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Carbon Leakage with Structural Gravity*

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Abstract

The future international climate policy architecture will most likely consist of partial climate policy initiatives like the EU's Emission Trading System. Trade integration threatens to undermine these systems' environmental effectiveness by shifting emissions to other countries. We estimate a gravity model based on 103 countries and use it to simulate several such climate policy experiments. The model's parameters are structurally linked to empirical estimates, i.e. bilateral trade costs and the elasticity of substitution are consistent with the data. Unlike previous empirical work, the approach allows to quantify emission relocation in general equilibrium. With trade liberalization experiments, the model also allows to deliver a perspective on environmental aspects of hypothetical FTA formation. We find that an EU emission allowance price of 15 US-\$ suffices to bring the EU on track for its Kyoto target but also leads to emission relocations of about 10% of the EU's emission savings.

JEL Classification: F18, F47, Q54, Q56

Keywords: gravity model, climate policy, leakage effects of trade, structural estimation.

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1 Introduction

Countries vary greatly with respect to their willingness to commit to international climate policy efforts. This is partly attributable to domestic political constraints, as for example in North America. It also reflects different risks of exposure to negative effects of global warming. For example small island states are more prone to rising sea levels or extreme weather events. In addition, there is a historical responsibility of industrialized countries for greenhouse gas (GHG) concentrations in the atmosphere.¹ Developing countries claim the same right for unconstrained growth. Political constraints and equity considerations make partial climate deals, like the Kyoto Protocol and the EU's Emission Trading System, a likely feature of the future climate policy architecture.

However, if only a sub-group of countries increases the costs of GHG emissions, this changes international relative goods prices (terms-of-trade effect). In response, production might shift to countries with lax climate regulation. The possibility to relocate production and engage in international trade can undermine the environmental effectiveness of a partial climate deal. *Carbon leakage* refers to such a situation where a stricter climate policy regulation in one country or region causes higher emissions elsewhere (Felder and Rutherford, 1993).² The extent of carbon leakage is typically quantified with a percentage number: the total emission increases in other countries as a share of emission savings in the climate-active region.

In this paper, we want to understand how unilateral climate policy shapes the location of emissions in a globalized world. Guided by an *estimated structural gravity model*, we *quantify the extent of leakage* in hypothetical climate policy scenarios. A large sample is crucial for this exercise because it allows to capture the majority of global production shifts. Hence, we work with the largest possible sample of 103 countries containing all major trading nations. More importantly, the sample does not concentrate on industrialized countries only but also comprises

¹This is referred to as “principle of common but differentiated responsibilities” under the United Nations Framework Convention on Climate Change (UNFCCC). The UNFCCC is an international environmental treaty and constitutes the legal framework for negotiations of GHG emission reductions in so-called “Protocols”.

²There are two additional reasons for carbon leakage aside from international trade. First, since the global climate is a global public good there is an incentive to free-ride on others' emission savings and to relax one's own climate policy efforts in response (see e.g. Carraro and Siniscalco, 1998; Congleton, 2001; Copeland and Taylor, 2005; Elliott et al., 2010). Second, depending on the supply elasticity of energy inputs a reduced energy demand in one part of the world may lower the world market energy price (see, e.g. Sinn, 2008). This can lead to increased energy demand, and thus emissions, in countries which do not have a strict climate policy in place (“supply-side leakage”). In this paper we focus on the leakage channel relating to trade and relative goods prices.

many developing countries with relatively low carbon prices.

Point of departure is the workhorse model in international trade: A new trade theory gravity model (in its form as derived in Anderson and van Wincoop, 2003, with Armington-type preferences). We allow for several production factors: labor, capital, land, and energy. They are combined in a Cobb-Douglas production function to produce a country's variety. Implicit carbon prices, i.e. the implicit price for burning fuels, are crucial to the analysis. Aside from country-specific energy market conditions they also reflect climate policy stringency. Climate policy adds a price premium to costly energy use (Aldy and Pizer, 2011). Whereas climate policy stringency is not observable, implicit carbon prices are. Thus they provide a simple way to calibrate our model to the data.

The model's key parameters are structurally linked to empirical estimates. The model gives rise to a standard gravity equation. Bilateral trade costs are consistently estimated from the gravity equation with importer and exporter fixed effects. As in Bergstrand et al. (2012), these estimated trade costs and observed factor cost shares are then fed back into the structural model to identify the elasticity of substitution.

We conduct two types of policy experiments: partial climate policy initiatives and trade liberalization. The latter scenarios discuss environmental aspects of regional free trade agreement (FTA) formation in the presence of carbon price differentials. The climate policy scenarios focus on the emission relocation implied by an increase in the EU's emission allowance price. Briefly, we also study the implications of commitments under the second period of the Kyoto Protocol (Kyoto II) for leakage.³

The theoretical possibility of carbon leakage is well documented (see e.g. Copeland and Taylor, 2005). But Di Maria and van der Werf (2008), for example, show that directed technical change weakens carbon leakage. So there exist theoretical arguments diminishing its role.

In this paper, we bring together two strands of literature that assess the importance of leakage. First, a growing body of literature assesses the competitiveness and leakage effects of unilateral climate policy with the help of computable general equilibrium (CGE) models. Results from such models are ambiguous. Resulting leakage rates are typically moderate and lie between 5 and 20% (Felder and Rutherford, 1993; Elliott et al., 2010; Burniaux and Oliveira Martins, 2012), but the leakage rate can even exceed 100% (Babiker, 2005). The models are sensitive to parameter choices (see, e.g., the literature survey in Burniaux and Oliveira Martins, 2012) like

³At the time of writing of this thesis, it was not clear whether the Kyoto Protocol would expire. Due to its recent extension for a second period from 2013-2020, we add a Kyoto II scenario.

elasticity of substitution and bilateral trade costs. These are often not founded on empirical estimates. In our structural gravity approach, we also employ simulation techniques to create counterfactual policy scenarios. Yet in contrast, our model's parameters are structurally linked to econometric estimates; i.e. the model's bilateral trade costs and elasticity of substitution are consistent with the data.

Second, an empirical strand of literature works with international trade data and applies the gravity equation in the context of climate policy.⁴ It provides ex-post evidence on actual policy experiments like carbon taxes or the Kyoto Protocol. The empirical evidence presented so far suggests a *direct* trade effect of climate policy (see for example World Bank, 2008). Employing a panel strategy to control for Kyoto's endogeneity, Aichele and Felbermayr (2011) estimate a Kyoto country increases its imports from non-Kyoto countries due to Kyoto commitment by about 5%. Sato (2011) finds that an electricity price gap of 10 US-\$ per MWh reduces exports by 1-2%. The evidence is also consistent with leakage: the carbon content of imports of Kyoto countries from non-Kyoto countries increases by 8% with Kyoto commitment (Aichele and Felbermayr, 2011). The empirical literature provides average treatment effects of climate policy or energy prices. Country-specific general equilibrium responses to policy changes are absorbed in country or country-and-time fixed effects. So, it cannot offer a *general equilibrium* (GE) quantitative perspective on the leakage problem. General equilibrium changes in GDPs and price levels are neglected. This paper fills the gap and goes beyond average treatment effects. We resort to structural estimation and simulation techniques to quantify leakage in general equilibrium.

Methodologically, the paper is related to structural gravity applications. In this strand of literature, policy experiments typically deal with the effects of trade costs on trade patterns and welfare in general equilibrium. Several studies investigate the effects of abolishing the Canada-US border (see, for example Anderson and van Wincoop, 2003; Bergstrand et al., 2012). Other studies simulate the gains from trade of trade liberalization (see for example Eaton and Kortum, 2002) or free trade agreement (FTA) formation (Egger et al., 2011; Egger and Larch, 2011) or deal with the role of trade imbalances for welfare (Dekle et al., 2007). So far, the structural gravity approach has not been applied to the carbon leakage context.

We find that leakage is moderate but non-negligible. An EUA permit price of 15 US-\$ allows

⁴This literature is embedded in a broader empirical literature exploring the pollution haven effect of environmental regulation stringency on trade flows with a focus on local pollutants (see Ederington et al., 2005; Levinson and Taylor, 2008, for some examples).

the EU to fulfill its Kyoto target. EU countries increase their import shares from non-EU countries. The induced emission relocation amounts to 10%. The counterfactual emission increase through production relocation in non-EU countries is heterogeneous and governed by proximity to the EU, country size, and relative carbon prices. Results are robust to the econometric estimation procedure chosen. Not accounting for country-specific heterogeneity in factor use leads to a slight underestimation of the extent of leakage. Emission limitations as negotiated for the second period of the Kyoto Protocol lead to 8% of emission relocation. This leakage rate is smaller than in the ETS scenario because with Kyoto II a larger part of the world is constrained.

The rest of the paper proceeds as follows. Section 2 describes our model and parameter identification strategy. Section 3 presents our empirical estimates of the model's parameters. Section 4 shows the results of counterfactual policy experiments.

2 Methodology

The gravity equation is the workhorse model of international trade. It explains bilateral trade flows with bilateral trade costs, GDPs and prices. A large model class featuring iceberg trade costs, constant elasticity of substitution preferences, perfect specialization, linear cost functions and one factor of production leads to an isomorphic formulation of the gravity equation and the gains from trade (Eaton and Kortum, 2002; Arkolakis et al., 2012). In a seminal paper, Anderson and van Wincoop (2003) rationalize the gravity equation with Armington (1969)-type preferences. The authors point out that it is important to account for the endogeneity of price levels or *multilateral resistance terms* in a structural gravity model. Krugman (1980)-type gravity models provide an alternative formulation with monopolistic competition and increasing returns to scale. Eaton and Kortum (2002) focus on technology differences between countries in a Ricardian continuum of goods framework. Chaney (2008) and Helpman et al. (2008) deal with firm heterogeneity and the role of zero trade flows. The empirical gravity specification resulting from many of these models (Anderson and van Wincoop, 2003; Eaton and Kortum, 2002; Feenstra, 2004, amongst them) is similar, and thus are trade cost parameter estimates. Even though the gravity equation is structurally similar, the theoretical underpinning of the gravity equation will determine both the magnitudes and the transmission mechanisms of comparative statics effects (Egger et al., 2011).

We follow the theoretical gravity formulation in Anderson and van Wincoop (2003). With this choice of the theoretical model, we shut down two potential transmission channels of climate policy shocks. Effects on the extensive margin of trade are neglected. We look at aggregate trade

flows in 103 countries. Since zero trade flows only make up 10% of our observations, this choice is defensible. In addition, it seems plausible that climate policy affects how much is traded (*intensive margin*) much rather than the decision to trade at all (*extensive margin*). Since there is no role of firm heterogeneity in the Anderson and van Wincoop (2003) model, we rule out effects on firm distribution as well. Climate policy might shut down firms at home while making production and possibly exporting profitable for relatively less efficient (and thus more energy-intensive) firms abroad. This may provide an additional leakage channel. To study these effects, one would require firm level information on trade and emission intensity however. Krugman (1980)-type models are not often used in structural gravity since the number of varieties needs to be calibrated. In conclusion, the Anderson and van Wincoop (2003) framework provides a good point of departure for our analysis.

The model extension in Section 2.1 allows for labor, capital, land and energy as production factors. This is key to disentangle the effects of carbon prices on trade and emissions. Section 2.2 describes our strategy to structurally estimate the model's parameters. Section 2.3 presents the methodology for evaluating counterfactual scenarios.

2.1 Gravity model with energy and conventional production factors

Trade flows. Our model world is populated by $i, j = 1, \dots, N$ countries. There is one sector of production. Sectoral varieties are differentiated by country of origin and each country produces one such variety. We assume that the representative consumer's preferences display a constant elasticity of substitution (CES) over varieties, with $\sigma > 1$ common across all countries. σ is a key parameter in international trade since it is a crucial driver of trade effects. The assumption of a common σ across all countries is fairly standard in the gravity literature (see for example Anderson and van Wincoop, 2003; Bergstrand et al., 2012; Anderson and Yotov, 2010). The corresponding Frechet-distribution parameter in Eaton and Kortum (2002)-type models or the Pareto parameter in Melitz (2003)-type models is typically assumed common across countries as well.⁵ So we follow the literature here.

In reality, industries display heterogeneity in their elasticity of substitution (see, e.g., Broda

⁵In a recent paper, Feenstra et al. (2012) work with a nested CES structure and distinguish two elasticities – a macro elasticity between domestic and foreign varieties on the upper tier and a micro elasticity between foreign varieties of different countries of origin. The micro elasticity which is linked to bilateral trade flows is still common across all foreign countries. To identify the macro elasticity as in Feenstra et al. (2012), we would need information on domestic unit values which we do not have. So we stick to the standard formulation.

and Weinstein, 2006). The sectoral effects of climate policy will crucially depend on the degree of product differentiation. A cost shock will translate into higher relocation effects the more substitutable/homogeneous a sector's varieties are. With a one sector model, we cannot capture this. However, with several sectors model calibration and simulation is computationally more involved. For this reason, there are only few applications of multi-sector structural gravity models. So in a first attempt we abstract from sectoral heterogeneity in relocation effects; accepting a potential aggregation bias. Nonetheless, including a sectoral structure is an important avenue for future research.

International trade of sectoral varieties is costly. $\tau_{ij} \geq 1$ units have to be shipped from country i to country j for one unit to arrive, i.e. a fraction of the quantity shipped between countries melts away (iceberg trade costs).⁶ Country i charges the ex-factory price p_i . Then, the price of goods from i shipped to j is $p_{ij} = \tau_{ij}p_i$. Let b_i be the usual positive parameter. So the consumer in country j maximizes her utility U_j over the consumed quantity c_{ij} of i 's variety

$$\max U_j = \left[\sum_{i=1}^N b_i^{\frac{1-\sigma}{\sigma}} c_{ij}^{\frac{\sigma-1}{\sigma}} \right]^{\frac{\sigma}{\sigma-1}}$$

subject to the budget constraint $\sum_{i=1}^N p_{ij}c_{ij} = Y_j$. National income Y_j comprises factor income (such as wage income, interest payments and land rents).

From the utility maximization problem, the value of bilateral trade flows X_{ij} from country i to j is determined as

$$X_{ij} = p_{ij}c_{ij} = \left(\frac{b_i p_i \tau_{ij}}{P_j} \right)^{1-\sigma} Y_j. \quad (1)$$

As usual, $P_j = \left[\sum_{i=1}^N (b_i p_i \tau_{ij})^{1-\sigma} \right]^{\frac{1}{1-\sigma}}$ is the ideal price index.

Gravity equation. Goods market clearing requires that a country's supply of its variety equals the quantity demanded (inclusive trade costs):

$$Y_i = \sum_{j=1}^N X_{ij} = (b_i p_i)^{1-\sigma} \sum_{j=1}^N \left(\frac{\tau_{ij}}{P_j} \right)^{1-\sigma} Y_j. \quad (2)$$

Define $Y^w \equiv \sum_i Y_i$ as world GDP and $\theta_i \equiv \frac{Y_i}{Y^w}$ as country i 's GDP share. Solving (2) for equilibrium scaled prices $(b_i p_i)^{1-\sigma}$ and plugging into (1) gives the gravity equation

$$X_{ij} = \frac{Y_i Y_j}{Y^w} \left(\frac{\tau_{ij}}{\Pi_i P_j} \right)^{1-\sigma}, \quad (3)$$

⁶In reality, trade costs differ between industries. Some industries are "footloose" because their trade costs are low, while others like cement, for example, have relatively high transportation costs. Due to the lack of a sectoral structure we abstract from this here.

where

$$\Pi_i \equiv \left[\sum_{j=1}^N \left(\frac{\tau_{ij}}{P_j} \right)^{1-\sigma} \theta_j \right]^{\frac{1}{1-\sigma}}. \quad (4)$$

Plugging equilibrium scaled prices into the ideal price index gives

$$P_j = \left[\sum_{i=1}^N \left(\frac{\tau_{ij}}{\Pi_i} \right)^{1-\sigma} \theta_i \right]^{\frac{1}{1-\sigma}}. \quad (5)$$

The system of equations (3)-(5) corresponds to the one in Anderson and van Wincoop (2003). Π_i and P_j are called outward and inward multilateral resistance terms or sellers' and buyers' incidence, respectively, and measure a country's trade barriers with all other countries. With symmetric trade costs $\tau_{ij} = \tau_{ji}$ outward and inward multilateral resistance are equivalent, $\Pi_i = P_i$, and the gravity equation simplifies to

$$X_{ij} = \frac{Y_i Y_j}{Y^w} \left(\frac{\tau_{ij}}{P_i P_j} \right)^{1-\sigma}, \quad (6)$$

with multilateral resistance terms as implicit solution to

$$P_j = \left[\sum_{i=1}^N \left(\frac{\tau_{ij}}{P_i} \right)^{1-\sigma} \theta_i \right]^{\frac{1}{1-\sigma}}. \quad (7)$$

This derivation assumes trade is multilaterally balanced; an assumption violated in the data. Trade imbalances could be accommodated in the model by adjusting countries' expenditure levels with nominal transfers as observed in the data (see, e.g., Dekle et al., 2007; Alvarez and Lucas, 2007). Since there is no theory of trade imbalances in the gravity framework we would keep nominal transfers in our application constant. In this case the choice of numeraire matters (Ossa, 2011). Changes in nominal prices have implications for real transfers.⁷ Due to these complications, we abstract from trade imbalances in our analysis.

The gravity equation in (3) implicitly considers countries' endowment and energy price differences via their effect on GDPs. In the following, we will lend the Anderson and van Wincoop (2003) framework more structure by explicitly modeling the production structure. This allows to investigate the effect of changes in implicit carbon prices for trade flows, emissions and leakage.

⁷In his structural gravity application on trade wars, Ossa (2011) therefore purges the actual data from trade imbalances before doing counterfactual analysis. But this implies a policy experiment evaluation against another hypothetical counterfactual.

Production. The representative firm in country i combines labor, capital, land and fossil energy to produce the output quantity q_i .⁸ Burning fossil energy causes CO₂ emissions, i.e. emissions and energy use are directly related via chemical processes. For simplicity, we assume a one-to-one relationship. That implies we can think of emissions as an input instead of a side output; a fairly standard modeling assumption in the trade and environment context.⁹ It will be convenient to model the production function directly with emissions instead of energy. In the data, we observe that factor cost shares add up to one on average (see Section 3.1). So for simplicity we assume a constant returns to scale Cobb-Douglas production function. Given our large sample of 103 countries, technologies are likely to differ across countries. To incorporate this into the model, we introduce productivity differences with a technology shifting parameter A_i . The higher A_i the more productive a country is. Let V_{if} be country i 's endowment with factor $f \in (\text{labor, capital, land})$ and E_i its emission level. A country's output level follows

$$q_i = A_i E_i^{\beta_i} \prod_f V_{if}^{\alpha_{if}}, \quad (8)$$

where β_i is the country-specific cost share of emissions (as well as energy) and α_{if} is the country-specific cost share of factor f .¹⁰ Constant returns to scale imply $\beta_i + \sum_f \alpha_{if} = 1$.

Let e_i denote a country's implicit carbon price and w_{if} denote its price of factor f . With perfect competition, the ex-factory price p_i is equal to the minimum unit costs dual to (8):

$$p_i = \frac{1}{A_i} \left(\frac{e_i}{\beta_i} \right)^{\beta_i} \prod_f \left(\frac{w_{if}}{\alpha_{if}} \right)^{\alpha_{if}}. \quad (9)$$

With Shepard's lemma, the factor market clearing conditions $\alpha_{if} \frac{p_i}{w_{if}} q_i = V_{if}$ pin down equilibrium factor prices as

$$w_{if} = \frac{\alpha_{if} p_i q_i}{V_{if}} \quad \forall f. \quad (10)$$

A constant fraction of nominal GDP is spent on labor, capital and land income.

In our data, we observe substantial variation in energy and implicit carbon prices across countries, see the data summary in Section 3.1. A country's implicit carbon price captures

⁸Even though we model labor, capital, land and energy as input factors only, the formulation of the production function is rather general. It is straightforward to extend the model to include more input factors that are in fixed supply.

⁹See for example Copeland and Taylor (2003). Typically, the modeling of emissions as an input factor is motivated with an abatement technology that uses up part of the output. Since we observe an implicit CO₂ price in the data and will alter it in counterfactual scenarios, we choose to model energy as a direct input instead.

¹⁰We use country-specific factor cost shares in the model because we observe this type of heterogeneity in our data, see Section 3.1.

country-specific energy market conditions like fuel endowments and energy mix. But it also reflects climate policy. Climate policy – be it a carbon tax, an emission cap-and-trade system or a feed-in tariff – constitutes a premium on energy prices (see, e.g., Aldy and Pizer, 2011). It differs across countries and reflects the perceived risk of exposure to adverse effects from global warming and willingness to contribute to a global public good. It implies that, in the end, the national government sets a country’s carbon price.

These observations motivate our stylized energy market model. Each country i is endowed with fossil fuel in the ground which is owned by the government, can be extracted but is not traded internationally. For simplicity we normalize extraction costs to zero. Fuel is elastically available at the prevailing carbon price set by the government. Fuel rents (inclusive carbon taxes) are rebated in a lump-sum fashion to the representative consumer and are thus part of national income.¹¹ Since energy and carbon prices are directly observable – while stringency of climate policy is not – this provides a simple way to calibrate the benchmark model and experiment with carbon taxes in counterfactual scenarios.

Alternatively, energy could be supplied on a world market at a given world price. Country-specific climate policy drives a wedge between the country’s and the world energy price. This leads to a similar formulation for implicit carbon prices. If the fuel world market price is normalized to zero, the outcome on national incomes is identical. Else resource ownership matters for national income because the non-tax part of fuel rents is transferred to resource-owning countries. With our stylized model, we abstract from these rent transfers.

This modeling of climate policy has several implications. First, leakage through free-riding is ruled out because there is no strategic component to climate policy. Second, supply-side leakage via the world energy price is not possible either. This would require a (rather) inelastic energy supply. On the contrary, in our model the energy supply reacts to demand changes only. Consequently, climate policy affects emissions through the production pattern and trade. This is the focus of the present paper.

Similar to the derivation of other factors’ unit requirements, Shepard’s lemma gives the unit emission intensity $\eta_i = \beta_i p_i / e_i$. So a country’s emission level is $E_i = \frac{\beta_i Y_i}{e_i}$. In consequence, energy usage – and thus emissions – react to the carbon price set by the government and the overall level of production. The latter is driven by technology, trade and GE effects.

¹¹This does not imply a government can increase national income by setting higher carbon taxes. This will reduce energy use, fuel rents and diminish other factor prices in general equilibrium.

With this production structure, we can rewrite trade flows from (1) using (9) and (10) as

$$X_{ij} = \frac{\left[\frac{b_i}{A_i} \left(\frac{e_i}{\beta_i} \right)^{\beta_i} \Pi_f \left(\frac{Y_i}{V_{if}} \right)^{\alpha_{if}} \right]^{1-\sigma} \tau_{ij}^{1-\sigma}}{\sum_{k=1}^N \left[\frac{b_k}{A_k} \left(\frac{e_k}{\beta_k} \right)^{\beta_k} \Pi_f \left(\frac{Y_k}{V_{kf}} \right)^{\alpha_{kf}} \right]^{1-\sigma} \tau_{kj}^{1-\sigma}} Y_j, \quad (11)$$

subject to the goods market clearing constraint (2). X_{ij} , Y_i and $\frac{Y_i}{V_{if}}$ are endogenously determined in the model.

The elasticity of substitution σ is a crucial model parameter. It governs how equilibrium prices and trade react to carbon price or trade cost shocks. In the next subsection, we show how (11) allows us to identify the parameter σ empirically.

2.2 Identifying the model's parameters

In this section, we describe the methodology to identify bilateral trade freeness $\tau_{ij}^{1-\sigma}$, the elasticity of substitution σ and the factor cost shares β_i and α_{if} empirically. With a constant returns to scale Cobb-Douglas production function $\beta_i = \frac{e_i E_i}{Y_i}$ and $\alpha_{if} = \frac{w_{if} V_{if}}{Y_i}$. Labor, capital and factor income as well as emissions and implicit CO₂ prices are given in GTAP8. So a country's factor cost shares are directly observable in the data. Country-specific factor cost shares are the default. In a robustness check, we use average factor cost shares in the production function. This will give us an idea how important factor cost share differences are for the extent of emission relocation. To get average estimates $\hat{\beta}$ and $\hat{\alpha}_f$ we run simple regressions of factor incomes on GDPs.

Typically, the gravity literature proceeds by estimating equation (6) or (11) in log-linearized form. Bilateral trade costs τ_{ij} are not observable. They are proxied by bilateral distance d_{ij} and a vector of dummy variables for other observables \mathbf{Z}_{ij} like contiguity, common language, and bilateral free trade agreements. As in Anderson and van Wincoop (2003) and many other gravity applications, the functional relationship is assumed to be $\tau_{ij}^{1-\sigma} = d_{ij}^{(1-\sigma)\varrho} e^{(1-\sigma)\delta \mathbf{Z}_{ij}}$. Country's price levels are endogenous. To avoid omitted variables bias due to the non-linear multilateral resistance terms, equation (11) is estimated with importer and exporter fixed effects. From these considerations, the gravity equation in estimable form follows as

$$\ln X_{ij} = a + (1-\sigma)\varrho \ln d_{ij} + (1-\sigma)\delta \mathbf{Z}_{ij} + \nu_i + \mu_j + \epsilon_{ij}, \quad (12)$$

where $a \equiv -\ln Y^w$, $\nu_i \equiv (1-\sigma) \ln \left[\frac{b_i}{A_i} \left(\frac{e_i}{\beta_i} \right)^{\beta_i} \Pi_f \left(\frac{Y_i}{V_{if}} \right)^{\alpha_{if}} \right]$, $\mu_j \equiv \ln \frac{Y_j}{\sum_{k=1}^N \left[\frac{b_k}{A_k} \left(\frac{e_k}{\beta_k} \right)^{\beta_k} \Pi_f \left(\frac{Y_k}{V_{kf}} \right)^{\alpha_{kf}} \right]^{1-\sigma} \tau_{kj}^{1-\sigma}}$ and ϵ_{ij} is an i.i.d. measurement error term.

General equilibrium effects are absorbed by fixed effects. In other words, the gravity parameter estimates could arise from a large class of models (for example Anderson and van Wincoop, 2003; Eaton and Kortum, 2002; Feenstra, 2004). They provide general and GE-consistent estimates for trade cost parameters $\widehat{\tau_{ij}^{1-\sigma}} = d_{ij}^{(1-\sigma)\varrho} e^{(1-\sigma)\delta \mathbf{Z}_{ij}}$.

In the presence of heteroskedasticity, OLS leads to biased estimates of trade cost elasticity parameters in a log-linearized gravity equation (Santos Silva and Tenreyro, 2006). Poisson pseudo maximum likelihood (PPML) estimation is suggested to circumvent the problem. This method also cures the problem of zero trade flows and a possible sample selection bias due to log-linearization.¹² So we apply both OLS and PPML estimation. After comparing the R^2 and the model fit of predicted with actual data, we choose PPML as default method and provide results from OLS estimation in a sensitivity check.

Theoretically, σ could be estimated with energy price and wage data. But due to the importer and exporter fixed effects, the impact of country-specific variables cannot be identified in (12). Consequently, σ cannot be estimated directly with this empirical specification. However, Bergstrand et al. (2012) provide a methodology to isolate σ by using (11). The first step involves dividing X_{ij} by the trade flow of a reference country m to the same importer j to get rid of j -specific unobservables:

$$\frac{X_{ij}}{X_{mj}} = \frac{\left[\frac{b_i}{A_i} \left(\frac{e_i}{\beta_i} \right)^{\beta_i} \prod_f \left(\frac{Y_i}{V_{if}} \right)^{\alpha_{if}} \right]^{1-\sigma} \tau_{ij}^{1-\sigma}}{\left[\frac{b_m}{A_m} \left(\frac{e_m}{\beta_m} \right)^{\beta_m} \prod_f \left(\frac{Y_m}{V_{mf}} \right)^{\alpha_{mf}} \right]^{1-\sigma} \tau_{mj}^{1-\sigma}}. \quad (13)$$

We can use the estimated gravity parameters from (12) to predict $\widehat{\tau_{ij}^{1-\sigma}}$ and $\widehat{\tau_{mj}^{1-\sigma}}$, respectively. Using these predicted trade costs, we can use the model structure (3)-(5) to predict \hat{X}_{ij} and \hat{X}_{mj} , respectively. Assuming taste parameters are identical between country-specific varieties, $b_i = b_m$, we can solve (13) for σ :

$$\hat{\sigma} = 1 - \ln \left[\frac{\hat{X}_{ij} \widehat{\tau_{mj}^{1-\sigma}}}{\hat{X}_{mj} \widehat{\tau_{ij}^{1-\sigma}}} \right] / \ln \left[\frac{A_m}{A_i} \frac{(e_i/\beta_i)^{\beta_i}}{(e_m/\beta_m)^{\beta_m}} \prod_f \frac{(Y_i/V_{if})^{\alpha_{if}}}{(Y_m/V_{mf})^{\alpha_{mf}}} \right], \quad (14)$$

where Y_i and V_{if} are observed in the data and A_i is an estimate of total factor productivity. Using all combinations i, j and m ($m \neq i$) gives $N^2(N-1)$ estimates for σ . In our sample, the distribution of elasticities of substitution is skewed to the right. Therefore, we follow Bergstrand et al. (2012) and use the median value as summary statistic $\hat{\sigma}$.¹³ Standard errors for $\hat{\sigma}$ are

¹²In our sample, we observe zero trade flows in about 10% of the observations.

¹³We drop all estimates of $\hat{\sigma}_{imj} < 1$ since they would imply higher trade costs increase trade.

obtained from bootstrapping.¹⁴

2.3 Counterfactual analysis

With the observed parameters β_i and α_{if} and the estimated parameters $\widehat{\tau_{ij}^{1-\sigma}}$ and $\hat{\sigma}$, we can create counterfactual worlds. In this paper, we are interested in two types of policy experiments: climate policy and trade liberalization scenarios. First, we are interested in the effect of a stricter unilateral climate policy on trade flows and emissions with the ultimate aim to assess the extent of carbon leakage. We can manipulate implicit carbon prices e_i to simulate this type of policy experiment. Second, we study the effect of trade liberalization – say for example an FTA between the EU and the USA or the EU and China – when carbon prices differ across countries. This provides a perspective on environmental aspects of FTA formation. To simulate this type of policy experiment, we can manipulate \mathbf{Z}_{ij} to generate counterfactual trade costs.

Let superscript c denote a variable's counterfactual value. First, we reformulate the goods market clearing condition (2) using (1) and dividing both sides by $Y^{w,c}$

$$\theta_i^c - \psi_i^c \sum_{j=1}^N \widehat{\tau_{ij}^{1-\sigma}}^c \psi_j^c = 0, \quad (15)$$

where $\psi_i^c \equiv (b_i p_i^c)^{1-\sigma}$ are scaled equilibrium prices in the counterfactual. We will be able to describe counterfactual changes in all variables with changes in ψ_i . Counterfactual GDPs depend on equilibrium prices. Hence, counterfactual GDP shares in (15) are endogeneous.

Counterfactual GDP. From the production structure (8) using $E_i = \frac{\beta_i Y_i}{e_i}$ we can find an expression for GDP that only depends on equilibrium prices, observables, and estimated parameters:

$$Y_i = (p_i A_i)^{\frac{1}{(1-\beta_i)}} \left(\frac{\beta_i}{e_i} \right)^{\frac{\beta_i}{1-\beta_i}} \prod_f V_{if}^{\frac{\alpha_{if}}{1-\beta_i}}. \quad (16)$$

The counterfactual change in GDPs is

$$\frac{Y_i^c}{Y_i} = \left(\frac{p_i^c}{p_i} \right)^{\frac{1}{(1-\beta_i)}} \left(\frac{e_i}{e_i^c} \right)^{\frac{\beta_i}{1-\beta_i}} = \left(\frac{\psi_i^c}{\psi_i} \right)^{\frac{1}{(1-\beta_i)(1-\hat{\sigma})}} \left(\frac{e_i}{e_i^c} \right)^{\frac{\beta_i}{1-\beta_i}}. \quad (17)$$

¹⁴See for example Anderson and Yotov (2010) for bootstrapping in a similar context. First, we generate 250 bootstrapped gravity parameter estimates which are then used to calculate 250 sets of *imj*-specific elasticities of substitution and the according median $\hat{\sigma}_r$ for the r th replication. The standard error follows as $\text{se}_{\sigma} = \sqrt{\frac{\sum_{r=1}^{250} (\hat{\sigma}_r - \hat{\sigma})^2}{250}}$.

Solve (17) for Y_i^c and divide both side by $Y^{w,c} \equiv \sum_{k=1}^N Y_k^c$ to find the equilibrium condition for counterfactual GDP shares:

$$\theta_i^c \equiv \frac{Y_i^c}{\sum_{k=1}^N Y_k^c} = \frac{\left(\frac{\psi_i^c}{\psi_i}\right)^{\frac{1}{(1-\beta_i)(1-\bar{\sigma})}} \left(\frac{e_i}{e_i^c}\right)^{\frac{\beta_i}{1-\beta_i}} \theta_i}{\sum_{k=1}^N \left(\frac{\psi_k^c}{\psi_k}\right)^{\frac{1}{(1-\beta_k)(1-\bar{\sigma})}} \left(\frac{e_k}{e_k^c}\right)^{\frac{\beta_k}{1-\beta_k}} \theta_k}. \quad (18)$$

In the counterfactual equilibrium, equilibrium prices ψ_i^c and GDP shares θ_i^c for all countries i are simultaneously determined from equations (15) and (18). After a shock (for example to e_i or $\tau_{ij}^{1-\sigma}$), the system adjusts in a non-trivial way due to the non-linear structure of the problem. Counterfactual GDP, emissions and trade flows follow from counterfactual equilibrium prices and GDP shares. The US price index is chosen as numeraire, i.e. $P_{\text{USA}} = P_{\text{USA}}^c = 1$.¹⁵

A first interesting outcome variable is a country's real GDP Y_j/P_j . In trade liberalization scenarios we can interpret it as a measure of gains from trade. Counterfactual changes in real GDP depend on how multilateral resistance terms, i.e. countries' multilateral trade barriers, react to the policy shock. They can be expressed in terms of equilibrium prices ψ_i^c

$$P_j^c = \left[\sum_{i=1}^N \widehat{\tau_{ij}^{1-\sigma}}^c \psi_i^c \right]^{\frac{1}{1-\bar{\sigma}}}. \quad (19)$$

The percentage change in real GDP $\Delta \frac{Y_j}{P_j} \equiv \left(\frac{Y_j^c/P_j^c}{Y_j/P_j} - 1 \right) \cdot 100$ is given by

$$\Delta \frac{Y_j}{P_j} = \left[\left(\frac{\psi_i^c}{\psi_i} \right)^{\frac{1}{(1-\beta_i)(1-\bar{\sigma})}} \left(\frac{e_i}{e_i^c} \right)^{\frac{\beta_i}{1-\beta_i}} \left[\frac{\sum_{i=1}^N \widehat{\tau_{ij}^{1-\sigma}}^c \psi_i^c}{\sum_{i=1}^N \widehat{\tau_{ij}^{1-\sigma}} \psi_i} \right]^{\frac{1}{1-\bar{\sigma}}} - 1 \right] 100. \quad (20)$$

Real GDP adjusts because of market size effects and non-trivial adjustments in trade cost weighted equilibrium prices.

Counterfactual emissions. The focus of this paper lies on explaining how emissions shift across the globe in reaction to partial climate policy shocks. Counterfactual changes in emissions (in %) can be expressed as

$$\Delta E_i \equiv \left[\frac{E_i^c}{E_i} - 1 \right] 100 = \left[\left(\frac{\psi_i^c}{\psi_i} \right)^{\frac{1}{(1-\beta_i)(1-\bar{\sigma})}} \left(\frac{e_i}{e_i^c} \right)^{\frac{1}{1-\beta_i}} - 1 \right] 100. \quad (21)$$

From (21), we see that emissions are affected in two ways in counterfactual climate policy scenarios. First, all countries with a carbon price shock ($\frac{e_i}{e_i^c} \neq 1$) will directly experience emission

¹⁵The solution to the multilateral resistance terms in (7) adopts a particular normalization (Anderson and van Wincoop, 2003, footnote 12). Using the US price index as numeraire ensures the same normalization in benchmark and counterfactual scenario.

changes. A counterfactual increase in a country's carbon price is associated with a proportional emission reduction. Second, there is a general equilibrium effect via changes in equilibrium prices, i.e. a terms-of-trade effect. It affects all countries' emissions, whether they actively changed their climate policy or not. A priori, the direction and magnitude of this effect is not clear and heterogeneous across countries. In the case of trade liberalization scenarios, only the equilibrium price channel remains.

For the counterfactual climate policy scenarios, we would like to express the extent of emission relocation in a single number. A natural choice is the amount of emission increases in other countries divided by the emission savings in the country or region with a carbon price shock. Let $N_\ell \subset N$ denote the subsample of countries pursuing the partial climate policy initiative, for example the European Union. Emission savings in this region are $\sum_{i \in N_\ell} \Delta E_i / 100 \cdot E_i$. What about emission changes in other countries? In our model, higher carbon prices shrink the size of the world (in terms of nominal GDP) since they reduce the implicit world "endowment" with emissions. Hence, we probably observe emission savings in all countries after a partial climate policy initiative. But we want to focus on emission changes brought about by production relocation. So we assess the extent of emission relocation against a situation where the counterfactual world GDP is produced without production relocation, i.e. without GDP share changes. In a shrunken world with benchmark GDP shares and energy prices, a country's emissions are given by $\bar{E}_i = \frac{\sum_k Y_k^c}{Y^w} E_i$. From this alternative baseline, unilateral climate policy shifts GDP shares and consequently counterfactual emissions according to

$$\Delta \bar{E}_i \equiv \left[\frac{E_i^c}{\bar{E}_i} - 1 \right] 100 = \left[\frac{\theta_i^c}{\theta_i} \frac{e_i}{e_i^c} - 1 \right] 100. \quad (22)$$

In all countries $i \notin N_\ell$, there is no carbon price change. Consequently, emission increases induced by production relocation into these countries are given by $\sum_{i \notin N_\ell} (\frac{\theta_i^c}{\theta_i} - 1) \bar{E}_i$. Summarized in a single number, the emission relocation (in percent) is given by

$$L = \frac{\sum_{i \notin N_\ell} (\frac{\theta_i^c}{\theta_i} - 1) \bar{E}_i}{-\sum_{i \in N_\ell} \left[\left(\frac{\psi_i^c}{\psi_i} \right)^{\frac{1}{(1-\beta_i)(1-\sigma)}} \left(\frac{e_i}{e_i^c} \right)^{\frac{1}{1-\beta_i}} - 1 \right] E_i} 100. \quad (23)$$

This is a measure for terms-of-trade leakage. It is similar in spirit to carbon leakage measures. But in (23) only the emission increases in foreign due to market size effects are considered. Typical carbon leakage measures would have total emission changes in other regions in the numerator, i.e. $\sum_{i \notin N_\ell} \left[\left(\frac{\psi_i^c}{\psi_i} \right)^{\frac{1}{(1-\beta_i)(1-\sigma)}} \left(\frac{e_i}{e_i^c} \right)^{\frac{1}{1-\beta_i}} - 1 \right] E_i$. L does not take into account endogenous responses in other countries' carbon prices (i.e. supply-side leakage and free-riding) either. The extent of emission relocation can be broken down by country as well.

L depends, amongst others, on market size, equilibrium price, and carbon price changes as well as the elasticity of substitution and emission cost shares. The extent of emission relocation is non-trivial and depends on direct and general equilibrium effects. In particular, it depends on the strength of redistribution of GDP shares across the globe. These will be higher, the higher the elasticity of substitution.

As is standard in the literature, we can also distinguish a scale and a technique effect of climate policy or trade liberalization (see for example Grossman and Krueger, 1993; Copeland and Taylor, 2003).¹⁶ The total effect on emissions can be decomposed into a change of emission intensities (*technique effect*)

$$\Delta\eta_i = \left[\left(\frac{\psi_i^c}{\psi_i} \right)^{\frac{1}{1-\sigma}} \frac{e_i}{e_i^c} - 1 \right] 100, \quad (24)$$

and a change in the scale of production (*scale effect*)

$$\Delta q_i = \Delta Y_i - \Delta p_i. \quad (25)$$

That is $\Delta E_i = \Delta\eta_i + \Delta q_i$.

Counterfactual trade flows. The reaction of trade flows to carbon price and trade cost shocks depends on changes in bilateral relative to multilateral trade barriers as well as market size effects influence bilateral trade patterns:

$$\Delta X_{ij} = \left[\frac{\widehat{\tau_{ij}^{1-\sigma}}^c / (P_i^c P_j^c)^{1-\sigma}}{\widehat{\tau_{ij}^{1-\sigma}} / (P_i P_j)^{1-\sigma}} \frac{\theta_i^c \theta_j^c Y^{w,c}}{\theta_i \theta_j Y^w} - 1 \right] 100. \quad (26)$$

In climate policy scenarios, the evolution of relative trade barriers is shaped by GE-driven changes in trade cost incidences only. The market size effect is driven by GDP shares and changes in nominal world GDP.

To study trade creation and trade diversion, it will be convenient to study trade shares $\frac{X_{ij}}{Y_j}$, i.e. country j 's import value from exporter i as a fraction of its GDP. In climate policy scenarios, we expect that climate-active countries will increase their import shares from other regions. While their respective share in the other country's GDP will most likely fall. But it all depends on non-trivial changes in GDPs and price levels. Alternatively, we can express bilateral trade in embodied CO₂ associated with the respective trade flow instead of in dollar values. This informs about bilateral emission relocation. As with goods trade, let's express emission imports as a share of domestic emissions $\frac{\eta_i' X_{ij}}{E_j}$. The import share is evaluated with the

¹⁶Note that in a one sector world, there is no effect on the sectoral composition of output (*composition effect*).

exporter's emission intensity $\eta'_i \equiv E_i/Y_i$ taking into consideration that trade flows are given in dollar values. It may rise or fall in the counterfactual. Ultimately, it is an empirical question how emission imports change in a given policy experiment.

3 Empirical evidence

Before we turn to counterfactual simulation, we structurally estimate the model and assess how well it predicts the benchmark data. Section 3.1 describes the data. Section 3.2 presents results for our structural gravity parameter estimates obtained with the methodology laid down in section 2.2.

3.1 Data

We investigate a cross-section of country pairs in the year 2007. This choice is driven by data availability of a cross-section of carbon and energy prices for that year. Additionally, the financial crisis had not yet hit the world economy and 2007 also coincides with the last year before the first Kyoto commitment period. Data on bilateral exports in free-on-board values stem from the UN Comtrade database.¹⁷ Bilateral distance and dummies for contiguity and common language are obtained from the CEPII distance dataset generated by Mayer and Zignago (2011). Data on bilateral free trade agreements (FTA) stem from the WTO homepage.

The method to identify σ requires information on capital stocks, labor force and land endowments. Data on labor force, population and land endowments are taken from the UN World Development Indicators (WDI) 2011. The labor force series comprises the economically active population aged 15 and older. For land endowments, we use the land area series which measures surface area.¹⁸ A country's physical capital stock is computed with the perpetual inventory method.¹⁹ The necessary data on investment and GDP in constant PPP-adjusted dollars are taken from the Penn World Tables 7.0. It is not available for Azerbaijan, Estonia, Russia and Ukraine. Consequently, these countries cannot be included in the computation of $\hat{\sigma}$ and the correlation of baseline predictions with actual data. Yet, the counterfactual equilibrium does not depend on fixed endowments and TFP, see (18). A large sample containing all important

¹⁷The exports series originally includes re-exports. The data series is adjusted for re-exports with the re-exports data provided by UN Comtrade.

¹⁸Arable land is not available for all countries. Results are unaffected by using arable land instead.

¹⁹The respective STATA routine "stockcapit" is due to Amadou (2011).

countries and a realistic production structure are important to ensure a credible benchmark. So despite the missing capital stock data for four countries, the default is to work with four production factors and the full sample. In a robustness check, we use labor and energy as only production factors and compute the fit in the whole sample.

The computation of a country's total factor productivity (TFP or A_i) stems from the production structure.²⁰ Take logs on both sides of (8) and solve for $\ln A_i = \ln q_i - \beta_i \ln E_i + \sum_f \alpha_{if} \ln V_{if}$. The output quantity q_i is proxied by a country's real GDP per capita from the PWT 7.0. TFP of the USA is normalized to one.

Finally, implicit carbon prices are constructed from the Global Trade Analysis Project (GTAP) 8 database. For its base year 2007, GTAP 8 provides information on a country's firms' expenses on fuels, i.e. oil, gas, coal and petroleum products. Tax payments for energy use are a part of this. Implicitly, we can think of these expenses as costs of CO₂ emissions. GTAP also features information on firms' fuel usage (in million tons of oil equivalents, Mtoe) and CO₂ emissions (in Mt of CO₂). This allows us to construct a country's average implicit CO₂ price as the sum of firms' fuel expenses divided by the firms' CO₂ emissions.²¹ In a similar vein, we could also construct an average fuel price. GTAP also provides information on firms' tax payments for fuel use. This gives an indication of the climate policy induced part of implicit CO₂ prices.

Table 1 provides summary statistics. There are 9,446 country pairs or equivalently 103 countries in the dataset.²² Average bilateral exports amount to about one billion US-\$. A country pair's major economic centers on average lie about 7,000 kilometers apart. About 30% of the country pairs have signed a free trade agreement. Average industrial CO₂ emissions amount to 192 Mt of CO₂. The average physical capital stock amounts to 1,602 billion US-\$. The average country's labor force is about 27 million people and its land area amounts to 999,000 square kilometers. In terms of implicit carbon prices, we observe substantial variation in our data. The average price for one ton of CO₂ is 322 US-\$ with a standard deviation of 177 US-\$ per ton. With below 100 US-\$ per t of CO₂, Mongolia, South Africa and Kazakhstan have the lowest carbon prices followed by China with 102 US-\$ per t of CO₂. On the other end of the distribution are the Netherlands, Sweden and Singapore with carbon prices above 800 US-\$. The correlation between a country's carbon and fuel price is 60%, and highly significant. The

²⁰For a detailed methodological description see, for example, Benhabib and Spiegel (2005), Hall and Jones (1999) or Hall (1990).

²¹This is the average carbon price for a country's industry. Households' and governments' expenses for energy as well as their emissions are disregarded.

²²A country list is relegated to the Appendix.

Table 1: Summary statistics for year of 2007

Variable	Observations	Mean	Std. Dev.	Min	Max
<i>Bilateral variables</i>					
Exports, million US-\$	9,446	1,232	7,897	0	310,480
Distance, km	9,446	7,237	4,483	60	19,812
Contiguity	9,446	0.03	0.17	0.00	1.00
Common language	9,446	0.13	0.33	0.00	1.00
FTA	9,446	0.28	0.45	0.00	1.00
<i>Country-specific variables</i>					
GDP, billion US-\$	103	522	1,556	4	14,062
Emission, Mt of CO ₂	103	192	630	1	4,886
Labor force, thousands	103	27,086	88,607	172	771,079
Physical capital, billion US-\$	99	1,602	4,360	18	33,245
Land area, thousand km ²	103	999	2,434	0	16,378
Implicit CO ₂ price, US-\$ per t CO ₂	103	322	177	62	1,010
Implicit CO ₂ tax, US-\$ per t CO ₂	103	37	45	-19	179
<i>Technology parameters</i>					
TFP	103	0.38	0.36	0.02	2.18
β	103	0.12	0.07	0.02	0.47
α_{labor}	103	0.44	0.12	0.15	1.21
α_{capital}	103	0.42	0.10	0.20	0.88
α_{land}	103	0.02	0.02	0.00	0.09

Note: The table shows summary statistics of bilateral and country-specific gravity variables in the year 2007. The physical capital stock is given in PPP-adjusted 2005 constant US-\$. Other monetary variables are in current US-\$. TFP is total factor productivity relative to the USA.

less than perfect correlation could be due to differences in countries' fuel mixes. On average, a country's implicit carbon tax is 13 US-\$ per ton of CO₂. The highest carbon tax is found in the Netherlands and Sweden (179 and 171 US-\$ per ton, respectively). But some countries also subsidize energy use. Countries with very low carbon taxes are typically oil-exporting countries like Bahrain, Qatar, United Arab Emirates or Saudi Arabia.

Table 1 also shows technology parameters as observed in the data. Productivity differs between countries. TFP ranges from a minimum of 0.02 in Ethiopia to a maximum of 2.18 in

Luxembourg. An average TFP of 0.38 implies the average sample country is less productive than the US. The average β observed in our data is 0.116 with a standard deviation of 0.07. We observe heterogeneity in countries' firms' emission use. Figure 1 plots countries' implicit payments for CO₂ emission against GDP; for scaling reasons on a per capita basis. The gray line results from a simple OLS regression of emission payments on GDP. It represents the estimated average emission cost share $\hat{\beta} = 0.072$ (standard error of 0.006, $R^2 = 0.9$). Countries above the gray line have higher than average emission cost shares, and vice versa. Table 1 also provides the average cost share of labor (44%), capital (42%) and land (2%).²³ Together with the energy cost share of 7%, these cost shares add up to approximately one. The assumption of constant returns to scale seems adequate. Repeating the simple OLS regression of factor payments on GDP, we find estimated average cost shares $\hat{\alpha}_{\text{labor}} = 0.633$ (s.e. 0.034), $\hat{\alpha}_{\text{capital}} = 0.282$ (s.e. 0.024), and $\hat{\alpha}_{\text{land}} = 0.004$ (s.e. 0.001). These values seem plausible, too. For example, the TFP literature (Hall, 1990; Benhabib and Spiegel, 2005) typically works with labor and capital shares of two and one thirds, respectively.

3.2 Structural gravity parameter estimates

With this data, we now apply the method laid out in section 2.2 to structurally estimate the model parameters. Table 2 provides gravity estimates and the implied estimate for $\hat{\sigma}$ for OLS and PPML estimation. Table 2 also shows correlations of trade flows, GDPs and emissions predicted from the benchmark model with actual data.

First, the upper panel in Table 2 column (1) shows gravity parameters from an OLS estimation of (12) with importer and exporter fixed effects. The parameter estimates of all trade cost proxies are sensible and highly statistically significant. Bilateral distance affects trade flows negatively. A shared border, a common language and a bilateral FTA on the other hand increase bilateral trade flows. With OLS, we are able to explain roughly 80% of the variation in bilateral trade flows.

Second, the estimated $\hat{\sigma}$ is 4.801 with a bootstrapped standard error of 0.031. Last, once we have solved the benchmark model for equilibrium scaled prices we can test how well the model predicts actual GDPs, CO₂ emissions and trade flows. The correlation of predicted with actual GDPs is 0.967 and highly statistically significant. The match between predicted and actual

²³The maximum observed cost share of labor is 1.21 in Belarus. Note that this must be a measurement error. Without Belarus, the maximum cost share of labor is 0.67, the average cost share of capital is 0.68. The averages are unaffected by excluding Belarus though.

Table 2: Estimation results

	OLS	PPML
<i>Gravity estimates</i>		
$(1 - \sigma)\varrho$	-1.311*** (0.036)	-0.626*** (0.036)
$(1 - \sigma)\delta_{\text{FTA}}$	0.436*** (0.058)	0.478*** (0.068)
$(1 - \sigma)\delta_{\text{Contiguity}}$	0.867*** (0.135)	0.439*** (0.077)
$(1 - \sigma)\delta_{\text{Common language}}$	0.932*** (0.072)	0.307*** (0.079)
Observations	9,446	10,506
R^2	0.782	0.881
F-statistic	165.079	
Log-likelihood		-5,714
<i>Parameter estimates</i>		
$\hat{\sigma}$	4.801 (0.031)	5.259 (0.048)
<i>Correlation baseline predictions with actual data</i>		
X_{ij}	0.697***	0.798***
Y_i	0.967***	0.972***
E_i	0.967***	0.960***

Note: OLS and Poisson pseudo maximum likelihood (PPML) gravity estimation includes exporter and importer fixed effects and constant (not shown). Heteroskedasticity-robust standard errors in parentheses. $\hat{\sigma}$ from Bergstrand et al. (2012) methodology, see Section 2.2. Technology assumptions: all four production factors with country-specific factor cost shares and TFP differences. Standard errors for $\hat{\sigma}$ obtained via bootstrapping. The lower part of the table shows correlations of the actual data with model predictions in the baseline. *, **, *** denotes statistical significance at the 10, 5 and 1% level, respectively.

emission levels is high, too. The correlation is 0.967. Ultimately, the correlation of predicted and actual trade flows is 0.697. This is comparable in size with the baseline correlations found in Bergstrand et al. (2012). In summary, the model is fairly successful in predicting actual data.

Column (2) presents the corresponding results from PPML estimation. First, all trade cost elasticities are highly significant. They differ from the respective OLS estimates, as is typical

(see for example Santos Silva and Tenreyro, 2006). Taking into account zero trade flows raises the explanatory power of the model to roughly 90%. Second, the estimated $\hat{\sigma}$ is 5.259 with a bootstrapped standard error of 0.048. It is significantly higher than the estimate obtained from OLS estimation – but in the same order of magnitude. Last, the correlation of model prediction and actual data is again very high. Correlation of both GDP and emissions is comparable to the OLS case. However, in terms of trade flows the model prediction with PPML-estimated trade costs and elasticity of substitution achieves a higher correlation of 80% with the actual data. Consequently, we choose PPML estimation and the ensuing parameter estimates as default.

We experiment with technology assumptions and the data used. Since technology is absorbed by importer and exporter fixed effects gravity estimates are unaffected. Table 3 presents the implications for the estimated elasticity of substitution in column (1) and the baseline model fit in columns (3)-(5). The first row replicates the default, i.e. four production factors and country-specific factor cost shares, for ease of comparison. Disregarding country heterogeneity in factor use leads to a lower correlation of predicted with actual data. Using labor and emissions as only production factors gives a comparable $\hat{\sigma}$. It leads to a lower correlation of predicted with actual data for GDPs and trade flows, though. If we use fuel prices and energy use instead of implicit CO₂ prices and emissions we again get results very similar to the default. Given that the implicit CO₂ price takes into account energy use and is not just based on emission taxation this is not surprising. With population instead of labor force in the calculation of σ the estimated elasticity of substitution is 4.855.

In summary, the default we choose is most successful in replicating the baseline scenario. Acknowledging country-specific factor use is important. The error from using labor and emissions only and disregarding capital and land seems minor. The finding of a σ in the order of magnitude of 5 is fairly robust.

The elasticity of substitution is a key parameter in international trade. Numerous studies provide an estimate. Anderson and van Wincoop (2003) assume $\sigma = 5$ in their benchmark, and consider a range of 2 to 10 as plausible. More recently, Feenstra et al. (2012) use a nested CES utility function and distinguish the Armington elasticity between domestic and imported varieties on the upper tier and imported varieties from different countries of origin on the lower tier. They find an elasticity of 3.1 between foreign varieties, while their estimates indicate a low substitutability between domestic and foreign goods i.e. an upper tier elasticity close to one. Bergstrand et al. (2012) uncover a $\hat{\sigma}$ of about 7 with their proposed method. They investigate the Canada-US border puzzle (where productivity differences might be minor) and labor is the only production factor. Given that our model relaxes the assumption of one production factor

Table 3: Elasticity of substitution, technology and data fit

	(1)	(2)	(3)	(4)	(5)
	Estimates		Correlation prediction with data		
	$\hat{\sigma}$	\hat{se}_{σ}	X_{ij}	Y_i	E_i
<i>PPML estimation</i>					
Default	5.259	(0.048)	0.798***	0.972***	0.960***
Average factor cost shares	5.259	(0.048)	0.619***	0.890***	0.971***
Labor and emission only	5.110	(0.048)	0.660***	0.916***	0.976***
Labor, emission only + avg. shares	5.159	(0.071)	0.613***	0.887***	0.970***
Fuel ^a	5.215	(0.065)	0.788***	0.981***	0.970***
Population ^b	4.855	(0.028)	0.784***	0.978***	0.967***
<i>OLS estimation</i>					
Average factor cost shares	4.801	(0.031)	0.501***	0.892***	0.972***
Labor only	4.746	(0.027)	0.527***	0.918***	0.974***
Labor only + avg. cost shares	4.743	(0.035)	0.497***	0.891***	0.970***
Fuel ^a	4.893	(0.052)	0.680***	0.979***	0.977***

Note: Elasticity of substitution $\hat{\sigma}$ estimated with Bergstrand et al. (2012) methodology based on gravity estimates from PPML and OLS estimation, respectively, as in Table 2. Standard errors for $\hat{\sigma}$ in column (2) obtained via bootstrapping. ^a Energy prices and energy use to compute $\hat{\sigma}$ and correlation. ^b Population instead of labor force. *, **, *** denotes statistical significance at the 10, 5 and 1% level, respectively.

and allows for TFP differences across countries it is no surprise that our estimate differs from their result.

Concluding, in our structural gravity model important model parameters are consistently estimated from the data. The estimated value of $\hat{\sigma} = 5.259$ lies well within the range of typical estimates. The model is fairly successful in replicating the baseline. It provides a benchmark against which to evaluate counterfactual scenarios.

4 Counterfactual climate and trade policy scenarios

We now conduct two types of policy experiments and evaluate their effects on GDPs, trade, emission and emission relocation. First, we develop climate policy scenarios. For example, we ask which ETS permit price would bring the EU in line with its Kyoto target of an emission

reduction of 8%. What fraction of emission savings relocates to non-EU countries? And how heterogeneous is carbon leakage across countries? The same policy experiment is repeated for emission targets promised for the second commitment period under the Kyoto Protocol.

A second set of policy experiments deals with the effect of trade liberalization on trade and emissions. More specifically, we want to shed light on environmental aspects of FTA formation. Recently, a discussion on a transatlantic FTA between the EU and the US has come up. We study effects on trade and emissions of this hypothetical FTA.

4.1 Counterfactual increase in the EU's emission allowance price

Under the Kyoto Protocol, the 27 European Union countries have promised a reduction of their GHG emissions by 8% on average in the period 2008-2012 compared to the base year 1990. To reach this goal, the EU's ETS has been in place since 2005. Via national allocation plans, each country is assigned a specific emission target. Subsequently emission certificates can be traded to ensure cost-minimizing emission reductions, e.g. on the European Climate Exchange in London or the European Energy Exchange in Leipzig. This implies there is one uniform EU emission allowance (EUA) permit price.

However, in 2007 the EUA permit price fell to almost zero.²⁴ At the same time, the EU's emissions still stood above 92% of the 1990 CO₂ emission level. Taking GTAP data to be model-consistent²⁵, the required emission reduction amounts to 131.8 Mt of CO₂. To reach its Kyoto target, the EU has to reduce its emission allowances. Or equivalently increase its carbon price via an increase in the EUA permit price; we simulate such a policy experiment. We add a uniform counterfactual EUA permit price to each EU country's implicit carbon price. The analysis focuses on emission effects, but also touches implications for trade shares and real GDP.

Let's start with the default modeling assumptions, i.e. country-specific factor cost shares, PPML estimation of trade costs and an estimated $\hat{\sigma} = 5.259$. Our model simulation predicts that an EUA permit price of 15 US-\$ will suffice to bring the EU approximately on track. This reduces nominal world GDP by about 0.01% because the world "emission endowment" has shrunk. Column (1) in Table 4 shows the corresponding EU emission savings of about 131.4 Mt of CO₂. Without production relocation the world emission savings could have been larger, though. Some emission migrates to other countries. The predicted emission relocation

²⁴See, EUA spot price data provided by the European Energy Exchange on www.eex.com.

²⁵In GTAP, EU emissions total 4,033 Mt of CO₂ (of which 3,109 Mt stem from domestic firms' emissions). The official UNFCCC data report 4,420 Mt of CO₂. So the GTAP data is approximately 5% below this level.

amounts to 10.0%.

Table 4: Key statistics ETS scenarios

	(1)	(2)	(3)	(4)	(5)
	Default	Sensitivity analysis			
Assumptions:		OLS	Avg. cost shares	Labor + emission	Fuel ^a
Δ EUA price (in US-\$ per t of CO ₂)	15	15	15	15	26
$\hat{\sigma}$	5.259	4.801	5.259	5.110	5.215
Emission saving (in Mt of CO ₂)	131.4	131.4	128.6	131.3	131.8
Emission relocation (in %)	10.0	10.1	9.0	10.0	10.9

Note: The table shows the assumed carbon price increase, estimated $\hat{\sigma}$ as well as counterfactual EU emission savings and emission relocation for the policy experiment of increasing the EUA price. Column (1) shows the default scenario. Columns (2)-(5) show the same statistics for sensitivity checks varying underlying assumptions. ^a In the fuel scenario the price increase is like an energy tax, given in US-\$ per toe.

These aggregate numbers mask considerable country heterogeneity. Starting with EU countries, we look at effects on their emissions, trade shares and real GDP. The results are summarized in Table 5. Then we turn to non-EU countries.

The average EU country's industrial emission falls by roughly 5%²⁶, but the effect ranges from -1.91% in Sweden to -12.08% in Estonia. First and foremost, this is explained by a *technique effect*, i.e. a reduction in EU countries emission intensities. Heterogeneity in the technique effect results from heterogeneity in the initial implicit carbon price across the EU since the counterfactual price increase is additive. For countries like Sweden and the Netherlands, with high CO₂ prices of 824 and 835 US-\$ per t CO₂, respectively, an extra charge of 15 US-\$ per ton matters relatively little. Consequently, the adjustment in their emission intensity is comparably small. On the other hand, for countries with relatively low initial implicit carbon prices like Estonia (120 US-\$ per t CO₂) the relative CO₂ price increase is large; and thus the technique effect. A small fraction of total emission reductions is explained by a *scale effect*, i.e. a reduction of the output level.

²⁶The emission change is measured against domestic firms' emissions, not against a country's total emissions. Households' CO₂ emissions from consumption activities like heating or car driving are not factored in.

Table 5: Heterogeneity of country effects for EUA permit price increase

Country	Emission effects			Trade share with non-EU countries				Real GDP
	Total	Tech- nique	Scale	Goods		Emissions		
				Import	Export	Import	Export	
	ΔE_i	$\Delta \eta_i$	Δq_i					$\Delta \frac{Y_i}{P_i}$
Estonia	-12.08	-10.87	-1.28	0.04	-1.00	12.43	-1.10	-1.06
Poland	-8.52	-7.69	-0.87	0.22	-0.61	8.55	-0.67	-0.86
Czech Republic	-8.32	-7.49	-0.86	0.27	-0.60	8.41	-0.67	-0.90
Slovenia	-8.20	-7.81	-0.41	0.16	-0.23	9.06	-0.31	-0.42
Bulgaria	-7.79	-6.07	-1.78	0.17	-1.37	6.88	-1.43	-1.57
Latvia	-6.84	-6.38	-0.47	-0.01	-0.29	7.02	-0.35	-0.31
Cyprus	-6.41	-5.52	-0.91	0.33	-0.67	5.85	-0.70	-1.02
Malta	-6.13	-5.34	-0.81	0.09	-0.56	5.91	-0.62	-0.69
Romania	-5.68	-5.14	-0.55	0.29	-0.35	5.68	-0.40	-0.67
Ireland	-5.58	-5.35	-0.23	-0.01	-0.09	5.88	-0.14	-0.11
Greece	-5.32	-4.29	-1.05	0.13	-0.73	5.10	-0.77	-0.90
Luxembourg	-4.93	-4.62	-0.32	0.08	-0.15	5.29	-0.20	-0.26
Denmark	-4.64	-4.34	-0.30	0.03	-0.14	4.74	-0.18	-0.20
Spain	-4.10	-3.79	-0.32	0.18	-0.16	4.19	-0.19	-0.36
Hungary	-3.69	-3.23	-0.47	-0.04	-0.27	3.59	-0.30	-0.26
Portugal	-3.59	-3.24	-0.36	0.10	-0.19	3.53	-0.21	-0.31
Slovak Republic	-3.56	-3.07	-0.50	0.19	-0.29	3.29	-0.31	-0.51
Germany	-3.48	-3.22	-0.25	0.10	-0.10	3.52	-0.12	-0.23
Finland	-3.35	-2.99	-0.37	0.09	-0.20	3.27	-0.23	-0.32
United Kingdom	-3.24	-3.04	-0.20	0.07	-0.07	3.38	-0.09	-0.17
Italy	-3.24	-2.99	-0.25	-0.06	-0.10	3.26	-0.12	-0.07
France	-2.77	-2.60	-0.18	0.27	-0.04	2.90	-0.06	-0.34
Austria	-2.75	-2.58	-0.17	0.21	-0.02	2.70	-0.04	-0.26
Lithuania	-2.74	-2.30	-0.44	0.13	-0.26	2.55	-0.27	-0.41
Belgium	-2.32	-2.02	-0.30	0.04	-0.14	2.22	-0.15	-0.21
Netherlands	-1.96	-1.74	-0.21	0.16	-0.06	1.54	-0.07	-0.26
Sweden	-1.91	-1.78	-0.13	-0.00	-0.01	1.81	-0.02	-0.04
EU average	-4.93	-4.43	-0.52	0.12	-0.32	4.91	-0.36	-0.47

Note: The policy experiment is an EUA permit price increase of 15 US-\$. The table shows percentage changes of the respective variables. Index $i \in \text{EU}$ refers to the respective EU country. For trade effects, $j \notin \text{EU}$ indexes non-EU countries.

Next, we investigate trade effects. Carbon leakage is observed when a unilateral strengthening of climate policy in one region results in production relocation and increased imports from other countries. Indeed, most EU countries increase imports (measured as a share of domestic GDP) from an average non-EU country. On average, the import share goes up by 0.12%, with large heterogeneity across the EU. And these average effects on countries' trade shares mask heterogeneity at the country-pair level. In general, import shares increase most from countries in close proximity to the EU. Such as, for example, Albania, Croatia, Turkey, Switzerland, Tunisia, Norway, Morocco or Russia. At the same time, the average EU country's share of exports in foreign GDP drops by roughly -0.32%. Least affected are Sweden (-0.01%) and Austria (-0.02%); whereas Bulgaria's (-1.37%) and Estonia's (-1.00%) export shares drop most. Distance also affects the change in bilateral export shares. They fall most with respect to countries like Brazil, Mexico and the USA. We will come back to this when discussing effects on non-EU countries' trade.

By looking at emission trade shares, we can investigate bilateral emission relocation. Due to trade, the CO₂ emitted during the production of the traded good flows virtually, i.e. embodied in the traded good, from the exporter to the importer. In all EU countries, emission imports as a share of domestic emissions go up; by between 1.8 and 12.4%. On the other hand, emission exports as a share of foreign emissions go down. That implies EU countries' net emission imports rise in our policy experiment. This supports the finding of emission relocation on the aggregate level.

Last, nominal GDP falls in all EU countries while the price levels increase. This results in an unambiguous reduction of real GDP of about -0.47% on average.²⁷ The country-specific real GDP changes display heterogeneity. Small EU and predominantly Eastern European countries like Bulgaria, Estonia, Poland and the Czech Republic are among the biggest losers.

In non-EU countries, emissions fall as well. By 0.009% on average, see Table 6. This mirrors the reduction in nominal world GDP. There are regional disparities though, driven by proximity to the EU. For ease of presentation, Table 6 summarizes average changes in percent by continent. Emission reductions are strongest in non-EU European countries and Africa. But production relocation leads to emission increases in non-EU countries, see column (2) in Table 6. Figure 2

²⁷Real GDP is a measure for welfare in the standard gravity literature without emissions. With CO₂ emissions, there is an additional welfare channel. Emission reductions on the world level will positively influence welfare everywhere. The magnitude of the effect depends on a damage function, typically in additive form. How this damage function looks like is an open issue.

Table 6: Region-specific effects in non-EU countries for EUA permit price increase

	(1)	(2)	(3)	(4)	(5)
Region	Emission	Emission relocation effects			Real GDP
		Total	Technique	Scale	
	ΔE_i	$\Delta \bar{E}_i$	$\Delta \eta_i$	$\Delta \theta_i - \Delta p_i$	$\Delta \frac{Y_i}{P_i}$
North America	-0.004	0.081	-0.004	0.085	0.135
Oceania	-0.005	0.080	-0.005	0.085	-0.110
South America	-0.006	0.079	-0.005	0.084	-0.023
Asia	-0.007	0.078	-0.006	0.083	0.009
Africa	-0.010	0.075	-0.009	0.084	-0.047
Non-EU Europe	-0.020	0.065	-0.016	0.080	-0.018
Average	-0.009	0.076	-0.008	0.084	-0.014

Note: The table shows regional average changes in respective variables (in %) for the policy experiment of a 15 US-\$ EUA permit price increase. Emission relocation effects refer to emission changes from a benchmark without emission relocation. According to theory, technique and scale effect add up to the total effect.

illustrates the country-specific heterogeneity in a world map. Emission relocation is a result of general equilibrium effects only. The magnitude is small and ranges from an increase of 0.058% in Albania to an increase of 0.082% in Canada. This implies country size matters a lot for absolute emission relocation, i.e. in tons of CO₂. About 30 and 24% of the aggregate emission relocation effect of 10.0% is attributable to emission increases in the US and China, respectively. India, Russia, Japan and Canada also contribute between 7 and 2%. The emission relocation effect is made up of a negative technique effect and a positive market size effect, see columns (3) and (4), respectively. All non-EU countries slightly reduce their emission intensity because equilibrium scaled prices fall. The positive scale effect reflects gains in GDP shares in most non-EU countries. In terms of real GDP, North America and Asia profit from the EUA permit price increase (relative to the US). However, with the policy experiment at hand real GDP on average falls in non-EU countries.

Furthermore, Table 7 shows heterogeneity in trade effects distinguished by continent and with respect to EU and non-EU trade partners. The share of exports to EU countries rises most in Africa and non-EU Europe. The share of EU imports falls most in North America and Asia. We also observe trade creation between non-EU countries. [Talk about emission imports]

So far, we focus on the effects of an EUA permit price of 15-US\$ because it corresponds

Table 7: Heterogeneity of trade effects in non-EU countries

Region	(1)	(2)	(3)	(4)
	Goods trade share		Emission trade share	
	Import	Export	Import	Export
<i>Trade with EU countries</i>				
Africa	-0.28	0.13	-0.36	4.83
Asia	-0.35	0.11	-0.37	4.85
Non-EU Europe	-0.29	0.15	-0.25	4.92
North America	-0.48	0.10	-0.42	4.89
Oceania	-0.24	0.11	-0.33	4.90
South America	-0.31	0.11	-0.37	4.74
<i>Trade with non-EU countries</i>				
Africa	0.10	0.06	0.06	0.07
Asia	0.03	0.05	0.04	0.05
Non-EU Europe	0.07	0.09	0.18	0.09
North America	-0.10	0.04	0.00	0.04
Oceania	0.14	0.04	0.09	0.05
South America	0.05	0.04	0.04	0.05

Note: The table shows changes in trade shares (in %) with EU and non-EU countries distinguished by continent.

nicely to the EU's Kyoto target. Nevertheless, we briefly discuss emission savings and implied emission relocation rates for a realistic range of EUA permit prices of 1-50 US-\$. EU emission savings appear to be approximately linear in the permit price, see the upper part of Figure 3. A 1 US-\$ increase in the permit price brings about 7.8 Mt of CO₂ emission savings. On the other hand, the lower part of Figure 3 shows that the extent of emission relocation also increases with the EUA permit price. A 50 US-\$ increase is associated with 1 percentage points higher emission relocation. The leakage problem is more severe, the more stringent climate policy gets.

Sensitivity analysis. Table 4, columns (2)-(5) provide sensitivity checks. We vary the gravity estimation procedure and the technology assumptions. To save space, the focus is on EU emission savings and emission relocation in the aggregate. In column (2), gravity parameters are estimated with OLS. The EUA permit price of 15 US-\$ per ton of CO₂ leads to virtually

the same EU emission savings and emission relocation. This is true on the aggregate level, but also the predicted country-specific effects are very much in line (compare for example Table 14 in Appendix 5). Predicted percentage emission increases in other countries are slightly larger (compare Figure 9 in Appendix 5) but the correlation between the predictions is 1.000 and highly statistically significant. Column (3) assumes average instead of country-specific factor cost shares. Implied emission savings drop to 128.6 Mt of CO₂. And the predicted emission relocation is 9.0% only. The heterogeneity of country-specific effects is also diminished, see Figure 4. So, disregarding country-specific factor intensities leads to an underestimation of leakage. If we use parameter estimates obtained from a model with labor and emissions as only production factors, emission relocation again is about 10.0%. Since emission relocation in the counterfactual does not depend on other production factors, see equation (23), this difference is attributable to a lower estimated $\hat{\sigma}$ only. Last, we analyze fuel prices instead of carbon prices. This requires a slight variation of the policy experiment because the policy variable is a country's energy price. An energy tax increase of about 26 US-\$ per toe would bring the EU on track. The predicted leakage rate is 10.9% and slightly higher than in the default. [This is explained by the less than perfect correlation between implicit carbon and energy prices. So relative price increases differ, and thus reactions.]

Summarizing, results are robust to the estimation technique chosen. However, the modeling of country-specific production features like country-specific factor cost shares matters. And the employed elasticity of substitution affects results as well. Figure 5 illustrates this point. It shows the extent of emission relocation plotted against elasticities of substitution in the range of 1 to 11. The function approximately grows logarithmically in σ . This implies results are very sensitive with respect to σ , especially for low levels of the parameter. Employing an elasticity of substitution informed by the data is crucial to get a reliable prediction of the extent of emission relocation. It is one of the major advantages of the structural gravity approach applied in this paper.

In conclusion, the EU ETS is a viable tool to help the European Union bring down its carbon emissions. An ETS price of around 15 US-\$ will suffice to bring the EU on track for its Kyoto target. However, one has to take this with a pinch of salt. Without trade, world emission savings could have been larger. The analysis shows that due to production relocation there is an emission increase in non-EU countries in the order of magnitude of around 10% of EU emission savings. This effect is non-negligible. Trade undermines the environmental effectiveness of the hypothetical increase in the EUA permit prices.

4.2 Other climate policy scenarios

The extent of emission relocation depends, amongst others, on a country's or region's climate policy stringency, the carbon price increase and the proximity to other trade partners. To conclude the section on climate policy scenarios, we briefly describe effects of policy experiments in other regions; with a focus on Kyoto II but also touching climate policy in the US, Canada and China. To save space the analysis focuses on the extent of emission relocation and applies the default method only.

The Kyoto Protocol is the first international treaty establishing country-specific emission limits. On the Conference of Parties in Doha in December 2012, the Kyoto Protocol has been prolonged for a second period from 2013-2020. In the following, we will refer to this second period as Kyoto II. Table 8 summarizes the promised emission reduction targets for Kyoto II, as well as the implied emission reductions requirements as of 2007. Kyoto II puts an emission cap on about 15% of world GHG emissions.²⁸ Kazakhstan, Belarus and Ukraine are already in line with their Kyoto II targets. This is explained by the choice of base year and massive emission reductions in the wake of industrial restructuring in these countries in the 1990s (*hot air*). However, compared to the benchmark year of our analysis the Kyoto II region has to reduce its CO₂ emissions by 490.2 Mt of CO₂ in total.

To simulate the Kyoto II policy experiment, we add a uniform carbon tax to the implicit carbon price in all Kyoto II countries.²⁹ In other words, we assume that the flexible mechanism Emission Trading aligns the climate policy price premium on CO₂ emissions in Kyoto II countries. The carbon tax is set at 39.1 US-\$ per ton of CO₂ because it ensures the required emission savings, compare Table 9. World nominal GDP falls by 0.2%. Our model predicts emission relocation of 8.0%. This is smaller than the leakage rate predicted for the EU ETS scenario. This seems sensible. Kyoto II applies to a larger region. Possibilities to shift production away are more limited. Thus, less of the achieved emission savings leak away.

Table 10 summarizes emission, trade and real GDP effects in Kyoto II and non-Kyoto II countries. Real GDP falls almost everywhere except in North America. The relative emission reduction in Kyoto II countries ranges from -6% in Croatia to -32% in Kazakhstan. The average emission reduction in the European Union is 11%. Due to its mere size, 315.6 Mt of CO₂ or

²⁸Note that Japan, Russia and Canada had emission caps for the first Kyoto period from 2008-2012 but have not committed to emission reductions under Kyoto II.

²⁹The exception being Iceland because it is not in the dataset; and New Zealand because it has not yet committed to a Kyoto II target.

Table 8: Kyoto II targets and emission saving requirements

	(1)	(2)	(3)
Country	Required CO2 savings		Target as of base year
Reference year:	2007		1990 ^a
	(in %)	(in Mt of CO2)	(in %)
Norway	35.7	23.8	-16
Croatia	25.7	5.8	-20
European Union	15.9	640.8	-20
Switzerland	14.4	6.3	-15.8
Australia	13.2	50.4	-2
Kazakhstan	-23.5	-45.9	-5
Belarus	-56.7	-30.9	-12
Ukraine	-60.5	-159.9	-24
Total	-9.7	490.2	

Note: The Table shows region-specific CO₂ emission saving requirements for Kyoto II between 2013-2020. Column (3) shows the promised target as specified in the Addendum to the Kyoto Protocol. Columns (1) and (2) show relative and absolute emission savings compared to 2007. Regions are sorted in descending order of the relative required emission reduction. New Zealand is a Kyoto II country but has not yet specified a target. Iceland is a Kyoto II country but not part of the dataset. ^a The Australian base year is 2000.

Table 9: Key statistics other climate policy scenarios

	(1)	(2)	(3)	(4)
Scenario:	Kyoto II	US Kyoto target	Canadian Kyoto target	China
Carbon tax (in US-\$ per t of CO ₂)	39.1	105.5	139.0	108.7
Emission saving (in Mt of CO ₂)	490.1	1,256.8	155.5	2,744.9
Emission relocation (in %)	8.0	7.1	9.9	3.2

Note: The table shows the carbon price increase assumed in the respective policy experiment, counterfactual emission savings for the respective region as well as emission relocation. Analysis based on default method, i.e. PPML and $\hat{\sigma} = 5.259$.

about 64% of the total emission reduction takes place in the EU. Within the Kyoto II countries, emission certificate trade will take place. Ukraine, Kazakhstan, Belarus and Australia generate

Table 10: Country effects for Kyoto II experiment

Country	Emission effects				Import shares ^a		Real
	Total		Technique	Scale	Goods	Emissions	GDP
	ΔE_i	$\Delta \bar{E}_i$	$\Delta \eta_i$	Δq_i	$\Delta \frac{X_{ji}}{Y_i}$	$\Delta \frac{\eta'_j X_{ji}}{E_i}$	$\Delta \frac{Y_i}{P_i}$
<i>Kyoto II countries</i>							
Kazakhstan	-32.267	-31.955	-28.334	-4.674	0.145	41.550	-4.413
Australia	-21.517	-21.223	-20.431	-1.220	0.317	26.482	-1.191
Ukraine	-19.815	-19.496	-14.181	-6.093	0.244	18.744	-5.305
Belarus	-12.375	-12.105	-7.065	-5.511	0.342	9.142	-4.723
European Union	-11.519	-11.242	-10.426	-1.172	0.359	12.645	-1.126
Switzerland	-9.265	-8.996	-9.047	-0.229	0.359	10.241	-0.326
Norway	-7.827	-7.557	-7.229	-0.621	0.204	8.159	-0.503
Croatia	-6.142	-5.856	-4.800	-1.376	0.315	5.883	-1.197
<i>Non-Kyoto II countries</i>							
North America	-0.016	0.258	-0.014	0.274	-1.223	-1.228	0.125
South America	-0.021	0.252	-0.019	0.272	-0.968	-1.088	-0.042
Asia	-0.033	0.241	-0.028	0.267	-1.020	-1.120	-0.035
Africa	-0.036	0.238	-0.033	0.272	-0.898	-1.042	-0.089
Oceania	-0.041	0.233	-0.039	0.273	-0.730	-1.057	-0.299
Europe	-0.069	0.205	-0.058	0.263	-0.697	-0.946	-0.247

Note: The table shows percentage changes of emissions, trade shares and real GDP for the policy experiment Kyoto II. ^a For Kyoto II countries import shares refer to imports from non-Kyoto II countries. For non-Kyoto II countries import shares refer to imports from Kyoto II countries.

more emission savings than they require. These countries will sell certificates to the EU, Norway, Switzerland and Croatia.³⁰ Emission relocation leads to emission increases in non-Kyoto II countries. Again, we see that proximity to the climate-active region matters. The additional emissions in other European countries is smallest.

Kyoto II countries increase their share in non-Kyoto II imports. Compared to their domestic emissions, Kyoto II countries now import more emissions from non-Kyoto II countries. The

³⁰This also implies negative real GDP effects for these countries are exaggerated because they receive additional income from international permit sales.

emission import share increases by 13.4% on average. On the other hand, they export less to non-Kyoto II countries, see the respective import shares of non-Kyoto II regions. Additionally, trade diversion leads to increased trade between non-Kyoto II countries (not shown).

The US is one of the world's largest CO₂ emitters with a comparatively low implicit carbon price of about 240 US-\$ per t of CO₂. There have been discussions about possible US climate policy initiatives like the Waxman-Markey bill in recent years. In this light, it is interesting to simulate US climate policy efforts. Let's take the hypothetical US Kyoto target as a reference point.³¹ The US emission savings required to meet this target would be huge: 1,255 Mt of CO₂ or 22% of the US firms' emissions in 2007. A carbon price of 105.5 US-\$ would suffice to achieve this goal, see column (1) Table 9. The simulated emission relocation rate is 7.1%.

Canadian CO₂ emissions have increased quite substantially over the last two decades. Emission savings fall short of the -6% Kyoto target by 155 Mt of CO₂ or 28% of Canadian firms' emissions. Our findings imply that an extra charge of about 139 US-\$ would bring Canada in line with its Kyoto promise. A price increase of almost 50%. Not so surprisingly, Canada withdrew from the Kyoto Protocol in 2011. Column (2) in Table 9 shows the resulting emission relocation amounts to 9.9%.

Until now, all policy experiments dealt with carbon price increases in industrialized countries. We find that a doubling of the Chinese implicit carbon price to, for example, the Indonesian level³² of 211\$ per t of CO₂ would amount to no more than 2.8% leakage. Similarly, a 1% increase in the Chinese implicit carbon price would lead to 2.3% emission relocation only.

Summarizing, a first insight from our counterfactual climate policy simulations is that carbon leakage is moderate but non-negligible. In various climate policy experiments we found emission relocation rates between 2 and 10%. The order of magnitude is in line with most CGE findings. As a regularity, large countries attract most of the emission relocation; and more so if their implicit carbon price is low. Relative emission increases are smallest in countries close to the climate-active region. [They are hampered most by the reduction of demand of trade partners.] However, if climate policy would take place in countries with very small initial carbon prices, leakage seems rather small.

³¹The US is an Annex B country under the Kyoto Protocol and would thus have an emission reduction target of 7% compared to 1990. However, it never ratified the treaty.

³²This is also in the neighborhood of the Mexican, US, Bulgarian or Ukrainian level.

4.3 Trade liberalization and emissions

With our framework, we can also study how trade liberalization affects trade and emissions. Globalization critics argue that trade liberalization could be bad for the environment when dirty production moves to countries with lax environmental regulation, i.e. these countries become *pollution havens*. Even though our model only features one sector of production, we might still learn how carbon price differentials shape countries' emissions and trade shares in trade liberalization scenarios.³³ We perform three counterfactual experiments. First, starting from a counterfactual without any free trade agreements, we introduce FTAs as observed in 2007. Second, we introduce a hypothetical FTA between EU countries and the USA. Third, we discuss the formation of a hypothetical free trade agreement between EU countries and China. These policy experiments deliver a perspective on environmental aspects of FTA formation. We apply the default method in all scenarios.

Effect of FTAs as observed in 2007. Regional trade integration is a defining feature of the organization of world trade. In 2007, an average sample country was in an FTA with roughly one quarter of all other sample countries. To evaluate the effects of regional trade liberalization on emissions and trade, we create a counterfactual world without free trade agreements and compare it to our benchmark.

Due to the regional reduction of trade barriers with FTA formation, nominal world GDP rises by 1.9%. There is substantial heterogeneity in the gains from trade across continents, see column (4) in the upper panel of Table 11. Real GDP increases most in North America and Europe. Canada and Chile benefit most from FTA formation with a real GDP increase of about 16%. But in some African countries like Ethiopia, Madagascar or Senegal, we even predict falling real GDPs.

Table 11 also shows average percentage increases in regional CO₂ emissions. Heterogeneous changes in world market shares explain the heterogeneity in emission increases across countries. This is displayed in a world map in Figure 6. But even though some countries lose world market shares, the overall increase in world demand overcompensates this negative effect and leads to emission increases in all but a few countries.³⁴ Again, we can decompose the total effect on emissions in a scale and a technique effect. While energy supply is elastic, other factors are in

³³The previous section focused on the extent of emission relocation closely linked to carbon leakage. In this Section, we hold climate policy and carbon prices constant, i.e. there is no leakage.

³⁴Without carbon price changes $\Delta E_i = \Delta Y_i = \Delta \theta_i + \Delta Y^w$.

Table 11: Region-specific average emission and real GDP changes (in %)

Region	Emission effects			Real
	Total	Technique	Scale	GDP
<i>Policy experiment: From no FTAs to FTAs as observed in 2007</i>				
North America	4.75	4.39	0.33	10.06
Europe	3.87	3.43	0.42	7.95
South America	2.87	2.54	0.31	5.81
Asia	2.07	1.73	0.32	3.91
Africa	1.00	0.86	0.12	1.78
Oceania	0.93	0.88	0.05	1.71
<i>Policy experiment: EU-USA FTA</i>				
EU	1.91	1.70	0.20	1.83
USA	1.90	1.77	0.13	2.18
Asia	1.05	0.88	0.17	-0.05
Non-EU Europe	0.96	0.74	0.23	-0.31
Oceania	0.89	0.85	0.05	-0.36
South America	0.87	0.78	0.09	-0.38
Africa	0.86	0.79	0.07	-0.39
North America	0.60	0.56	0.04	-0.83
<i>Policy experiment: EU-China FTA</i>				
China	1.23	1.06	0.18	2.53
EU	0.25	0.22	0.03	0.58
North America	-0.04	-0.04	-0.00	0.10
South America	-0.06	-0.05	-0.01	-0.09
Oceania	-0.07	-0.06	-0.00	-0.20
Africa	-0.09	-0.08	-0.01	-0.18
Non-EU Europe	-0.13	-0.11	-0.03	-0.20
Asia	-0.14	-0.12	-0.02	-0.22

Note: The table shows region-specific changes in emissions and real GDP (in %) from various trade liberalization scenarios.

fixed endowment. This leads to an increase in emission intensity in all regions. The scale effect is largest in Europe. Here, output growth contributes most to emission increases.

Table 12: Trade share changes (in %) from FTAs as observed in 2007

from/to	Africa	Asia	Europe	North America	Oceania	South America
Africa	19.79	-0.26	-9.90	-14.37	-6.42	-1.27
Asia	1.15	2.39	-16.23	-13.96	-5.92	-2.32
Europe	-7.92	-14.91	10.48	-17.41	-15.76	-19.32
North America	-11.55	-12.57	-17.15	10.31	-8.83	-4.62
Oceania	-5.76	-6.77	-17.96	-11.12	50.95	-12.36
South America	-0.46	-3.23	-20.26	-5.83	-10.85	6.22

Note: The table shows counterfactual percentage changes in trade shares, i.e. $\Delta \frac{X_{ij}}{Y_j}$ where j is the importer and $i \neq j$, from a counterfactual switch of a world without FTAs to one with FTAs as observed in 2007.

Finally, the model predicts trade creation and trade diversion. The bilateral import share of countries signing an FTA goes up by 21.5% on average. Whereas the bilateral import share of countries not in an FTA drops by 15.5%. So trade is diverted away towards country pairs engaging in bilateral trade liberalization. Since FTA formation predominantly takes place within continents, we observe an increase in within-continent trade shares (compare Table 12). On the other hand, trade between continents is reduced in relative terms.

In summary, FTA formation generates gains from trade. But it also generates increases in emissions. These are larger for small countries and concentrate in regions with a lot of regional trade liberalization.

EU-USA free trade agreement. The formation of a transatlantic free trade agreement between the EU and the US is a realistic policy scenario. At the moment, the European Union is assessing effects of such an FTA. Carbon prices between the EU and the US differ substantially.³⁵ Therefore, the question of its environmental effects merits discussion.

The formation of an EU-USA FTA increases nominal world GDP by 1.5%. Our model predicts gains from trade of 2.18% for the US, and 1.83% for an average EU country. Within

³⁵ Compared to most EU countries, the US has a relatively low implicit CO₂ price of 238\$ per t of CO₂. The price is lower in some Eastern European countries (Estonia, Slovenia, Poland, Czech Republic, Latvia and Bulgaria). However, the GDP-weighted EU carbon price is 484\$ per ton of CO₂, i.e. more than double the US price. The simple average still is 400\$ per t of CO₂.

the EU, small countries benefit more in terms of real GDP than, e.g., France or Germany. Canada is amongst the biggest losers of such an FTA. Its real GDP falls by almost 1.4%. The model predicts emission increases in most countries. Figure 7 shows emission increases are larger for countries farther away from the EU or the US. This could be explained by trade creation. Table 13 shows trade shares of the US in EU GDP and of the EU in the US GDP go up. But also non-members start to trade more amongst each other; at the cost of trade shares with the EU and US. The extent of trade diversion is largest within other North American countries.

EU-China free trade agreement. Last, we briefly discuss emission effects of trade liberalization between the EU and China. While the differences in carbon prices are large between EU countries and the US, they are even more pronounced between the EU and China. In our data, the implicit Chinese CO₂ price is about 100\$ per t of CO₂ only.

With an EU-China free trade agreement, nominal world GDP rises by 0.16%. China benefits most from the opening up of the EU Single Market for Chinese products. Its gains from trade amount to 2.53% of real GDP. EU countries also experience a small increase of real GDP of 0.58% on average. Emission increases are quite substantial in China, 1.23%; while moderate in the EU. They range from 0.07% in the Netherlands to 0.47% in Cyprus. Unlike in the EU-USA FTA scenario, emissions actually go down in other regions. Emissions (and GDP) fall most in other European and other Asian countries. The negative effect of the EU-China FTA on other regions' world market share is not overcompensated by the increase in world GDP. Figure 8 visualizes country-specific heterogeneity in emission effects in a world map. The predicted trade creation and trade diversion effects are as expected and heterogeneous across regions.

The most striking difference between the EU-USA and EU-China FTA policy experiment is certainly the predicted emission outcome. While the emission increase is quite similar in the US and the EU in the former experiment, the latter experiment predicts a huge relative increase in Chinese emissions. Even though our model only features one sector, which effectively shuts down the composition effect of sectoral specialization, China attracts a lot of emission with trade liberalization. This is in line with the pollution haven hypothesis.

5 Conclusions

This paper is the first to quantify emission relocation effects of partial climate policy with a structural gravity model. This approach has two major advantages. First, important model parameters like bilateral trade costs and elasticity of substitution are structurally linked to em-

Table 13: Trade share changes (in %) from EU-USA and EU-China FTA

<i>Policy experiment: EU-USA FTA</i>								
from/to	EU	USA	Africa	Asia	Non-EU Europe	North America	Oceania	South America
EU	-6.62	49.74	-1.93	-2.42	-1.68	-0.84	-2.17	-1.86
USA	50.14	-7.38	-2.28	-2.77	-2.03	-1.18	-2.50	-2.22
Africa	-2.96	-3.57	1.87	1.34	2.14	3.04	1.63	1.90
Asia	-3.23	-3.82	1.58	1.07	1.85	2.74	1.37	1.58
Non-EU Europe	-2.58	-3.17	2.28	1.76	2.55	3.49	2.04	2.29
North America	-2.04	-2.63	2.89	2.35	3.12	4.06	2.62	2.92
Oceania	-3.24	-3.83	1.60	1.09	1.86	2.74	1.32	1.65
South America	-2.89	-3.49	1.90	1.40	2.20	3.10	1.72	2.01
<i>Policy experiment: EU-China FTA</i>								
from/to	EU	China	Africa	Asia	Non-EU Europe	North America	Oceania	South America
EU	-2.31	50.83	-0.67	-0.51	-0.58	-1.08	-0.70	-0.83
China	52.13	-9.98	-4.12	-3.97	-4.03	-4.52	-4.15	-4.29
Africa	-1.03	-5.29	0.62	0.77	0.70	0.21	0.58	0.45
Asia	-0.87	-5.14	0.78	0.95	0.88	0.37	0.75	0.62
Non-EU Europe	-0.94	-5.20	0.72	0.87	0.81	0.31	0.67	0.53
North America	-1.23	-5.48	0.43	0.58	0.52	0.05	0.39	0.24
Oceania	-1.12	-5.37	0.54	0.70	0.63	0.12	0.46	0.36
South America	-1.15	-5.42	0.50	0.63	0.58	0.07	0.46	0.31

Note: The table shows counterfactual percentage changes in trade shares, i.e. $\Delta \frac{X_{ij}}{Y_j}$ where j is the importer, from two policy experiments: a hypothetical EU-USA free trade agreement and a EU-China FTA, respectively.

pirical estimates. Second, previous empirical studies confirm that carbon leakage is empirically relevant. But they are not able to quantify carbon leakage in general equilibrium. Country-specific reactions to climate policy are absorbed in importer and exporter fixed effects in the empirical gravity estimation. A structural gravity model takes these general equilibrium effects via GDPs and price levels into account and enables quantification of leakage.

We find moderate leakage rates in the range of 2-10% depending on the size of the climate-

active region. An EUA permit price of 15 US-\$ allows the EU to fulfill its Kyoto target. EU countries increase their import shares from non-EU countries. The induced emission relocation amounts to 10%. The counterfactual emission increase through production relocation in non-EU countries is heterogeneous and governed by proximity to the EU, country size, and relative carbon prices. Results are robust to the econometric estimation procedure chosen. Not accounting for country-specific heterogeneity in factor use leads to a slight underestimation of the extent of leakage. Emission limitations as negotiated for the second period of the Kyoto Protocol lead to 8% of emission relocation. This leakage rate is smaller than in the ETS scenario because with Kyoto II a larger part of the world is constrained.

Carbon leakage has important implications for the design of a future climate policy architecture. Since the predicted leakage is moderate but non-negligible, it is even more important to strive for the first best: a global climate deal. Policy efforts should be directed in this direction. If this is politically not feasible, partial climate deals could be designed such that leakage is prevented. The literature discusses several options. Climate policy could target footprints, i.e. the GHG embodied in consumption, instead of domestic emissions (see proposals in Bastianoni et al., 2004; Eder and Narodoslawsky, 1999; Peters, 2008). But this system requires a lot of information about a good's emission intensity and production chain. It might be hard to administer. Equivalently, a domestic CO₂ tax could be accompanied by carbon-related border tax adjustments for imports and tax exemptions for exports. But the conformity of such measures with rules of the World Trade Organization is an open issue and depends on their exact design (see the discussions in Bhagwati and Mavroidis, 2007; Ismer and Neuhoﬀ, 2007; Goh, 2004; Sindico, 2008).

Some limitations of our policy experiment simulations merit discussion. First, we look at emissions as input directly. In reality, climate policy often does not impose a single carbon price but affects different energy inputs differently. We abstract from fuel substitution in our study. Second, we assume a regionally disintegrated energy market with horizontal energy supply. Consequently, emissions react very flexibly to carbon price changes. Supply-side carbon leakage is ruled out by assumption. A model with vertical energy supply has a leakage rate of 100%. Still, it might be interesting to study production relocation. Third, our analysis focuses on aggregate output. Sectoral adjustments in production are disregarded. However, due to sectoral differences in energy intensity, degree of product differentiation and trade costs one expects heterogeneous relocation and trade responses at the sectoral level. This is an avenue for future research. Last, the estimated emission relocation effects do not factor in emissions at upstream parts of the production chain. There are no intermediate inputs. And free-riding and

supply-side leakage are ruled out. Thus, the predicted leakage rates might be interpreted as a lower bound of the true effect.

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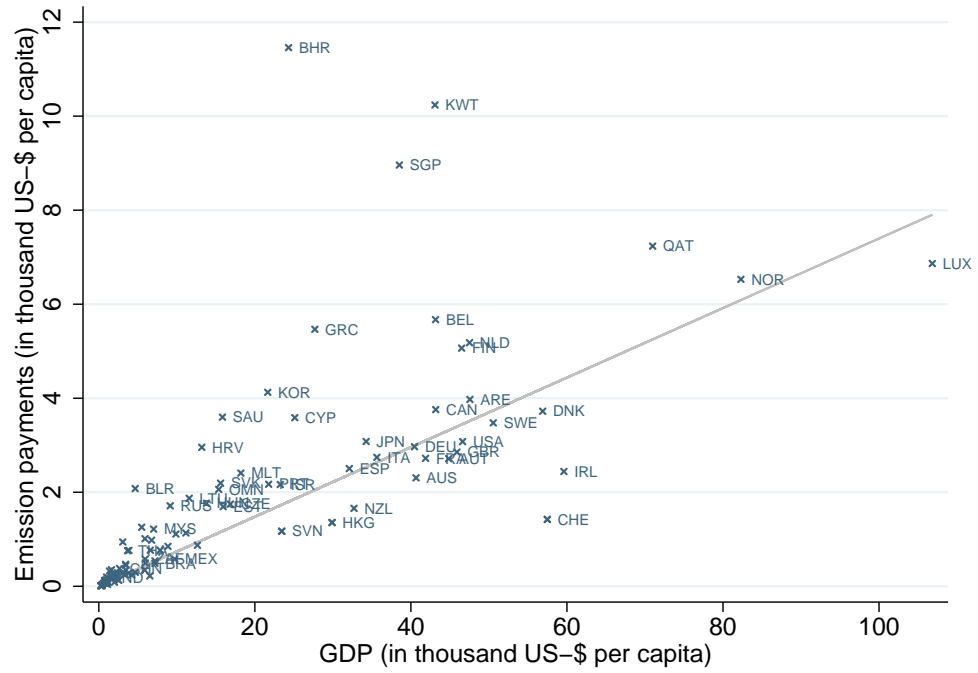
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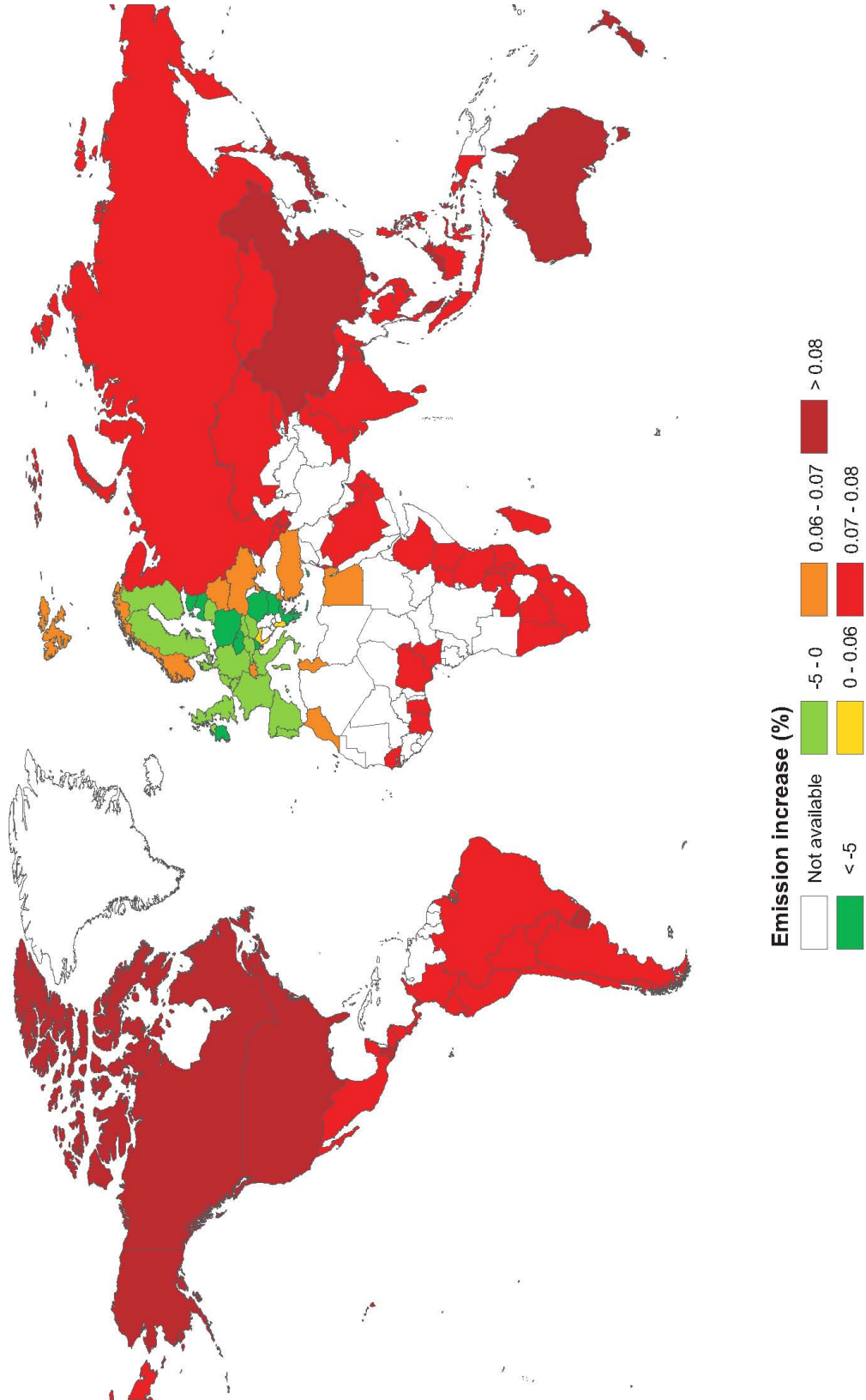
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Figure 1: Implicit payments for emissions and GDP



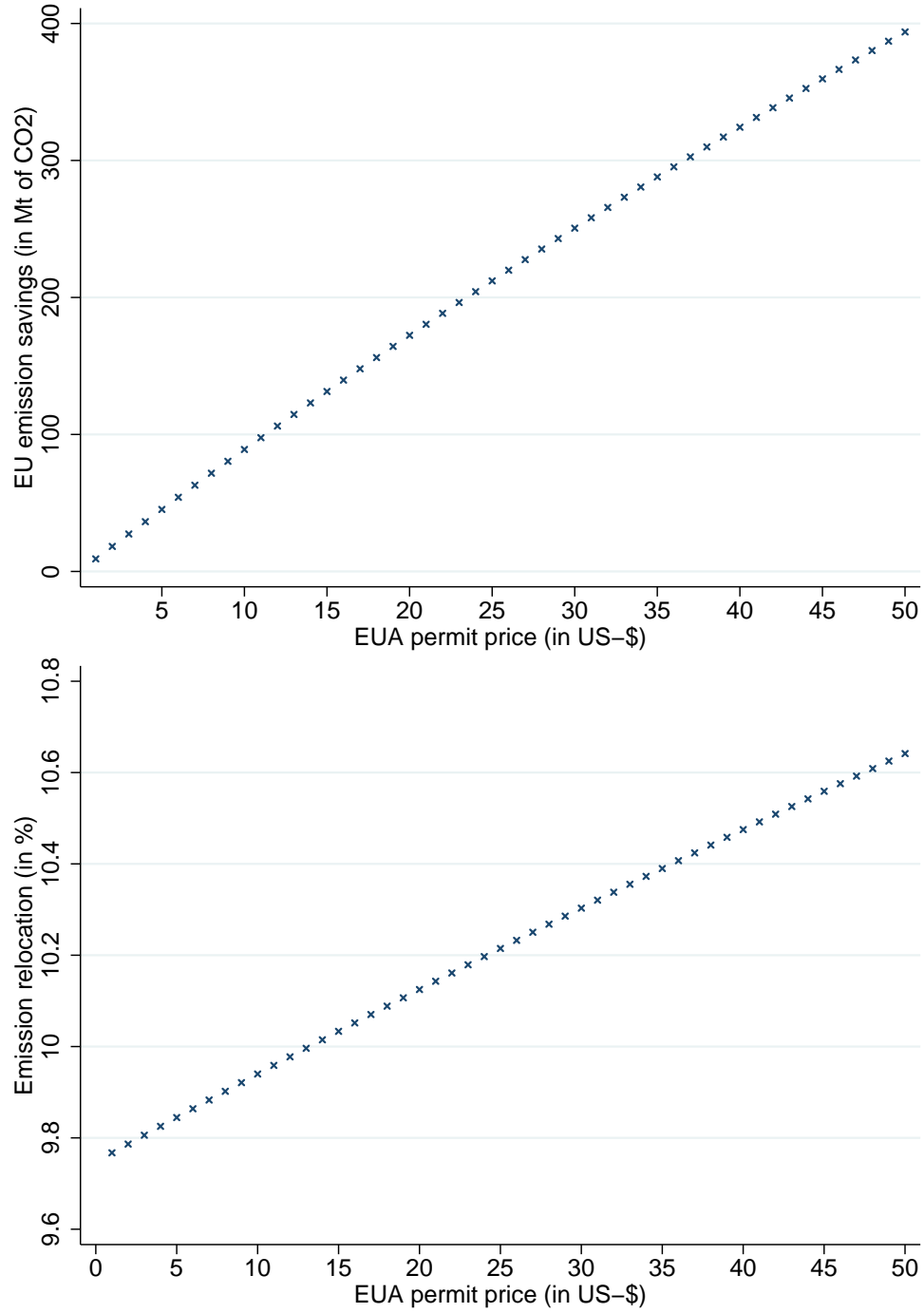
Note: The graph shows countries' per-capita implicit emission payments and GDPs. The gray line results from a simple OLS regression of emission payments on GDP, the slope coefficient is the average $\hat{\beta} = 0.072$, robust standard error of 0.006. Countries above the gray line have higher than average emission cost shares, and vice versa.

Figure 2: Country-specific emission increase from EUA permit price increase



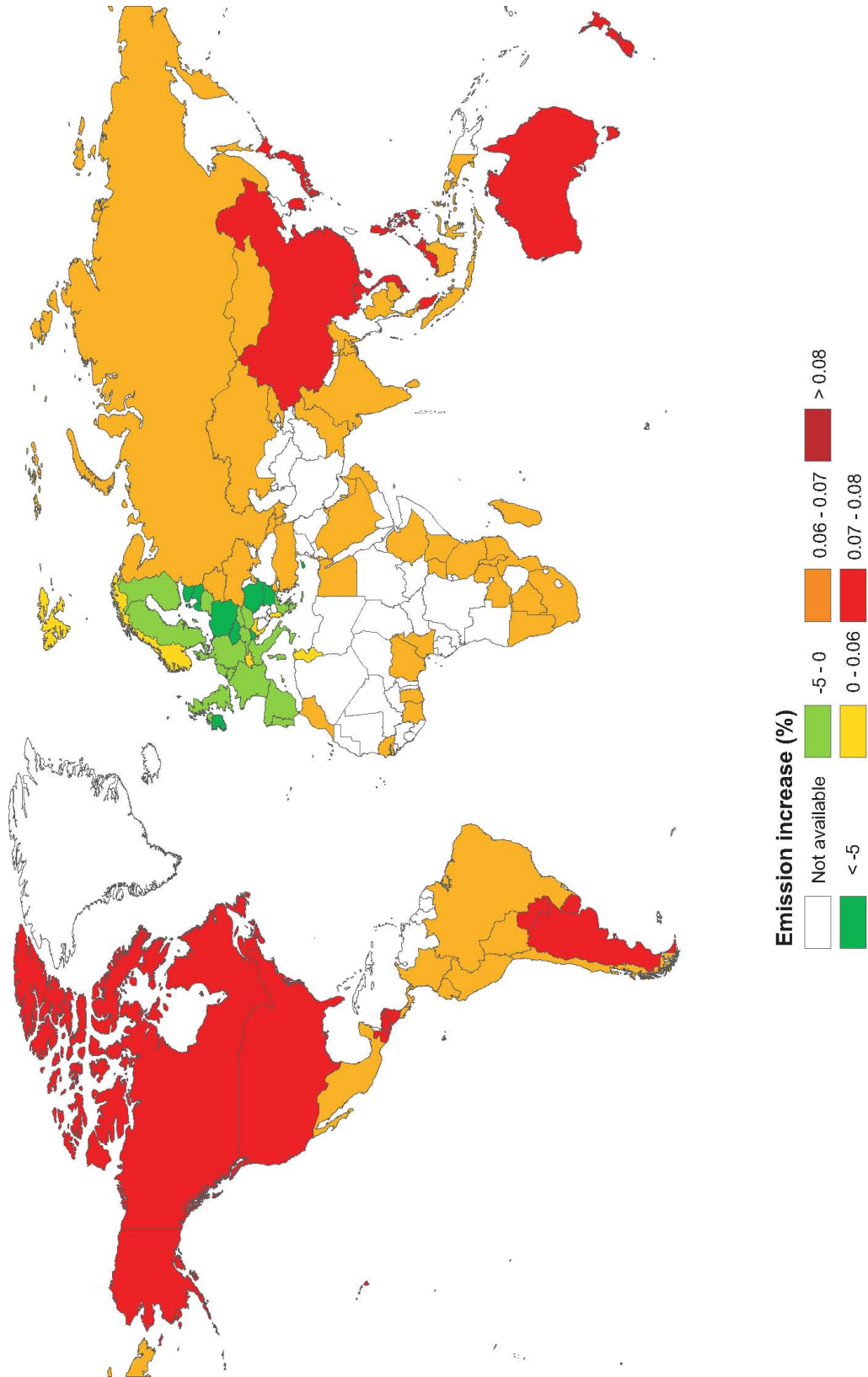
Note: The graph shows countries' emission increase (in %) due to emission relocation, i.e. $\Delta \bar{E}_i$, resulting from an EUA permit price increase of 15 US-\$ using the default method; i.e. PPML estimation and $\hat{\sigma} = 5.259$.

Figure 3: Emission savings, emission relocation and ETS permit price



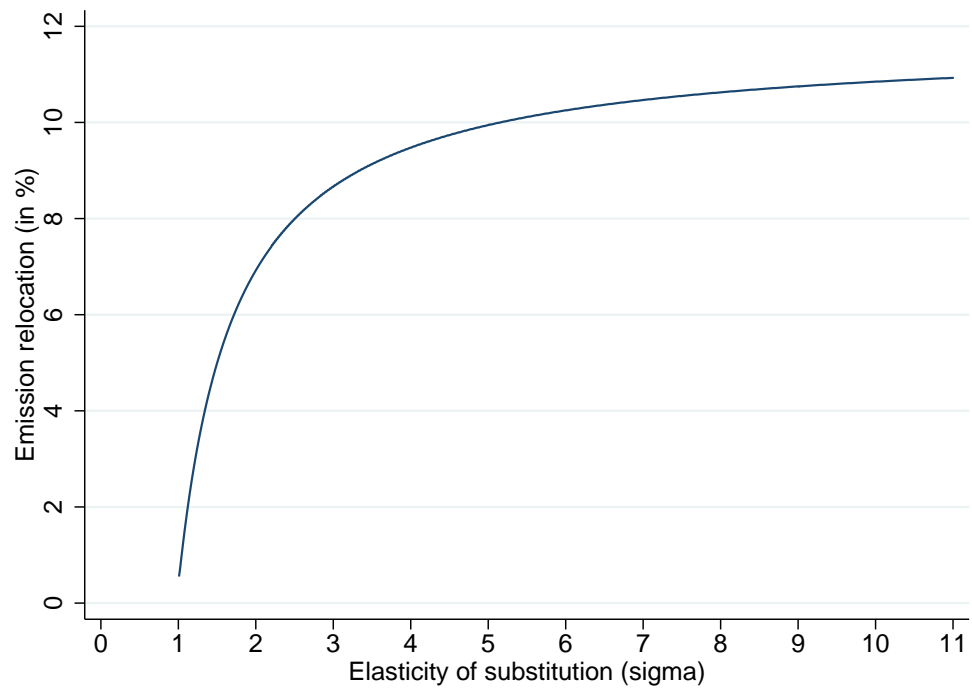
Note: The upper part of the graph shows EU emission savings, the lower part the extent of emission relocation depending on the ETS price. The calculation assumes the default elasticity of substitution of $\hat{\sigma} = 5.259$.

Figure 4: Country-specific emission increase from EUA permit price increase with average factor cost shares



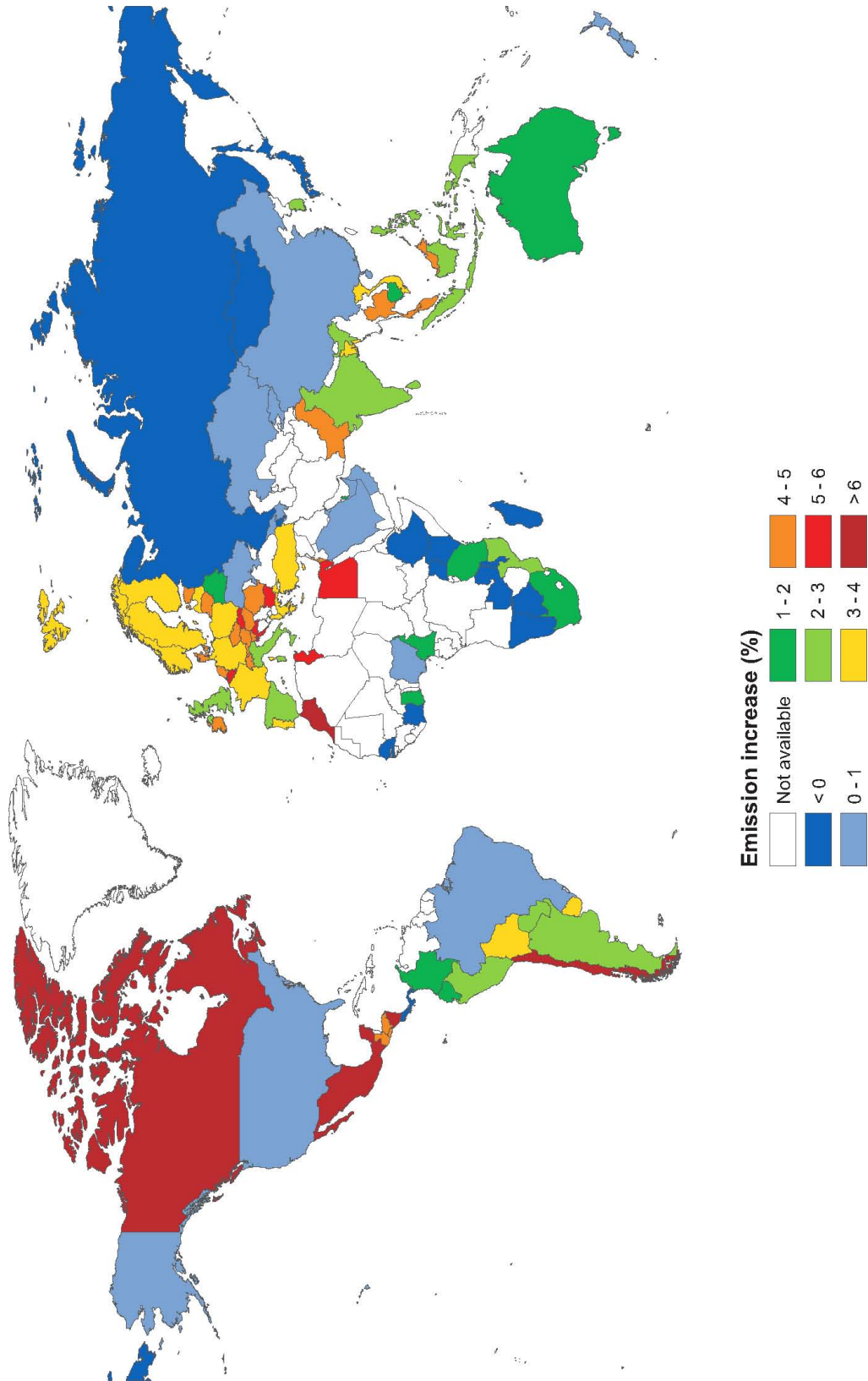
Note: The graph shows countries' emission increase (in %) due to emission relocation, i.e. $\Delta \bar{E}_i$, resulting from an EUA permit price increase of 15 US-\$ using PPML estimation and $\hat{\sigma} = 5.259$ but average factor cost shares.

Figure 5: Emission relocation and elasticity of substitution of ETS price of 15 US-\$



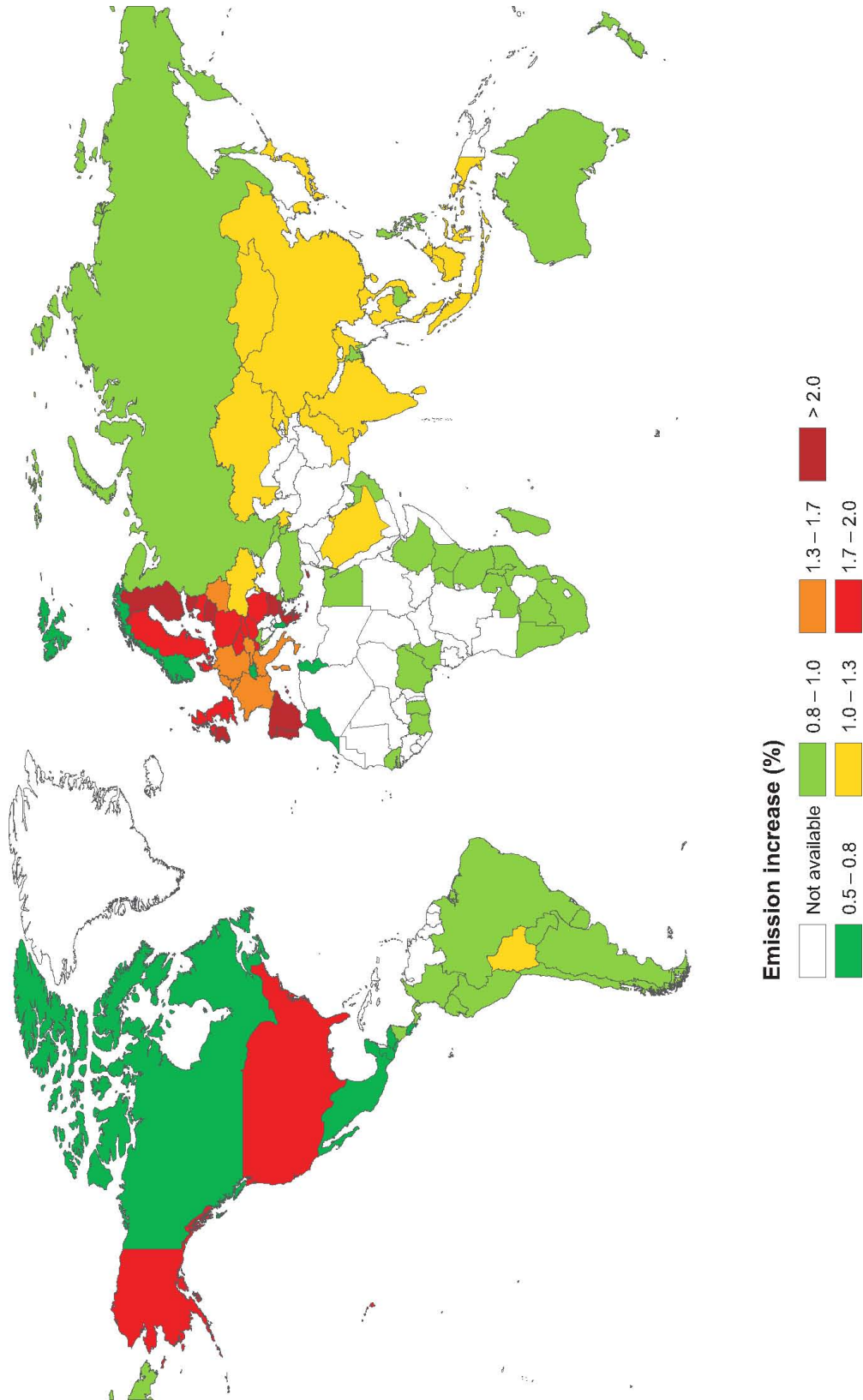
Note: The graph shows the extent of carbon leakage depending on the elasticity of substitution (σ) for an ETS price of 15 US-\$.

Figure 6: Country-specific emission increase from FTAs as of 2007 compared to no FTAs



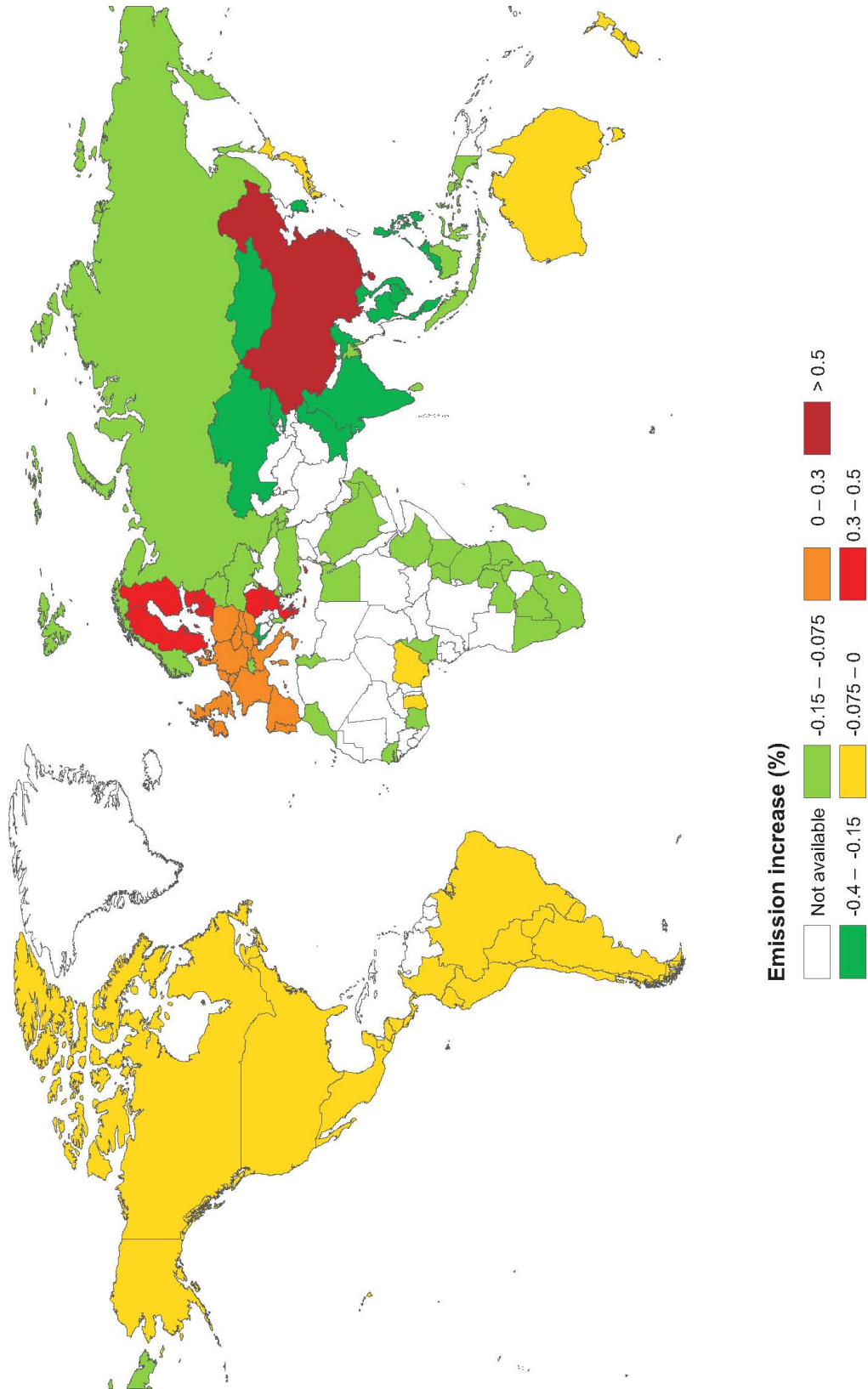
Note: The graph visualizes country-specific emission increases (in %) due to the policy experiment of a counterfactual switch of a world without FTAs to one with FTAs as observed in 2007 using the default method; i.e. PPML estimation and $\hat{\sigma} = 5.259$.

Figure 7: Country-specific emission increase from EU-USA free trade agreement



Note: The graph visualizes country-specific emission increases (in %) due to the policy experiment of introducing a transatlantic FTA using the default method; i.e. PPML estimation and $\hat{\sigma} = 5.259$.

Figure 8: Country-specific emission increase from EU-China free trade agreement



Note: The graph visualizes country-specific emission increases (in %) due to the policy experiment of introducing an FTA between the EU and China using the default method; i.e. PPML estimation and $\hat{\sigma} = 5.259$.

Appendix

Data

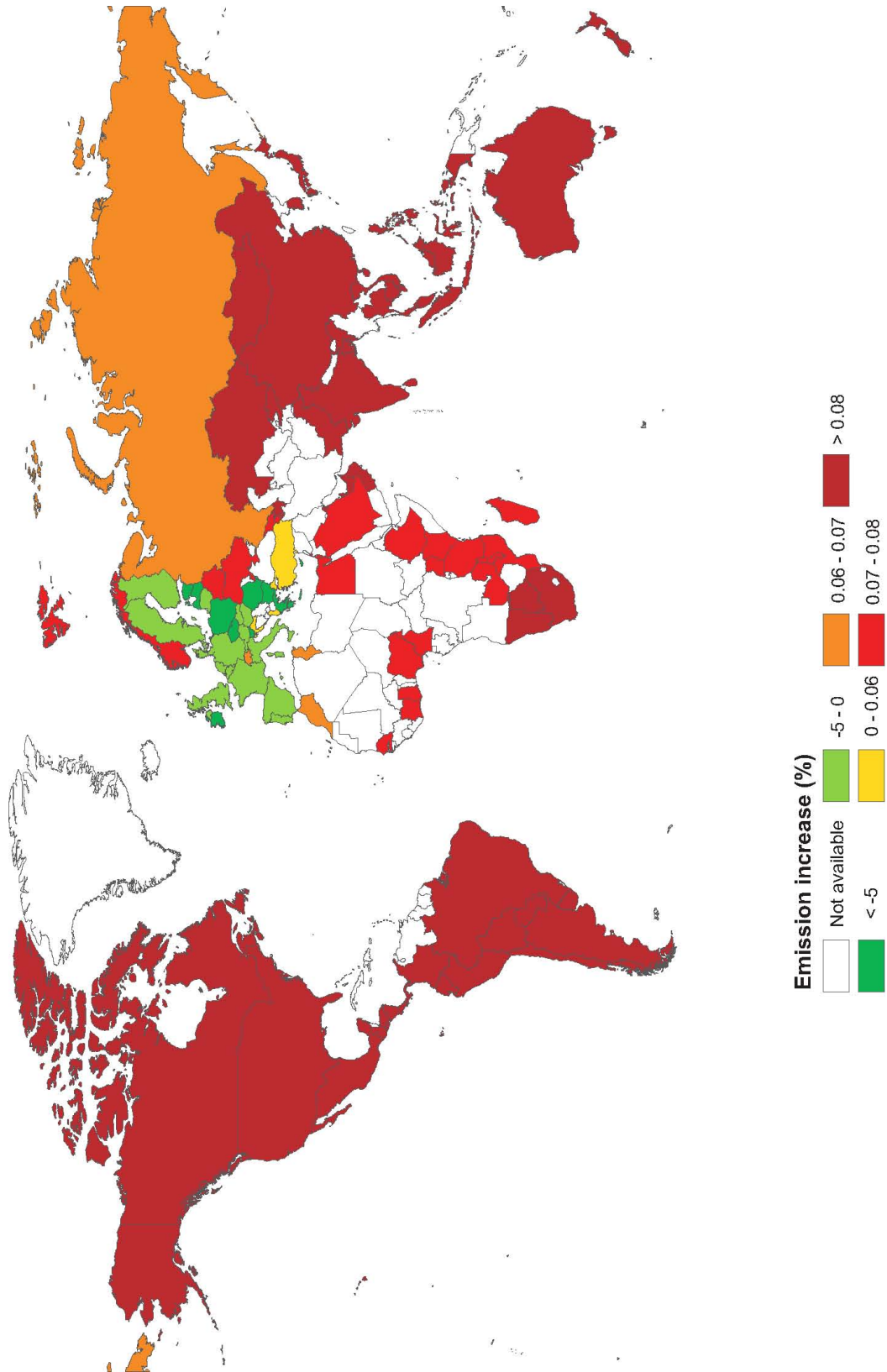
The 103 countries are: Albania, Argentina, Armenia, Australia, Austria, Azerbaijan, Bahrain, Bangladesh, Belarus, Belgium, Bolivia, Botswana, Brazil, Bulgaria, Cambodia, Cameroon, Canada, Chile, China, Colombia, Costa Rica, Croatia, Cyprus, Czech Republic, Côte d'Ivoire, Denmark, Ecuador, Egypt, El Salvador, Estonia, Ethiopia, Finland, France, Georgia, Germany, Ghana, Greece, Guatemala, Honduras, Hong Kong, Hungary, India, Indonesia, Ireland, Israel, Italy, Japan, Kazakhstan, Kenya, Kuwait, Kyrgyzstan, Latvia, Lithuania, Luxembourg, Madagascar, Malawi, Malaysia, Malta, Mauritius, Mexico, Mongolia, Morocco, Mozambique, Namibia, Netherlands, New Zealand, Nicaragua, Nigeria, Norway, Oman, Pakistan, Panama, Paraguay, Peru, Philippines, Poland, Portugal, Qatar, Republic of Korea, Romania, Russia, Saudi Arabia, Senegal, Singapore, Slovakia, Slovenia, South Africa, Spain, Sri Lanka, Sweden, Switzerland, Thailand, Tunisia, Turkey, Uganda, Ukraine, United States of America, United Arab Emirates, United Kingdom, United Republic of Tanzania, Uruguay, Vietnam, Zambia

Table 14: Sensitivity: Heterogeneity of country effects for EUA permit price increase with OLS

Country	Emission effects			Trade share with non-EU countries				Real GDP
	Total	Tech- nique	Scale	Goods		Emissions		
				Import	Export	Import	Export	
ΔE_i	$\Delta \eta_i$	Δq_i	$\Delta \frac{X_{ji}}{Y_i}$	$\Delta \frac{X_{ij}}{Y_j}$	$\Delta \frac{\eta'_j X_{ji}}{E_i}$	$\Delta \frac{\eta'_i X_{ij}}{E_j}$	$\Delta \frac{Y_i}{F_i}$	
Estonia	-12.07	-10.86	-1.28	0.09	-0.94	12.49	-1.04	-1.08
Poland	-8.53	-7.69	-0.87	0.31	-0.53	8.65	-0.60	-0.89
Czech Republic	-8.32	-7.49	-0.86	0.35	-0.53	8.50	-0.60	-0.93
Slovenia	-8.20	-7.80	-0.41	0.16	-0.23	9.07	-0.30	-0.42
Bulgaria	-7.76	-6.04	-1.77	0.18	-1.33	6.90	-1.39	-1.54
Latvia	-6.84	-6.38	-0.47	0.01	-0.28	7.03	-0.34	-0.32
Cyprus	-6.42	-5.53	-0.92	0.48	-0.55	6.00	-0.58	-1.08
Malta	-6.15	-5.36	-0.81	0.26	-0.42	6.09	-0.48	-0.77
Romania	-5.68	-5.14	-0.55	0.35	-0.30	5.75	-0.34	-0.70
Ireland	-5.57	-5.35	-0.23	-0.01	-0.10	5.88	-0.15	-0.12
Greece	-5.34	-4.31	-1.05	0.30	-0.59	5.28	-0.63	-0.97
Luxembourg	-4.92	-4.61	-0.32	0.08	-0.15	5.30	-0.20	-0.27
Denmark	-4.64	-4.34	-0.30	0.05	-0.13	4.75	-0.17	-0.21
Spain	-4.10	-3.79	-0.32	0.19	-0.14	4.21	-0.18	-0.37
Hungary	-3.69	-3.23	-0.47	0.00	-0.24	3.64	-0.26	-0.28
Portugal	-3.59	-3.24	-0.36	0.13	-0.16	3.56	-0.19	-0.33
Slovak Republic	-3.56	-3.07	-0.50	0.20	-0.27	3.31	-0.30	-0.52
Germany	-3.47	-3.22	-0.25	0.09	-0.10	3.51	-0.13	-0.23
Finland	-3.35	-2.99	-0.37	0.10	-0.20	3.28	-0.22	-0.32
United Kingdom	-3.24	-3.04	-0.20	0.07	-0.08	3.37	-0.10	-0.17
Italy	-3.24	-2.99	-0.25	-0.06	-0.10	3.26	-0.13	-0.07
France	-2.77	-2.59	-0.18	0.26	-0.06	2.88	-0.08	-0.34
Austria	-2.75	-2.59	-0.17	0.23	-0.01	2.71	-0.03	-0.28
Lithuania	-2.74	-2.30	-0.44	0.17	-0.23	2.59	-0.24	-0.43
Belgium	-2.31	-2.01	-0.30	0.03	-0.15	2.21	-0.16	-0.21
Netherlands	-1.95	-1.74	-0.21	0.16	-0.07	1.53	-0.08	-0.26
Sweden	-1.91	-1.78	-0.13	-0.02	-0.03	1.79	-0.04	-0.04
EU average	-4.93	-4.43	-0.52	0.15	-0.29	4.95	-0.33	-0.49

Note: The policy experiment is an EUA permit price increase of 15 US-\$. Results based on OLS estimations. The table shows percentage changes of the respective variables. Index $i \in \text{EU}$ refers to the respective EU country. For trade effects, $j \notin \text{EU}$ indexes non-EU countries.

Figure 9: Country-specific emission increase from EUA permit price increase with OLS estimation



Note: The graph shows countries' emission increase (in %) due to emission relocation, i.e. $\Delta \bar{E}_i$, resulting from an EUA permit price increase of 15 US-\$ using the default method; i.e. OLS estimation and $\hat{\sigma} = 4.801$.