriate BAU scenario because all counterfactual experiments are compared against the BAU, and the magnitude of the results depends on the BAU projections for GDP, energy efficiency improvements, etc. In this paper, the estimates for the BAU case are taken from the Bohringer and Rutherford (2000) paper, where forward calibration to the year 2010 of the GTAP-EG dataset is done based on the U.S. Department of Energy (DOE (1998)) data.

To calculate the leakage rate, the carbon emissions are restricted to the quantities assigned by the Kyoto Protocol. The Protocol commits Annex B countries to the reduction of their aggregate CO_2 equivalent emissions on average by 5.2% below 1990 levels in the period from 2008 to 2012. The amounts for all Annex B countries are presented in Appendix 1. The individual commitments by the Annex B regions as they are defined in the paper are shown in Table 1, where the Kyoto targets and each region's share in the total Annex B emissions are reported[3]. Table 1 also presents the amount of 1990, 1995, and 2010 emissions, the regional shares and associated changes necessary to meet the Kyoto obligations. The USA, the European Union, and the former Soviet Union are the largest contributors to carbon emissions among the Annex B regions. Based on the forecasts,

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[3] The same statistics for the full GTAP-EG dataset is presented in Appendix 4

the share of the United States increases from 35 to 39% in 20 years, while the share of the former Soviet Union decreases from 21 to 17%. Considering the cutback necessary to meet the Kyoto target, the USA, Canada, and Japan have to decrease their emissions by one-third. The former socialist block (FSU and CEA) is not affected by the Kyoto Protocol due to structural changes and a decrease in economic growth. They are approximately at the target by the year 2010.

	USA	CAN	EUR	JPN	OOE	FSU	CEA
Kyoto target	4532.3	401.9	3011.0	998.1	309.4	2904.6	934.0
Kyoto share	34.6	3.1	23.0	7.6	2.4	22.2	7.1
1990 emission	4783.4	427.5	3291.4	1061.8	288.3	2909.6	1003.8
1990 share	35.2	3.1	23.7	7.7	2.1	21.0	7.2
1990 change	-7.0	-6.0	-8.5	-6.0	7.3	-0.2	-7.0
1995 emission	5460.5	506.3	3599.4	1256.8	318.0	2548.9	763.0
1995 share	37.8	3.5	24.9	8.7	2.2	17.6	5.3
1995 change	-17.0	-20.6	-16.3	-20.6	-2.7	14.0	22.4
2010 emission	6600.0	590.3	3901.3	1452.0	381.3	2915.0	936.0
2010 share	39.3	3.5	23.3	8.7	2.3	17.4	5.5
2010 change	-31.3	-31.9	-22.8	-31.3	-18.9	-0.4	-0.2

Table 1. Carbon dioxide emissions (Mt CO_2), region's share (%) in the total Annex B emissions, and the reduction (%) by the Kyoto Protocol.

In order to account for the change in carbon emissions, a quantity instrument such as emission permit is introduced to the GTAP-EG model. The quantity of permits in each region is limited to the Kyoto target. These permits can be used for production and final demand. In the BAU case the permit price is equal to zero because there are no restrictions on emissions. In a counterfactual experiment, the permit price is positive. The carbon permits are non-tradable between regions. As such, each region has a different permit price. The price is higher for the regions with a higher required emission abatement. To be able to decompose carbon leakage at a sectoral level, sector-specific carbon taxes are introduced. They are calculated by recreating the quantity instrument (emission permit) equilibrium based on a price instrument (carbon tax). The results of the modeling are presented in the next section.

4 The Results

As it has already been noted, the mitigation efforts by the Annex B countries may affect the amount of carbon emissions in the rest of the world. The resulting carbon leakage is measured as the ratio of the additional emissions in the non-Annex B countries to the change in the carbon emissions in the Annex B countries. The decomposition technique allows us to estimate the contributions to the leakage of each sector of an economy for every Annex B country.

4.1 Regional decomposition

The results of the decomposition at the regional level are presented in Table 2. We have assumed a unit elastic fossil-fuel supply in our baseline case. The Armington elasticity between domestic and imported goods is four, and the elasticity between imports from various countries equals eight. The estimated leakage rate is 10.5%, which is to say if we denote the total decrease in carbon emissions by the Annex B countries (approximately 3600 Mt CO_2) as 100%, then the increase in carbon emissions by the non-Annex B countries in comparison to BAU scenario is about 380 Mt, or 10.5% of that number.

The existing models estimate the magnitude of the total carbon leakage and an associated increase in the carbon emissions by the non-Annex B countries. Our calculations for the baseline case show that most of the increase in the emissions is going to happen in China (CHN, 3.16% in the total 10.5% leakage), the rest of the world region (ROW, 2.58%), the Middle East (MPC, 2.54%), and the rest of Asia (ASI, 1.37%). The results for disaggregated regions are reported in Appendix 7.

The novelty of our model is that it allows us to obtain the magnitudes for the induced leakage. The corresponding numbers in Table 2 show which country's actions cause the increase in the non-Annex B emissions. The European Union and the USA are the largest contributors with 4.34% and 3.08% induced leakage, respectively. Compliance with the Kyoto Protocol by the Central European region (CEA) has no effect on the leakage rate. The model also calculates the contribution to the leakage from every pair of abating-nonabating regions. The region ROW has the highest increase (1.53% toward the total 10.5% leakage, or a 15% share of the total leakage) due to the change in carbon limits in the region EUR. The results obtained for the disaggregated dataset attribute most of that increase to the South Africa. The next two largest contributing pairs are CHN-EUR (1.12%) and MPC-USA (0.96%).

	USA	CAN	EUR	JPN	OOE	FSU	CEA	Total leakage
CHN	0.75	0.38	1.12	0.68	0.22	0.03	0.00	3.16
IND	0.20	0.03	0.19	0.10	0.03	0.01	0.00	0.56
BRA	0.11	0.02	0.09	0.05	0.01	0.00	0.00	0.28
ASI	0.45	0.06	0.53	0.25	0.07	0.01	0.00	1.37
MPC	0.96	0.15	0.88	0.40	0.11	0.04	0.00	2.54
ROW	0.61	0.11	1.53	0.26	0.08	0.01	0.00	2.58
Induced leakage	3.08	0.75	4.34	1.74	0.51	0.10	0.00	10.5

Table 2. Regional decomposition

The numbers for a region's emissions and abatement as a share of the total Annex B emissions and abatement are helpful to depict the following results caused by the structure of global trade. For example, the USA has the largest carbon emissions and the largest abatement by the Kyoto Agreement, but their contribution to leakage is lower than that of the European Union. In order to assess relative contributions, we introduced two ratios. The leakage-emissions ratio (LE) relates emissions increase in the non-Annex B regions due to a carbon tax in a particular region or sector to total carbon emissions in that region or sector. Accordingly, the leakage-abatement ratio (LA) shows how leakage induced by a particular sector or region is related to abatement in that sector or region.

Table 3 shows the share of leakage, emissions, and abatement of a particular region as a percentage of the total Annex B numbers. The carbon restrictions introduced by the European Union and the USA lead to 41% and 29% of the total leakage, respectively. Table 3 also reports the ratios introduced above. The region OOE (Australia and New Zealand) has the highest LE ratio, i.e., in the case of introduction of the Kyoto Agreement, OOE induces the increase of 4.3 ton of carbon emissions in the non-Annex B per each 100 tons of its own emitted carbon. This region also has the highest LA ratio, which tells us that for each 100 tons of carbon decrease, OOE induces 22.7

tons of carbon emissions in the non-Annex B countries. The adjusted leakage ratios show that despite the largest carbon emissions, the USA is a modest contributor to the global leakage in relative terms.

	USA	CAN	EUR	JPN	OOE	FSU	CEA
% leakage	29.4	7.1	41.4	16.6	4.9	0.9	0.0
% emissions	39.3	3.5	23.3	8.7	2.3	17.4	5.5
% abatement	54.2	5.1	26.0	12.4	1.9	0.3	0.0
LE ratio	1.7	4.1	3.7	4.2	4.3	0.1	-0.5
LA ratio	5.5	12.9	16.3	13.3	22.7	2.8	–

Table 3. Regional shares and adjusted leakage ratios

The precision of the decomposition method depends on the numerical methods of calculating the line integral and derivatives. The values of the differences between the results obtained from the decomposition method and from the direct calculations are reported in Appendix 8.

4.2 Sectoral decomposition

The same decomposition procedure allows us to estimate the sectoral contribution to the leakage. The results are represented in Table 4. It reports the data on which sector in which Annex B country causes an increase in the non-Annex B carbon emissions. The Central European region (CEA) and the food products industry (FPR) do not contribute to the leakage; therefore, they are not represented in the table. In absolute terms, the carbon tax on the chemical industry (CRP) is the major source for the emission migration. It contributes 2.08% in the total 10.5% leakage (or a 20% share). The carbon taxes on iron and steel industry (I_S), and final demand (FNL) are the next largest contributors. They induce the leakage at the rates of 1.70% and 1.56%, respectively.

It is also possible to rank the contributions to the leakage from carbon taxes by considering the sector and region where they are levied. The carbon tax on final demand in the USA is the leader here with 0.85% in 10.5% leakage. The taxes on the chemical industry in the European Union (0.80%) and the USA (0.75%) follow the lead. Different industries play different roles in the different regions. For example, in the USA contributions are the largest from the taxes on final demand, the chemical industry, and trade and transport, while for Japan the major contributors are the iron and steel industry, chemical industry, and dwellings. This particular result can be useful for an exploration of the question of tax exemptions for certain industries in different regions.

	USA	CAN	EUR	JPN	OOE	FSU	total contribution
CRP	0.75	0.14	0.80	0.31	0.04	0.03	2.08
I_S	0.27	0.08	0.64	0.54	0.07	0.08	1.70
FNL	0.85	0.07	0.47	0.17	0.01	-0.01	1.56
DWE	0.10	0.05	0.64	0.19	0.06	-0.02	1.01
SER	0.14	0.06	0.42	0.11	0.05	0.00	0.77
T_T	0.37	0.05	0.16	0.06	0.02	0.00	0.65
NFM	0.12	0.06	0.14	0.05	0.13	0.03	0.54
NMM	0.10	0.02	0.25	0.11	0.02	0.00	0.50
OMN	0.19	0.08	0.12	0.03	0.03	0.01	0.46
ELE	0.04	0.06	0.24	0.05	0.05	-0.01	0.43
PPP	0.05	0.04	0.11	0.03	0.01	0.00	0.23
OME	0.04	0.01	0.09	0.02	0.01	0.00	0.17
OMF	0.06	0.00	0.07	0.02	0.00	0.00	0.15
TRN	0.02	0.01	0.06	0.02	0.00	0.00	0.10
LUM	0.02	0.01	0.03	0.03	0.01	0.00	0.10
CNS	0.01	0.00	0.03	0.02	0.00	0.00	0.06
TWL	0.01	0.00	0.03	0.00	0.00	0.00	0.04
AGR	-0.05	0.00	0.04	0.01	0.00	-0.01	-0.0

Table 4. Sectoral decomposition

We can enhance our analysis by decomposing the leakage even further to the level where we can attribute an increase in carbon emissions in a particular non-Annex B region to a carbon tax in a certain sector of a particular Annex B region. The results are presented in Appendix 6. The biggest contributor to the leakage is the carbon tax on the iron and steel industry in Japan as it affects China (it accounts for 0.31% in the total 10.5% leakage). The next largest contributions are from the tax on the chemical industry in the USA as it affects China (0.28%), and from the tax on the chemical industry in the European Union as it affects China (0.27%). A less expected finding is that the tax on dwellings in the European Union accounts for a sizable increase in pollution (0.27%) in the rest of the world. This result is driven by the trade patterns and the large size of the sector.

Another way of looking at the results presented in Appendix 6 can be described as follows. The single largest effect of a carbon tax on any given Annex B industry on any given non-Annex B country is that of the tax on the chemical industry as it affects China (0.78% in the total 10.5%

increase). China also is going to be affected by the Annex B tax in the iron and steel industry (0.73%). Another large increase in carbon emissions occurs in the Middle East region due to the taxes on final demand (0.65%) and on the chemical industry (0.52%).

Carbon taxation of final demand increases the emissions in the Middle East because most of the pollution comes from fuel consumption and not from fuel production. A drastic change in final demand by the Annex B regions (and most of the change comes from the United States, who is the major importer of the Middle East oil) results in a drop in oil imports from the Middle East. Access to cheap oil in that region and a change in the cost of energy-intensive products create a situation where the Middle East countries find it profitable to produce energy-intensive goods in their region.

Table 5 reports the sectoral shares in leakage, total emissions and total abatement. Final demand, dwellings, transport and trade, services, and chemical industry have large shares in the total carbon emissions. Final demand, dwellings, and services are among the major contributors because of the size of these sectors and their extensive usage of electricity. As mentioned earlier, in addition to estimating leakage in absolute terms, it is informative to compare relative values. In the carbon tax design, sectors with high relative contribution should be taxed more heavily. Therefore, besides the above mentioned shares, Table 5 also reports the LE and LA ratios.

The importance of relative leakage can be illustrated by the examples of dwellings and services on one side, and the non-ferrous metal industry (NFM) and mining (OMN) on the other side. In absolute terms, services and dwellings are the major contributors to leakage, while the NFM and OMN sectors contribute rather moderately. However, if we adjust the leakage for sectoral carbon emissions, the picture is reversed. NFM and OMN have high ratios of induced leakage to their emissions, and dwellings and services have moderate relative leakage. It should be noted that some industries are among the leaders both in absolute and relative terms, such as the iron and steel industry and the chemical industry.

	% of tot. leakage	% of tot. emissions	% of tot. abatement	LE ratio	LA ratio
CRP	19.9	10.5	20.9	4.3	20.5
I_S	16.2	6.2	20.7	5.8	28.2
FNL	14.9	19.1	16.6	1.7	10.5
DWE	9.7	12.4	24.9	1.7	6.9
SER	7.4	11.4	28.2	1.4	5.0
T_T	6.2	12.0	12.7	1.1	9.0
NFM	5.1	2.4	17.8	4.7	26.3
NMM	4.7	2.5	24.9	4.0	16.2
OMN	4.4	1.4	25.2	7.0	28.0
ELE	4.1	7.1	34.3	1.2	3.6
PPP	2.2	2.4	29.2	1.9	6.4
OME	1.6	2.3	25.7	1.3	5.2
OMF	1.5	1.4	28.7	2.0	7.0
TRN	1.0	1.3	27.9	1.3	4.7
LUM	0.9	1.1	26.8	1.5	5.7
CNS	0.5	1.3	17.7	0.5	2.9
TWL	0.0	1.3	26.8	0.3	1.2
AGR	0.0	3.7	14.6	-0.2	-1.2

Table 5. Sectoral shares and adjusted leakage ratios

A sector's high contribution to leakage could justify an exemption from the carbon tax to increase efficiency of global carbon reduction. However, exemptions in some sectors imply increased tax rates for others and higher costs for an economy as a whole. Based on the analysis of German environmental regulations, Bohringer and Rutherford (1997) concluded that exemptions can significantly increase the welfare cost of taxes. The cost of exemptions increases with the target level of emission reductions and with the share of the exempted sectors in economic activity and total emissions. Our calculations confirm their findings and show that exemptions of any sector from a carbon tax decrease welfare. Table 6 illustrates the trade-off between the sectoral exemptions and the magnitudes of the change in welfare. Tax exemptions in the chemical, iron and steel, and non-ferrous metals sectors decrease the total carbon leakage but have a negative effect on regional welfare. The exemptions in the dwellings, services, transport and trade sectors increase the leakage but also have a negative effect on welfare. As one can see, a tax exemption for a certain industry may increase or decrease total leakage. The sign depends on the mechanism through which this sector affects carbon emissions: energy markets or non-energy markets. The chemical and iron and steel industries are likely to move to non-abating regions due to the change in cost of production.

Transport, services and dwellings are likely to affect the leakage through the change in demand for and, hence, change in international price for fossil fuels.

	CRP	I_S	DWE	SER	T_T	NFM	NMM	OMN
% contribution to leakage	19.9	16.2	9.7	7.4	6.2	5.1	4.7	4.4
% Δ in leakage if exempted	-5.8	-3.1	+5.0	+4.4	+3.5	-0.6	0.0	-0.9
% Δ in welfare in								
USA	-0.2	-0.0	-0.1	-0.1	-0.1	-0.0	-0.0	-0.0
CAN	-0.6	-0.1	-0.3	-0.4	-0.6	-0.1	-0.1	-0.2
EUR	-0.1	-0.1	-0.2	-0.1	0.1	-0.0	-0.0	0.0
JPN	-0.1	-0.4	-0.1	-0.1	0.1	-0.0	-0.1	0.0
OOE	0.0	0.0	-0.0	-0.0	0.1	-0.0	0.0	-0.0
FSU	-0.0	-0.2	0.0	0.0	0.1	-0.1	-0.0	-0.0
CEA	0.1	-0.0	0.1	0.0	-0.0	-0.0	0.0	0.0

Table 6. Change in welfare due to the sectoral exemptions

It should be noted that the GTAP-EG model (as most of the Kyoto-related models) does not account for the possible scenario where the OPEC countries decrease their oil extraction and change the world price in anticipation of the effects of the Kyoto Protocol. A dynamic model of the OPEC market power by Berg *et al* (1997) shows that OPEC will reduce its production in order to maintain a high price level when the carbon tax is introduced. A promising direction for future research is the development of a model which would fully account for the OPEC pricing power.

4.3 Fossil-fuel Contributions

Our model also distinguishes regional and sectoral leakage contributions by the type of fossil fuel tax. Tables 7 and 8 present the results for specific fossil fuels. A tax on oil in the USA is the major contributor (a 23.4% share) to induced leakage, followed by a tax on coal in Europe (19.5%), and a tax on gas in Europe (13.7%). In terms of increased non-Annex B emissions, the tax on coal will have the greatest effect in China (a 21% share) and the tax on oil will have the greatest effect on the Middle East region (14.3%).

Annex B	coal	oil	gas	non-Annex B	coal	oil	gas
USA	9.6	23.4	-2.8	CHN	21.3	8.6	-0.6
CAN	3.7	2.8	0.1	IND	2.2	3.8	-0.6
EUR	19.5	9.9	13.7	BRA	0.9	2.3	-0.4
JPN	6.7	6.9	3.2	ASI	3.4	8.5	1.5
OOE	3.6	0.0	0.8	MPC	2.6	14.3	8.4
FSU	-0.2	-0.9	1.2	ROW	12.1	4.2	7.5
total	42.4	41.8	15.8	total	42.4	41.8	15.8

Table 7. Regional leakage contribution of different fossil fuel taxes (%)

At a sectoral level, the impact of the taxes on different fossil fuels also varies. As one can see from Table 8, the chemical industry, final demand, and transport are sensitive to the tax on oil, while the iron and steel industry and dwellings are most affected by the tax on coal. It is possible to use the decomposition procedure to estimate the impact of a certain fossil-fuel tax in a particular sector of a particular Annex B country. In the interest of concision, we do not report these results here. They are available from the author upon request.

Sector	coal	oil	gas	Sector	coal	oil	gas
CRP	3.6	14.2	3.0	NFM	3.1	1.0	1.1
I_S	12.6	2.4	2.0	NMM	2.6	1.1	1.1
FNL	0.4	11.3	3.8	OMN	1.8	1.7	0.9
DWE	5.1	1.9	2.9	ELE	3.7	0.3	0.1
SER	4.8	1.5	1.2	PPP	1.4	0.5	0.2
T_T	0.4	5.9	0.1	total	42.4	41.8	15.8

Table 8. Sectoral leakage contribution of different fossil fuel taxes (%)

As we have stressed several times, besides the magnitude of the total contributions to the leakage in absolute terms, it is important to estimate the leakage induced by a tax on a certain fossil-fuel in relationship to the total carbon emissions from that fossil fuel. In absolute terms, the tax on oil has almost the same contribution (41.8%) to leakage as the tax on coal (42.4%), and the carbon tax on gas contributes 15.8%. Hence, the ratio of the leakage contribution for taxes on coal:oil:gas is 1:0.99:0.37. The ratio adjusted for the total emissions from a particular fossil fuel (LE ratio) is 1:0.69:0.47. This ratio is close to the carbon content of fossil fuels. This result confirms the usual suggestion that the carbon tax should be levied on fossil fuels according to their carbon content.

4.4 Elasticity

There are several factors that substantially affect leakage. The elasticity of supply plays a crucial role (Manne, Richels (2000)). Burniaux and Martins (2000) found that coal supply elasticity is the key parameter for the leakage rate. However, there is no consensus on the exact values for the supply elasticities for fossil fuels, especially for coal. For example, Light *et al* (1999) argues that coal supply elasticity is low, and based on that assumption they found leakage of about 20 percent. Their work is in contrast to the results from Burniaux and Martins (2000), whose claim about the high coal elasticity in the GREEN model leads to the much lower magnitude for the leakage of 5 percent.

We test the results of our model with respect to different values of fossil-fuel supply elasticity. As previously reported, the leakage rate estimation for our baseline case is obtained with a unit elastic supply of coal, gas, and crude oil. Table 9 shows the results for different values of supply elasticity. The first three rows represent the cases where we change the elasticity for a particular fossil-fuel and keep other values at unity. The last row reports the numbers for the cases where we change the supply elasticities for all fossil fuels. Based on these different values, the leakage rate ranges from 5 to 15 %. The higher the elasticity, the lower the magnitude of leakage. The coal supply elasticity is indeed the major determinant for leakage. However, oil and gas supply matters as well.

	0.5	5	10	20
coal	12.3	8.3	7.9	7.7
oil	11.9	9.1	8.9	8.7
gas	11.7	9.3	9.1	9.0
all	14.7	5.8	5.1	4.7

Table 9. Leakage Rate for different fossil-fuel supply elasticity

The magnitudes for regional and sectoral contributions to carbon leakage vary with the values for supply elasticity. As an example, Tables 10 and 11 report the contributions based on coal supply elasticity ranging from 0.5 to 20. The shares of induced leakage of Japan, Canada and OOE (Australia and New Zealand) are most affected by the assumed values. As expected, the share of the coal-intensive OOE region falls with higher elasticity. Also, the leakage shares of coal-intensive China and the oil-intensive Middle East move in opposite directions with a change in coal supply elasticity.

Annex B	0.5	1	20	non-Annex B	0.5	1	20
USA	29.5	29.4	30.9	CHN	33.9	30.1	24.1
CAN	7.4	7.1	6.3	IND	5.4	5.3	5.9
EUR	40.9	41.4	37.8	BRA	2.4	2.6	3.1
JPN	15.4	16.6	20.5	ASI	12.1	13.1	14.7
OOE	5.7	4.9	3.3	MPC	21.3	24.2	30.4
FSU	1.2	0.9	1.2	ROW	25.0	24.6	21.7

Table 10. Change in regional contributions to the carbon leakage with different coal supply elasticity

At the sectoral level, the shares of electricity (ELE), other machinery (OME), services (SER), dwellings (DWE), textile (TWL), and agriculture (AGR) decrease with an increase in the coal supply elasticity. However, the shares of iron and steel (I_S), chemical (CRP), non-ferrous metals (NFM), non-metallic minerals (NMM), final demand (FNL) move in the opposite direction. The reasons for such a difference might be the share of coal in production and a degree of substitutability between coal, gas, and oil.

Sector	0.5	1	20	Sector	0.5	1	20
ELE	6.3	4.5	-0.9	LUM	1.2	0.7	0.7
I_S	14.8	16.1	19.1	CNS	0.5	0.4	0.4
CRP	17.7	20.0	25.3	TWL	0.7	0.4	-0.3
NFM	4.9	5.0	5.4	OMF	1.6	1.5	1.1
NMM	4.3	4.4	5.3	AGR	0.5	-0.1	-1.1
TRN	1.1	1.0	0.4	T_T	5.8	6.4	7.2
OME	1.7	1.4	0.9	SER	8.9	7.4	3.6
OMN	3.8	4.2	5.4	DWE	10.7	9.8	6.8
PPP	2.4	1.8	1.2	FNL	13.0	15.1	19.5

Table 11. Change in sectoral contributions to the carbon leakage with different coal supply elasticity

While fossil-fuel supply elasticities represent the leakage mechanisms that operate through energy markets, the trade substitution (Armington (1969)) elasticity is an important factor for non-energy markets. An increase in production costs of energy-intensive industries in the Annex B regions leads to the loss of their market share in a global market. Higher values of Armington elasticity mean an easier switch to a product from another region. As a result, the abating industry would lose a greater proportion of its market share. Burniaux and Martins (2000) found that the leakage rate is not very sensitive to the Armington elasticities. Their result contrasted with the finding by Bernard and Vielle (2000) who reported that the leakage rate increases substantially with trade substitutability. As has already been mentioned in Section 2, the Armington trade elasticity has two nests. One nest describes how easily one can substitute domestic goods and services with imports (we denote this nest as d). Another nest shows the substitutability among imports from various countries (m). Table 12 represents the results of the leakage rate estimation for the values of $d = 1$, 4, 8, and the values of $m = 4$, 8, 16. Our simulations confirm the result that Armington elasticity is an important factor in determining the leakage rate. Higher Armington elasticities lead to the higher leakage.

	4	8	16
1	6.9	8.2	10.3
4	9.4	10.5	13.0
8	11.8	13.0	15.4

Table 12. Leakage Rate for different Armington elasticity

4.5 Aggregation

Most of the existing models employed in the Kyoto-related research are based on very aggregated datasets. Usually, the models consider about 8-20 regions of the world and up to 10 sectors, five or six of which are energy sectors, such as coal, gas, oil, crude, heat, and electricity, leaving the analysis with only a few industrial sectors. Building global detailed datasets is a very challenging task. It is hard to obtain disaggregated data of a good quality. Sometimes even when data are available, calculations for the datasets with high dimensionality might be very complicated or time consuming. Therefore, it is important to explore how the level of aggregation affects the results. For this purpose, we run the GTAP-EG model for different dataset sizes.

Tables 13 summarizes the results of the decomposition procedure described above for the different levels of aggregation. The table shows the Annex B region's contribution to the induced leakage and the non-Annex B region's contribution to the increase in pollution. It also presents the data on the shares of the sectoral carbon taxes and the magnitude of the leakage rate. Cases A, B, and C have the same number of regions but different sectoral aggregation. The sectors in case C are aggregated into two non-energy sectors (Y and EIS) in the same fashion as in Bohringer and Rutherford (2000) and Rutherford and Paltsev (2000)[4]. In case B, some of the Y and EIS sectors are disaggregated.

The results are reported in the following way. For datasets with more than 13 regions and 8 sectors, the individual sectoral and regional contributions are integrated into the corresponding aggregated sectors and regions. Therefore, it is possible to compare the results for disaggregated datasets with the models where sectors Y and EIS are treated as homogeneous. A comparison between cases A, B, and C shows that sectoral aggregation does not result in substantial differences in the contribution to leakage.

Case D depicts the fully disaggregated regions as they are defined in the GTAP-EG dataset. It is found that regional disaggregation lowers leakage while sectoral disaggregation works in the opposite direction. While running the disaggregated model does not greatly change the sectoral contributions, the regional disaggregation has a substantial effect on the magnitude of the results. Regional disaggregation lowers the leakage induced by the European Union (from 43% to 36%) and increases the induced leakage for the USA (from 28% to 34%). It also affects the magnitude of the results for China and the Middle East. However, the major conclusions from the modeling are still the same.

The detailed information on the regional decomposition for the full 45 GTAP-EG regions is presented in Appendix 7. It has the same pattern as the results for the base dataset, which confirms the outcome that, in absolute terms, the main regions which induce the leakage are the European Union, the USA, and Japan. The regions which are going to increase the emissions the most are China, the Middle East, South Africa, and Korea. Considering abating and non-abating countries reveals the following pairs as the biggest contributors towards carbon leakage: USA - Middle East, Europe - South Africa, Japan - China, USA - China, USA - Mexico, Europe - China, USA - Korea.

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[4] The energy-intensive sector (EIS) consists of the following industries: I_S, CRP, NFM, NMM, TRN, and PPP. The Y sector combines T_T, AGR, OME, OMN, FPR, LUM, CNS, TWL, OMF, SER, and DWE.

Dataset	A (base) 13x23	B 13x15	C 13x8	D 45x8	E 13x8gl
Regions					
Annex B					
USA	29	29	28	34	28
CAN	7	7	8	7	8
EUR	41	41	43	36	40
JPN	17	17	15	18	18
OOE	5	5	5	4	5
FSU	1	1	1	1	1
CEA	0	0	0	0	0
Non-Annex B					
CHN	30	30	31	24	32
IND	5	5	5	5	4
BRA	3	3	2	3	2
ASI	13	13	13	13	13
MPC	24	24	24	30	25
ROW	25	25	25	25	24
Sectors					
Y	32	35	34	30	37
EIS	49	47	46	50	46
ELE	4	4	5	1	4
FNL	15	14	15	19	13
Leakage Rate	10.5	10.4	9.6	7.4	10.8

Table 13. Decomposition and leakage for different scenarios

4.6 International Capital Mobility

There is another potential mechanism for leakage which is related to capital movements and operates through non-energy markets. Besides losing the market shares due to carbon restrictions, energy-intensive industries in the Annex B regions might find that foreign direct investment is reallocating into the non-abating regions. A change in a pattern of foreign direct investment affects the magnitude of the leakage because new carbon-intensive production facilities will be moved in the non-Annex B countries. A degree of capital mobility is a key parameter to measure this effect. Our calculations for the baseline case show that the leakage rate changes from 10.5% to 12.5% with no restrictions on capital movements. The same calculation for the dataset which has 8 sectors (case E) gives a corresponding change from 9.6% to 10.8%. The values reported in Table 13 show that allowing capital to be global does not greatly change the sectoral and regional contributions to the leakage. This result is in concordance with the conclusion of Burniaux and Martins (2000) that the degree of international capital mobility does not significantly affect the leakage.

5 Conclusion

Estimation of the magnitude of carbon leakage is important for policy makers because high values for leakage create a serious doubt as to the effectiveness of the Kyoto Agreement. On the other hand, low leakage would help to attain the goal of climate stabilization. Our analysis confirms moderate values for leakage. Depending on the assumptions about fossil-fuel supply elasticities and trade substitution possibilities, the estimates for the leakage rate range from 5 to 15 percent.

The importance of this paper is that it provides the values for the regional and sectoral contributions toward the increase in carbon emissions by the non-Annex B countries resulting from the Kyoto Agreement. This information is valuable for the debate on the tax exemptions for certain industries in the Annex B countries as it reveals the most- and least- leakage contributing sectors of the economy. As expected, the carbon tax in the chemical industry makes the largest contribution (20%) to leakage in absolute terms. Introducing carbon restrictions in the iron and steel industry and in final demand also leads to a sizable increase in non-Annex B emissions. The regions where the emissions will rise the most due to the implementation of the Kyoto Agreement are China (24-32% of the total increase), and the Middle East (24-30%). The leakage is mostly induced by the actions of the European Union (36-51% of the contribution to carbon leakage based on different scenarios), the USA (28-34%), and Japan (13-18%).

It is also important to assess the relative regional and sectoral contributions. The leakage-emissions ratio (LE) and the leakage-abatement ratio (LA) provide information about relative leakage. High sectoral contribution to leakage could lead to an exemption in order to increase efficiency of global CO_2 reduction. However, the results of the modeling show that sectoral exemptions from a carbon tax are welfare-worsening.

This paper offers a good starting point for further exploration of the issues of optimal carbon taxation. The optimal taxation problem is a very challenging task. A promising direction for our future research is to solve the problem with a new numerical technique called Mathematical Programs with Equilibrium Constraints (MPEC). This technique is still under development. Based on the application of MPEC to the optimal taxation problem, Light (1999) discusses some merits and potential pitfalls of the use of the technique in economic research.

The degree of data disaggregation used in the modeling is an important factor for studying particular sector-specific effects. However, the disaggregation does not substantially change the leakage rate and regional effects. In this study, we assume that the Kyoto Agreement is going to be implemented by all parties at the same time. Due to the path-dependency of the decomposition method, the sequence in which the policy instruments are implemented affects the results. Our study confirms the previous findings that the degree of international capital mobility does not significantly change the leakage rate. Fossil-fuel supply elasticity and Armington elasticity are much more influential factors in projecting the total world emissions of CO_2.

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Appendix 1. Emission Limits under the Kyoto Protocol

Appendix 1 contains the list of Annex B countries, the data about their baseyear emissions (Mt CO2), and the assigned amount (%) by the Kyoto agreement.

Country	1990 emissions	%change under Kyoto
Australia	262.99	108
Austria	59.36	87
Belgium	109.11	92.5
Bulgaria	73.48	92
Canada	427.53	94
Croatia	16.61	95
CzechRepublic	141.83	92
Denmark	52.39	79
Estonia	25.50	92
Finland	54.36	100
France	378.31	100
Germany	981.42	79
Greece	72.28	125
Hungary	77	94
Iceland	2.22	110
Ireland	33.24	113
Italy	408.15	93.5
Japan	1061.77	94
Latvia	15.63	92
Liechtenstein	0	92
Lithuania	21.44	92
Luxembourg	10.86	72
Monaco	0	92
Netherlands	161.27	94
NewZealand	25.35	100
Norway	29.76	101
Poland	449.06	94
Portugal	41.47	127
Romania	195.48	92
Russia	2181	100
Slovakia	54.17	92
Slovenia	12.74	92
Spain	215.02	115
Sweden	52.65	104
Switzerland	44.24	92
Ukraine	666	100
UnitedKingdom	585.29	87.5
UnitedStates	4873.42	93

Appendix 2. Structure of the GTAP-EG model blocks

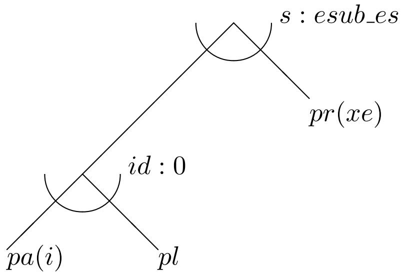

Fig. A.1. Fossil fuel production

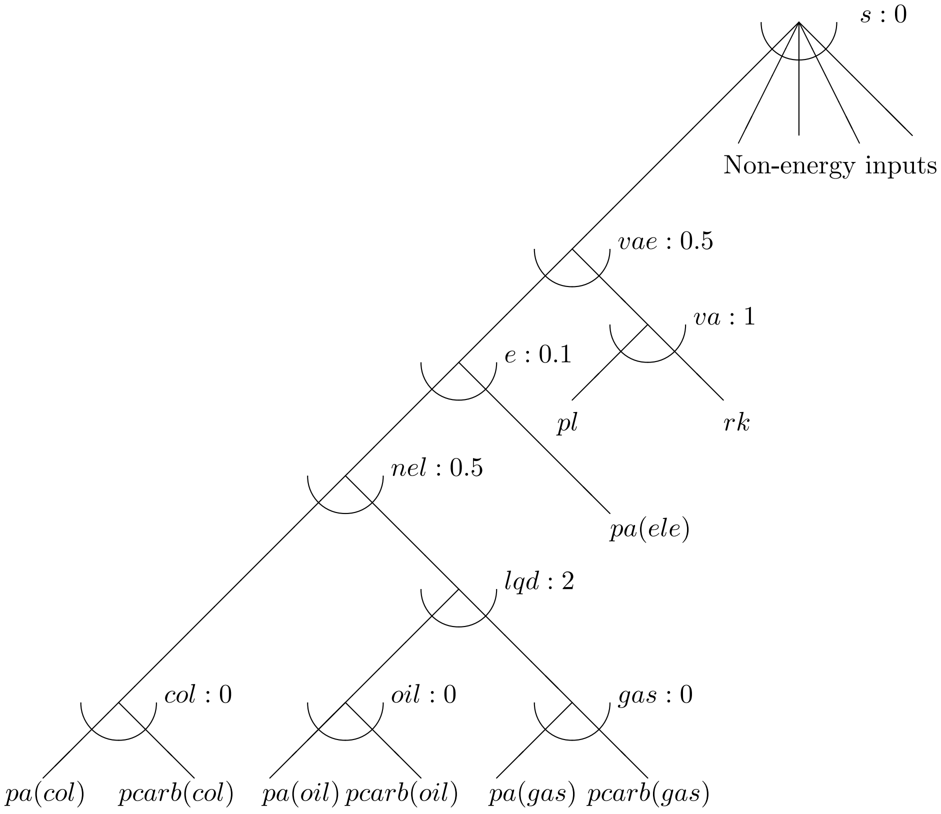

Fig. A.2. Non-fossil fuel production

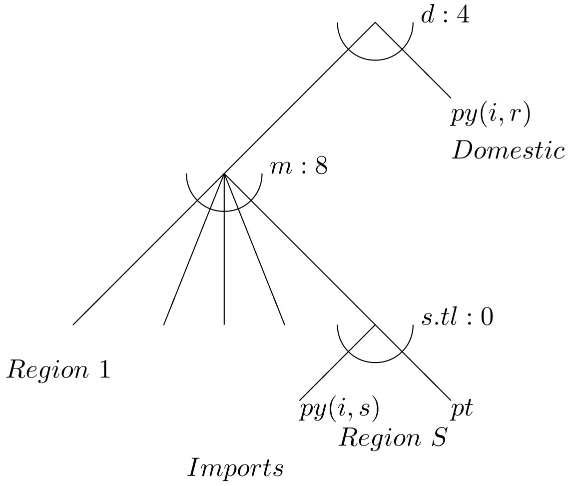

Fig. A.3. Armington aggregation

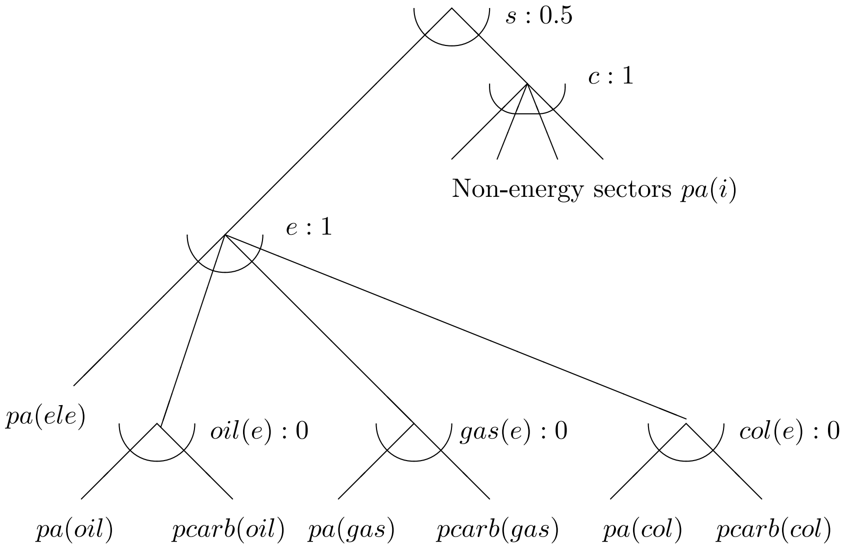

Fig. A.4. Final demand

Appendix 3. Regional and Sectoral Identifiers in the Full GTAP-EG Dataset

Regions:

The Annex B regions are denoted by (*). CEA includes Bulgaria, Czech Republic, Hungary, Poland, Romania, Slovakia, and Slovenia. REU includes Austria, Belgium, Spain, France, Giblartar, Greece, Ireland, Italy, Luxembourg, Netherlands, and Portugal. EFT includes Switzerland, Iceland, and Norway. FSU includes Armenia, Azerbaijan, Belarus, Estonia, Georgia, Kazakhstan, Kyrgyzstan, Lithuania, Latvia, Moldova, Russia, Tajikistan, Turkmenistan, Ukraine, and Uzbekistan.

AUS	Australia (*),
NZL	New Zealand (*),
JPN	Japan (*),
KOR	Republic of Korea,
IDN	Indonesia,
MYS	Malaysia,
PHL	Philippines,
SGP	Singapore,
THA	Thailand,
VNM	Vietnam,
CHN	China,
HKG	Hong Kong,
TWN	Taiwan,
IND	India,
LKA	Sri Lanka,
RAS	Rest of South Asia,
CAN	Canada (*),
USA	United States of America (*),
MEX	Mexico,
CAM	Central America and Caribbean,
VEN	Venezuela,
COL	Columbia,
RAP	Rest of Andean Pact,
ARG	Argentina,
BRA	Brazil,
CHL	Chile,
URY	Uruguay,
RSM	Rest of South America,
GBR	United Kingdom (*),
DEU	Germany (*),
DNK	Denmark (*),
SWE	Sweden (*),
FIN	Finland (*),
REU	Rest of EU (*),
EFT	European Free Trade Area(*),
CEA	Central European Associates (*),
FSU	Former Soviet Union (*),
TUR	Turkey,
RME	Rest of Middle East,
MAR	Morocco,
RNF	Rest of North Africa,
SAF	South Africa,
RSA	Rest of South Africa,
RSS	Rest of Sub-Saharan Africa,
ROW	Rest of World

Sectors:

GAS	Natural gas works
ELE	Electricity and heat
OIL	Refined oil products
COL	Coal
CRU	Crude oil
I_S	Iron and steel industry
CRP	Chemical industry
NFM	Non-ferrous metals
NMM	Non-metallic minerals
TRN	Transport equipment
OME	Other machinery
OMN	Mining
FPR	Food products
PPP	Paper-pulp-print
LUM	Wood and wood-products
CNS	Construction
TWL	Textiles-wearing apparel-leather
OMF	Other manufacturing
AGR	Agricultural products
T_T	Trade and transport
SER	Commercial and public services
DWE	Dwellings,
CGD	Investment composite

Appendix 4. Carbon dioxide emissions (Mt CO2) and their reduction by the Kyoto Protocol for the GTAP-EG regions

	Kyoto target	emissions 1990	change from 1990	emissions 1995	change from 1995	emissions 2010	change from 2010
AUS	284.0	263.0	108.0	285.8	78.9	337.3	84.2
NZL	25.4	25.4	100.0	32.1	79.4	44.0	57.6
JPN	998.1	1061.8	94.0	1256.8	79.4	1452.0	68.7
USA	4532.3	4873.4	93.0	5460.5	99.4	6600.0	68.7
CAN	401.9	427.5	94.0	506.3	122.4	590.3	68.1
GBR	512.1	585.3	87.5	607.3	83.0	671.0	76.3
DEU	775.3	981.4	79.0	973.0	84.3	1004.7	77.2
DNK	41.4	52.4	79.0	68.1	79.7	73.3	56.4
SWE	54.8	52.7	104.0	64.3	60.8	66.0	83.0
FIN	54.4	54.4	100.0	59.4	85.2	62.3	87.2
REU	1499.8	1489.1	100.7	1734.5	91.5	1928.7	77.8
EFT	73.2	76.2	96.0	92.7	86.5	95.3	76.8
CEA	934.0	1003.8	93.0	763.0	78.9	936.0	99.8
FSU	2904.6	2909.6	99.8	2548.9	114.0	2915.0	99.6

Appendix 5. Regions and sectors in the base dataset

The sectors in the base dataset are the same as in the full GTAP-EG presented in Appendix 3. The regions are aggregated in the following way.

	Symbol	Aggregated from
Annex B		
United States	USA	USA
Canada	CAN	CAN
Europe	EUR	GBR,DEU,DNK,SWE,FIN,REU,EFT
Japan	JPN	JPN
Other OECD	OOE	AUS,NZL
Former Soviet Union	FSU	FSU
Central European Associates	CEA	CEA
Non-Annex B		
China	CHN	CHN,HKG,TWN
India	IND	IND
Brazil	BRA	BRA
Other Asia	ASI	KOR,MYS,PHL,SGP,THA,VNM,LKA,RAS
Mexico + OPEC	MPC	IDN,MEX,RME,RNF
Rest of world	ROW	CAM,VEN,COL,RAP,ARG,CHL,URY,RSM, TUR,MAR,SAF,RSA,RSS,ROW

Appendix 6. Sectoral decomposition for the base dataset

Appendix 6 shows the results of sectoral decomposition for the base dataset.

	USA	CAN	EUR	JPN	OOE	FSU	rowsum
ELE.CHN	0.06	0.05	0.10	0.02	0.03	--	0.26
ELE.IND	--	--	0.01	--	--	--	0.01
ELE.BRA	--	--	--	--	--	--	--
ELE.ASI	-0.01	--	0.02	0.01	0.01	--	0.02
ELE.MPC	-0.04	--	0.01	0.02	0.01	--	-0.02
ELE.ROW	0.04	0.01	0.11	0.01	0.01	--	0.17
I_S.CHN	0.08	0.05	0.20	0.31	0.04	0.05	0.73
I_S.IND	0.02	--	0.05	0.03	0.01	--	0.12
I_S.BRA	0.03	0.01	0.04	0.02	--	--	0.10
I_S.ASI	0.03	--	0.04	0.07	0.01	0.01	0.16
I_S.MPC	0.05	0.01	0.09	0.05	0.01	--	0.22
I_S.ROW	0.06	0.01	0.21	0.06	0.01	0.01	0.37
CRP.CHN	0.28	0.06	0.27	0.15	0.02	--	0.78
CRP.IND	0.04	0.01	0.04	0.01	--	--	0.11
CRP.BRA	0.02	--	0.01	0.01	--	--	0.03
CRP.ASI	0.13	0.02	0.12	0.06	0.01	0.01	0.35
CRP.MPC	0.21	0.03	0.19	0.06	0.01	0.02	0.52
CRP.ROW	0.08	0.01	0.17	0.02	--	--	0.29
NFM.CHN	0.03	0.03	0.04	0.02	0.06	0.01	0.19
NFM.IND	--	--	0.01	--	0.01	--	0.03
NFM.BRA	--	--	--	--	--	--	0.01
NFM.ASI	--	--	0.01	--	0.01	--	0.02
NFM.MPC	0.02	0.01	0.02	0.01	0.02	0.01	0.09
NFM.ROW	0.05	0.02	0.07	0.02	0.03	0.01	0.20
NMM.CHN	0.05	0.02	0.09	0.06	0.01	--	0.23
NMM.IND	--	--	0.01	--	--	--	0.02
NMM.ASI	0.01	--	0.03	0.02	--	--	0.07
NMM.MPC	0.02	--	0.04	0.01	--	--	0.08
NMM.ROW	0.01	--	0.07	0.01	--	--	0.09
TRN.CHN	0.01	0.01	0.02	--	--	--	0.03
TRN.IND	--	--	--	--	--	--	0.01
TRN.ASI	--	--	0.01	--	--	--	0.01
TRN.MPC	0.01	--	0.01	0.01	--	--	0.03
TRN.ROW	--	--	0.02	--	--	--	0.03
OME.CHN	0.02	0.01	0.03	--	--	--	0.06
OME.IND	--	--	--	--	--	--	0.01
OME.ASI	--	--	0.01	--	--	--	0.02
OME.MPC	--	--	0.01	0.01	--	--	0.03
OME.ROW	0.01	--	0.04	--	--	--	0.05
OMN.CHN	0.04	0.03	0.02	0.01	0.01	--	0.11
OMN.IND	0.03	0.01	--	--	--	--	0.05
OMN.BRA	--	--	--	--	--	--	0.01
OMN.ASI	--	--	--	--	--	--	0.01
OMN.MPC	0.05	0.01	0.02	0.01	0.01	--	0.09
OMN.ROW	0.07	0.03	0.07	0.01	0.01	--	0.20
FPR.CHN	--	--	--	--	--	--	--
PPP.CHN	0.02	0.03	0.03	0.01	--	--	0.09

PPP.IND	--	--	--	--	--	--	--
PPP.ASI	--	--	0.01	--	--	--	0.02
PPP.MPC	0.01	--	0.02	0.01	--	--	0.05
PPP.ROW	0.01	--	0.04	--	--	--	0.06
LUM.CHN	0.01	0.01	0.01	0.01	--	--	0.05
LUM.ASI	--	--	--	--	--	--	--
LUM.MPC	--	--	0.01	0.01	--	--	0.02
LUM.ROW	--	--	0.01	--	--	--	0.02
CNS.CHN	--	--	0.01	--	--	--	0.01
CNS.ASI	--	--	--	--	--	--	0.01
CNS.MPC	--	--	0.01	0.01	--	--	0.02
CNS.ROW	--	--	0.01	--	--	--	0.01
TWL.IND	--	--	--	--	--	--	--
TWL.ASI	--	--	0.01	--	--	--	0.02
TWL.MPC	--	--	0.01	--	--	--	0.02
TWL.ROW	--	--	0.02	--	--	--	0.02
OMF.CHN	0.03	--	0.03	0.01	--	--	0.06
OMF.IND	--	--	--	--	--	--	--
OMF.ASI	--	--	0.01	--	--	--	0.01
OMF.MPC	0.02	--	0.01	0.01	--	--	0.03
OMF.ROW	0.01	--	0.02	--	--	--	0.03
AGR.CHN	-0.03	--	0.01	-0.01	--	-0.01	-0.04
AGR.ASI	--	--	--	--	--	--	--
AGR.MPC	--	--	0.01	0.01	--	0.01	0.04
AGR.ROW	-0.01	--	0.01	--	--	--	--
T_T.CHN	0.01	0.01	-0.01	-0.01	--	--	-0.01
T_T.IND	0.03	--	0.01	--	--	--	0.05
T_T.BRA	0.02	--	0.01	--	--	--	0.03
T_T.ASI	0.09	0.01	0.04	0.02	0.01	--	0.16
T_T.MPC	0.17	0.02	0.06	0.02	0.01	--	0.28
T_T.ROW	0.06	0.01	0.05	0.02	--	--	0.13
SER.CHN	0.05	0.04	0.09	0.02	0.02	-0.01	0.22
SER.IND	--	--	0.01	--	--	--	0.02
SER.BRA	--	--	0.01	--	--	--	0.01
SER.ASI	0.01	--	0.05	0.01	0.01	--	0.08
SER.MPC	0.03	0.01	0.08	0.04	0.01	0.01	0.17
SER.ROW	0.06	0.01	0.18	0.02	0.01	--	0.27
DWE.CHN	0.03	0.04	0.13	0.05	0.03	-0.01	0.27
DWE.IND	--	--	0.01	0.02	--	--	0.03
DWE.BRA	--	--	0.01	--	--	--	0.01
DWE.ASI	0.01	--	0.08	0.02	0.01	--	0.11
DWE.MPC	0.02	--	0.13	0.06	0.01	--	0.23
DWE.ROW	0.03	0.01	0.27	0.04	0.01	--	0.36
FNL.CHN	0.07	--	0.05	0.03	--	--	0.14
FNL.IND	0.07	0.01	0.02	0.01	--	--	0.11
FNL.BRA	0.04	--	0.01	0.01	--	--	0.07
FNL.ASI	0.18	0.01	0.08	0.03	--	--	0.31
FNL.MPC	0.38	0.03	0.16	0.07	0.01	--	0.65
FNL.ROW	0.11	0.01	0.14	0.03	--	--	0.29
ELE.colsum	0.04	0.06	0.24	0.05	0.05	-0.01	0.43
I_S.colsum	0.27	0.08	0.64	0.54	0.07	0.08	1.70
CRP.colsum	0.75	0.14	0.80	0.31	0.04	0.03	2.08

NFM.colsum	0.12	0.06	0.14	0.05	0.13	0.03	0.54
NMM.colsum	0.10	0.02	0.25	0.11	0.02	--	0.50
TRN.colsum	0.02	0.01	0.06	0.02	--	--	0.10
OME.colsum	0.04	0.01	0.09	0.02	0.01	--	0.17
OMN.colsum	0.19	0.08	0.12	0.03	0.03	0.01	0.46
PPP.colsum	0.05	0.04	0.11	0.03	0.01	--	0.23
LUM.colsum	0.02	0.01	0.03	0.03	0.01	--	0.10
CNS.colsum	0.01	--	0.03	0.02	--	--	0.06
TWL.colsum	0.01	--	0.03	--	--	--	0.04
OMF.colsum	0.06	--	0.07	0.02	--	--	0.15
AGR.colsum	-0.05	--	0.04	0.01	--	-0.01	-0.01
T_T.colsum	0.37	0.05	0.16	0.06	0.02	--	0.65
SER.colsum	0.14	0.06	0.42	0.11	0.05	--	0.77
DWE.colsum	0.10	0.05	0.64	0.19	0.06	-0.02	1.01
FNL.colsum	0.85	0.07	0.47	0.17	0.01	-0.01	1.56

-- is reported when the number is less than 0.01

Appendix 7. Regional decomposition for 45 regions

Appendix 7 shows the results of calculations for 45 regions (14 Annex B).

	USA	AUS	NZL	JPN	CAN	GBR	DEU	DNK
KOR	0.202	0.033	0.005	0.106	0.027	0.020	0.023	0.003
IDN	0.080	0.017	0.002	0.097	0.012	0.006	0.016	0.002
MYS	0.031	0.009	--	0.030	0.005	0.003	0.006	--
PHL	0.020	--	--	0.008	0.002	0.001	0.002	--
SGP	0.033	--	--	0.014	0.005	0.002	0.009	--
THA	0.034	0.001	--	0.014	0.004	0.004	0.004	--
VNM	0.007	0.001	--	0.004	--	--	--	--
CHN	0.288	0.049	0.051	0.358	0.049	0.033	0.060	0.019
HKG	0.014	0.001	--	0.004	0.003	--	0.008	--
TWN	0.102	0.017	-0.002	0.059	0.092	0.009	0.018	--
IND	0.140	0.016	0.005	0.068	0.018	0.013	0.019	0.003
LKA	0.001	--	--	0.002	--	--	--	--
RAS	0.024	--	--	0.009	0.003	0.001	0.003	--
MEX	0.287	0.002	0.001	0.044	0.046	0.007	0.015	0.002
CAM	0.053	--	--	0.020	0.006	0.002	0.004	--
VEN	0.064	--	--	0.024	0.009	0.002	0.005	--
COL	0.047	0.002	--	0.010	0.013	0.001	0.001	--
RAP	0.020	0.001	--	0.007	0.003	--	0.002	--
ARG	0.014	--	--	0.004	0.001	--	0.001	--
BRA	0.124	0.005	--	0.032	0.029	0.005	0.007	--
CHL	0.019	0.001	--	0.006	0.005	--	0.002	--
URY	--	--	--	--	--	--	--	--
RSM	0.002	--	--	--	--	--	--	--
TUR	0.059	0.008	--	0.028	0.007	0.007	0.057	0.003
RME	0.394	0.024	0.004	0.185	0.049	0.023	0.050	0.007
MAR	0.009	--	--	0.002	0.001	--	0.004	--
RNF	0.145	0.008	--	0.045	0.021	0.005	0.014	0.002
SAF	0.110	0.019	-0.012	0.063	0.040	0.010	0.146	-0.011
RSA	0.023	0.002	--	0.008	0.002	0.001	0.002	--
RSS	0.023	--	--	0.022	0.003	--	0.002	--
ROW	0.036	0.007	--	0.026	0.004	0.004	0.007	0.003
colsum	2.405	0.229	0.059	1.299	0.459	0.164	0.486	0.038

	SWE	FIN	REU	EFT	CEA	FSU	rowsum
KOR	--	--	0.115	0.003	-0.003	0.006	0.538
IDN	--	--	0.069	0.003	--	0.008	0.312
MYS	0.001	--	0.031	0.001	--	0.003	0.122
PHL	--	--	0.008	--	--	--	0.044
SGP	--	--	0.030	0.002	--	0.001	0.098
THA	--	--	0.015	0.001	--	--	0.081
VNM	--	--	0.005	--	--	--	0.020
CHN	--	0.002	0.218	0.008	-0.002	0.036	1.168
HKG	--	--	0.022	--	--	--	0.050
TWN	-0.002	-0.002	0.096	0.006	-0.004	-0.002	0.386
IND	--	0.001	0.080	0.003	-0.002	0.004	0.367
LKA	--	--	--	--	--	--	0.004

RAS	--	--	0.011	--	--	--	0.054
MEX	0.002	--	0.045	0.004	--	0.003	0.458
CAM	--	--	0.013	0.001	--	--	0.102
VEN	0.001	--	0.017	0.002	--	--	0.128
COL	0.001	--	0.008	--	--	--	0.083
RAP	--	--	0.007	--	--	--	0.041
ARG	0.002	--	0.002	--	--	--	0.025
BRA	0.004	--	0.032	0.002	--	--	0.240
CHL	--	--	0.006	--	--	--	0.040
URY	--	--	--	--	--	--	0.002
RSM	--	--	--	--	--	--	0.003
TUR	0.001	--	0.162	0.005	--	0.002	0.337
RME	0.004	--	0.270	0.015	-0.002	0.015	1.038
MAR	--	--	0.013	--	--	--	0.030
RNF	0.001	--	0.069	0.004	--	0.006	0.322
SAF	-0.013	-0.004	0.365	-0.011	-0.013	-0.013	0.676
RSA	--	--	0.010	--	--	--	0.049
RSS	--	--	0.008	--	--	--	0.061
ROW	--	--	0.035	0.003	--	0.005	0.129
colsum	0.006	-0.001	1.762	0.055	-0.031	0.079	7.008

-- is reported when the number is less than 0.001

Appendix 8. Precision

Two parameters can be used for estimating the precision of the decomposition method. One parameter shows the number of segments in a line integral. Another parameter represents a perturbation for numerical calculation of a derivative. From equation (6) we know that

$$\Delta Z^s = \sum_{ib} \left[\Delta X_{ib} \int_{t=0}^{t=1} \frac{\partial F}{\partial X_{ib}} dt \right] = \sum_{ib} \Delta Z^s_{ib} \tag{7}$$

where ΔZ^s is the total change in endogenous variable (representing the carbon emissions in the non-Annex B region) obtained from the model, and ΔZ^s_{ib} is the calculated by the decomposition method change in endogenous variable associated with a certain exogenous carbon tax. The precision of the method, ε, can be checked as the difference:

$$\varepsilon^s = \Delta Z^s - \sum_{ib} \Delta Z^s_{ib} \tag{8}$$

The precision of the method is affected by the number of segments, λ, by which the integral $\int_{t=0}^{t=1} \frac{\partial F}{\partial X_{ib}} dt$ is divided for its numerical calculation. An increase in the number of segments improves the precision but increases the time of calculation. Table A.8.a shows ε for different λ.

λ	CHN	IND	BRA	ASI	MPC	ROW
5	-0.002	-1.58E-4	-7.36E-5	-4.48E-4	-0.003	-0.001
10	-8.89E-4	-8.78E-5	-4.26E-5	-2.26E-4	-8.66E-4	-7.52E-4
15	-5.04E-4	-4.97E-5	-2.51E-5	-1.22E-4	-4.25E-4	-4.26E-4
20	-3.70E-4	-3.76E-5	-1.87E-5	-9.32E-5	-2.94E-4	-3.06E-4
25	-2.51E-4	-2.46E-5	-1.20E-5	-6.43E-5	-2.11E-4	-1.98E-4
30	-1.65E-4	-1.51E-5	-7.21E-6	-4.27E-5	-1.58E-4	-1.18E-4

Table A.8.a. Epsilon for different λ.

Another parameter, τ, shows the perturbation for calculating a partial derivative as

$$\left. \frac{\partial F}{\partial X_{ib}} \right|_t \approx \frac{F(X^0_{ib} + t\Delta X_{ib} + \tau) - F(X^0_{ib} + t\Delta X_{ib})}{\tau} \tag{9}$$

Table A.8.b presents the precision for different differentiation perturbations. It shows that the choice of τ is important to assure a small deviation between the model calculations and the sum of decomposed estimates for the carbon emissions.

τ	CHN	IND	BRA	ASI	MPC	ROW
1	0.009	9.52E-4	4.36E-4	0.003	0.006	0.009
0.1	0.002	1.75E-4	7.21E-5	5.03E-4	0.001	0.002
0.01	-2.25E-4	-2.56E-5	-1.17E-5	-5.48E-5	-1.45E-4	-1.30E-4
0.001	-4.79E-4	-5.07E-5	-2.20E-5	-1.24E-4	-3.41E-4	-3.54E-4
0.0001	-3.70E-4	-3.76E-5	-1.87E-5	-9.32E-5	-2.94E-4	-3.06E-4
0.00001	2.81E-4	3.98E-5	1.94E-5	1.20E-4	1.87E-4	2.47E-4

Table A.8.b. Epsilon for different τ