Trade, Fossil Fuel Supply, and Leakage: The Consequences of Unilateral Withdrawals from the Paris Agreement*

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Abstract

Countries that drop out of the Paris Agreement harm the effectiveness of the international initiative to lower greenhouse gas emissions in two ways. First, by canceling their own reduction commitments, they fall back on a business as usual emission path, directly reducing the extent of the global emission reduction. Second, carbon leakage may occur in response to the climate policy of Paris member countries, actually increasing the withdrawing country's emissions above the level it would have experienced in the complete absence of the Paris Agreement. This leakage in turn occurs via two channels: emission-intensive production is shifted from committed to non-committed countries and the climate policies of Paris members lower their fossil fuel demand, driving down energy prices and hence leading to more energy-intensive production in non-committed countries. We develop an extended multi-sector structural gravity model with emissions from production and a constant elasticity of fossil fuel supply function which allows a decomposition of emission changes into scale, composition, and technique effects. We use the extended framework to simulate the consequences of unilateral withdrawals from the Paris Agreement. We find that a US withdrawal would have the strongest effect, eliminating a third of the world emssions reduction, while a potential Chinese withdrawal would imply the highest leakage rate (12.1%). We find leakage to be primarily driven by technique effects that are induced via the energy-market leakage channel.

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1 Introduction

> *The coming into force of [the] Paris Agreement has ushered in a new dawn for global cooperation on climate change.*
> (UN Secretary General Ban Ki-Moon, November 15th, 2016)
>
> *[I]n order to fulfill my solemn duty to protect America and its citizens, the United States will withdraw from the Paris Climate Accord.*
> (US President Donald Trump, June 1st, 2017)

In December 2015, the parties to the United Nations Framework Convention on Climate Change (UNFCCC) reached a joint agreement to combat climate change. With its 195 signing countries, the Paris Agreement constitutes a truly global consensus to take appropriate measures to keep global warming well below two degrees Celsius. One centerpiece of the agreement are the Nationally Determined Contributions (NDCs) in which every country specifies an individual greenhouse gas (GHG) emission reduction target. Figure 1 shows the different national reduction targets, standardized to reductions compared to a business as usual (BAU) scenario in 2030, to make the targets comparable.

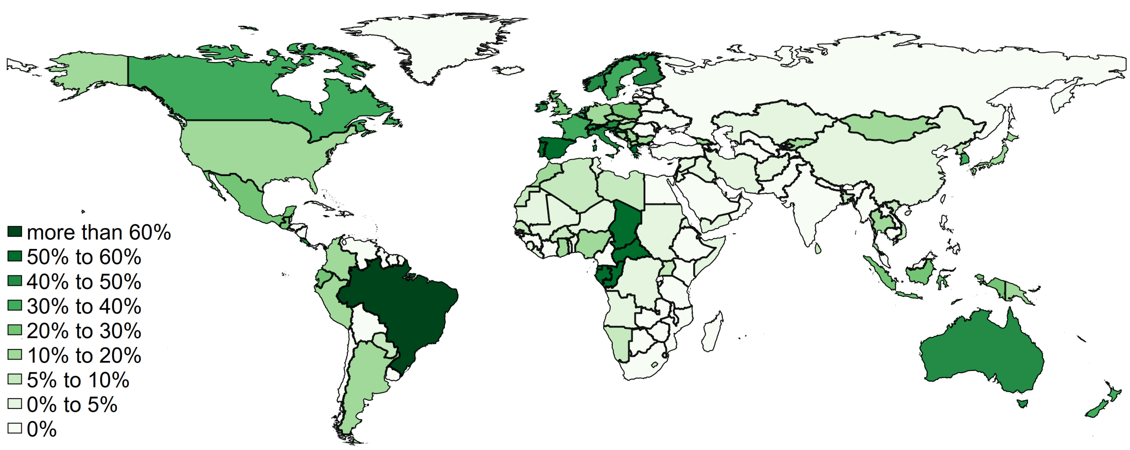

Figure 1: Emission Reduction Targets in the Paris Agreement

Notes: This figure shows the emission reduction targets specified in the individual countries' NDCs (or, where nor NDCs are yet available, the Intended NDCs). To make the targets comparable, all are given as reductions below the business as usual emission path in 2030. For details on the targets and their standardization, see section 3.

The large heterogeneity in ambition of the targets becomes evident at first sight. While some Asian and African countries merely commit to not *increase* their emissions beyond the BAU path and some have very mild targets (like the 3.1% of China), e.g. large parts of Europe and the Americas formulate strong targets that in some cases lower their emission by more than half. What is more crucial though and most likely explains at least part of the enthusiasm expressed for example in the first opening quote by the former UN Secretary General Ban Ki-Moon, is the fact that *every country* has a target. The subglobal coverage of the Paris Agreement's most prominent predecessor, the Kyoto Protocol, has severely harmed its effectiveness due to leakage effects (see e.g. Aichele and Felbermayr, 2012, 2015). Carbon leakage refers to the phenomenon that climate policies undertaken in some countries can actually lead to *increased* emissions in other places where no such policies are undertaken due to (i) production shifts of emission-intensive goods towards the un- (or less) regulated countries and (ii) falling fossil fuel prices on the world market that incentivize a more fossil fuel-intensive production (see e.g. Felder and Rutherford, 1993).

As the second opening quote by US President Donald Trump clearly shows, the hope of actually achieving the world emission reduction that would result from adding up all national targets appears overly optimistic. The United States have announced their withdrawal, other signing countries of the agreement (such as e.g. Iran, Russia, and Turkey) have not yet moved on to ratification. Countries that decide not to commit to their emission targets harm the effectiveness of the Paris Agreement in two ways. First and most obviously, the sum of the national targets is lowered if some countries drop their target. Second and potentially just as importantly, withdrawals can induce carbon leakage that lowers the actually achieved world reduction below the remaining sum of national targets. The first effect can easily be calculated by combining the national targets shown in figure 1 with data on the national emission levels and is shown in figure 2 and (for the five countries with the strongest effects) in table 1.

Withdrawing country	USA	BRA	CHN	JPN	ESP
World reduction lost (direct effect)	25.5%	6.5%	5.4%	5.0%	4.5%

Table 1: Top Five Direct Reduction Losses

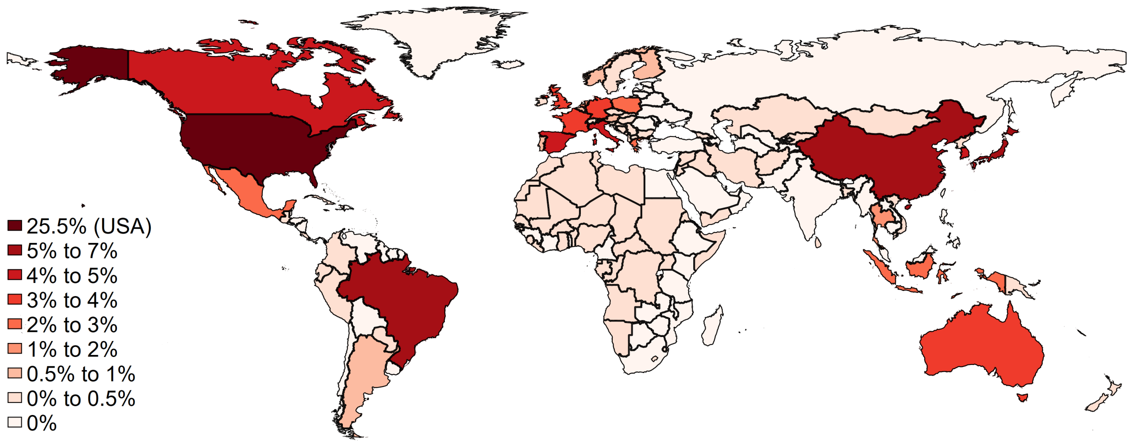

Figure 2: World Reduction Lost by Withdrawn Commitments (Direct Effect Only)

Notes: This figure shows for every country in turn, which share of the world emission reduction due to the Paris Agreement would be lost if the respective country withdraws from the agreement and its target specified in the NDC is hence no longer part of the global reduction. Endogenous adjustments of withdrawing country to other countries' climate policies with potentially resulting emission *increases* in the withdrawing country beyond the BAU path are not taken into account at this point.

China (7241 Mt CO_2)[1] and the United States (5108 Mt CO_2) are by far the largest emitters. Unsurprisingly, their withdrawals would directly lower the world emission reduction comparatively strongly. Even though the US comes second in terms of emissions, its combination of large emissions with a rather ambitious NDC reduction target (20%) makes the direct effect of a US withdrawal the by far strongest of all countries: more than a quarter of the global reduction would be lost due to the absence of the US target. China (5.4% world reduction loss) comes in third, while Brazil (6.5%) has the second strongest effect. These two similar numbers come about in very different ways: very large emissions and a mild target in one case (China) and much lower emissions (about 5% of the Chinese level) and a very ambitious target (69%) in the other case (Brazil). Besides these three countries, a group of European countries, as well as a few more large developed countries (Australia, Canada, and Japan) combine high emission levels and strong targets to notable direct reduction losses in case of withdrawal of three to five percent. All African and most Asian countries

[1]The emission data used here refer to the year 2011 and capture only carbon and no other GHG emissions. For details, see section 3.

have either sufficiently low emissions or very small targets (or both), so that the loss of their target would not alter the achieved world reduction conceivably.

Two prominent examples illustrate the limitations of considering only the direct effect of removing a withdrawing country's target particularly well: India and Russia. Both these countries have targets that imply only a commitment to *not increase* emissions above the BAU path. Obviously, removing such a "zero target" does not change the sum of targets and hence, these countries' withdrawals are depicted with a zero effect in figure 2. But indeed, an Indian or Russian decision to withdraw from the Paris Agreement and to not take any climate policy measures may induce carbon leakage and therefore harm the achieved global emission reduction indirectly. Such leakage effects will not only introduce effects for countries with zero targets, but it will also amplify the effects of all other countries' withdrawals.

Different from the direct effects, leakage effects (and hence the total effects) of unilateral withdrawals cannot be simply calculated, but have to be simulated in a general equilibrium model framework. The most common approach to investigate the global effects of different trade and climate policies is the use of computable general equilibrium (CGE) models (see e.g. Böhringer, Balistreri, and Rutherford, 2012, for an overview of various prominent CGE models). A recent strand of literature (Egger and Nigai, 2015; Larch and Wanner, 2017; Larch, Löning, and Wanner, 2018; Shapiro, 2016; Shapiro and Walker, 2018) incorporates environmental components into structural gravity models as an alternative approach.[2] Gravity models are the workhorse models in the empirical international trade literature. Just as CGE models, they can be used to conduct ex ante analyzes of different policy scenarios. Compared to typical CGE models, they tend to sacrifice some detail in the model structure in favor of higher analytical tractability and direct estimation of key model parameters.

Given gravity's great success in predicting trade flows (see e.g. Head and Mayer, 2014; Costinot and Rodríguez-Clare, 2014, for surveys on gravity models and their performance), it is likely to capture well leakage that occurs via production shifts and international trade. In fact, the main model of Larch and Wanner (2017), as well as the models by Shapiro (2016) and Shapiro and Walker

[2]Pothen and Hübler (2018) develop a hybrid model, combining an Eaton and Kortum (2002)-type gravity trade structure with a CGE model production structure.

(2018) exclusively focus on this leakage channel. In this paper, we extend the model of Larch and Wanner (2017) by considering fossil fuel resources that are internationally traded and supplied according to a constant elasticity of fossil fuel supply function as proposed in the CGE context by Boeters and Bollen (2012). The resulting extended gravity model will capture leakage effects via international trade and via the international fossil fuel market and hence allow a quantification of the total emission reduction losses associated with unilateral withdrawals from the Paris Agreement. At the same time, the model structure remains tractable enough to allow an analytical and quantitative decomposition of the national emission changes into scale, composition, and technique effects as is often done in the theoretical and empirical literature on trade and the environment (see e.g. Grossman and Krueger, 1993; Copeland and Taylor, 1994, 2003). Such a decomposition can generate important insights on the channels via which international climate policies are effective.

Our analysis of the effects of unilateral withdrawals complements other studies that investigate the Paris Agreement and its implications. For example, Rogelj, den Elzen, Höhne, Fransen, Fekete, Winkler, Schaeffer, Sha, Riahi, and Meinshausen (2016) analyze whether the individual national targets are sufficient to jointly achieve the two (or even 1.5) degree Celcius target. Aldy and Pizer (2016), Aldy, Pizer, and Akimoto (2017), and Iyer, Calvin, Clarke, Edmonds, Hultman, Hartin, McJeon, Aldy, and Pizer (2018) aim to make the different NDCs comparable in their implied required mitigation efforts of the different countries. Rose, Wei, Miller, Vandyck, and Flachsland (2018) investigate one particular way for actually achieving the reduction pledges in an efficient way, namely by linking different emissions trading schemes. Böhringer and Rutherford (2017) show that the introduction of carbon tariffs is not a credible threat towards the US in order to try to keep them in the agreement. Kemp (2017) considers measures that can be taken in order to reduce the harm done to the effectiveness of the agreement due to a US withdrawal, e.g. by incorporating cooperation with US states.

The rest of this paper proceeds as follows. Section 2 develops our extended structural gravity model, shows how counterfactual analyzes can be performed in this framework, and derives the emission change decomposition. In section 3, the data sources and descriptive statistics are presented, as well as the gravity estimation procedure. We discuss the results of simulating the unilateral withdrawal for every country in section 4. Section 5 concludes.

2 Model

In this section, we develop an extended structural gravity model including a non-tradable and multiple tradable sectors, a multi-factor production function including an energy input, energy production including an internationally tradable fossil fuel resource, a constant elasticity of fossil fuel supply (CEFS) function following Boeters and Bollen (2012), as well as emissions associated to the fossil fuel usage. The model builds on the framework by Larch and Wanner (2017), but importantly deviates by (i) modeling the energy-market leakage channel using a CEFS function[3], (ii) linking emissions directly to fossil fuel use rather than to general energy use, and (iii) explicitly including a carbon tax which countries can use to achieve emission reduction targets.

2.1 Demand

Consumers in country $j \in \mathcal{N}$ (where $\mathcal{N}$ denotes the set of all countries in the world) obtain utility according to the following utility function:

$$U^j = (U_S^j)^{\gamma_S^j} \left[\prod_{l \in \mathcal{L}} (U_l^j)^{\gamma_l^j} \right] \left[\frac{1}{1 + (\frac{1}{\mu^j} \sum_{i \in \mathcal{N}} R^i)^2} \right], \tag{1}$$

with

$$U_l^j = \left[\sum_{i \in \mathcal{N}} (\beta_l^i)^{\frac{1-\sigma_l}{\sigma_l}} (q_l^{ij})^{\frac{\sigma_l - 1}{\sigma_l}} \right]^{\frac{\sigma_l}{\sigma_l - 1}}, \tag{2}$$

where subscript S denotes the non-tradable sector, $l \in \mathcal{L}$ is one of the tradable sectors (with $\mathcal{L}$ being the set of all tradable sectors), γ represents sectoral expenditure shares, μ^j is a parameter that captures j's disutility from global carbon emissions, R^i is country i's fossil fuel use which is proportional to its emissions, β_l^i represents the utility parameter for tradable goods, q_l^{ij} is the

[3] The base model of Larch and Wanner (2017) only features the trade leakage channel, while the small model extension presented in their work relies on an energy resource in fixed supply.

amount of good l from country i consumed in country j, and σ_l stands for the sectoral elasticity of substitution. (1) and (2) hence combine linear utility from non-tradable good consumption and CES utility from tradable goods consumption in an upper-tier Cobb-Douglas utility function (implying constant sectoral expenditure shares), as well as disutility from global emissions in the functional form chosen by Shapiro (2016) in order to ensure almost constant social costs of carbon around the baseline emission level.

Carbon emissions are treated as a pure externality (and are therefore not taken into account in the consumption decisions). Demand for non-tradable goods is then simply given by the corresponding expenditure $\mathfrak{X}_S^j$ divided by the non-tradable good price ($q_S^j = \frac{\mathfrak{X}_S^j}{p_S^j}$). Demand for tradable goods l from i in j follows from CES utility as:

$$q_l^{ij} = \left(\frac{\beta_l^i p_l^{ij}}{P_l^j} \right)^{-\sigma_l} \left(\frac{\beta_l^i \mathfrak{X}_l^j}{P_l^j} \right), \tag{3}$$

where p_l^{ij} is the price including trade costs from i to j and P_l^j is the sectoral price index in j, given by:

$$P_l^j = \left[\sum_{i \in \mathcal{N}} (\beta_l^i p_l^{ij})^{1-\sigma_l} \right]^{\frac{1}{1-\sigma_l}}. \tag{4}$$

2.2 Supply

Each country produces a non-tradable good S, as well as a differentiated variety of each of $l \in \mathcal{L}$ tradable goods according to the following Cobb-Douglas production functions:

$$q_S^i = A_S^i (E_S^i)^{\alpha_{SE}^i} \prod_{f \in \mathcal{F}} (V_{Sf}^i)^{\alpha_{Sf}^i}, \tag{5}$$

$$q_l^i = A_l^i (E_l^i)^{\alpha_{lE}^i} \prod_{f \in \mathcal{F}} (V_{lf}^i)^{\alpha_{lf}^i}, \tag{6}$$

where A is a sector- and country-specific productivity parameter, α denotes the production cost shares, and V_{Sf}^i and V_{lf}^i the usages of a production factor $f \in \mathcal{F}$. Countries are endowed with a fixed factor supply V_f^i and factors are mobile across sectors, but internationally immobile. E_S^i and E_l^i denote the energy inputs in producing non-tradable and tradable goods, respectively. Different from the other production factors, countries are not endowed with a fixed energy supply, but the energy inputs have to be produced themselves according to the following (again Cobb-Douglas) production function:

$$E^i = A_E^i (R^i)^{\xi_R^i} \prod_{f \in \mathcal{F}} (V_{Ef}^i)^{\xi_f^i}, \tag{7}$$

where ξ denotes the input cost shares and R^i is the usage of a freely internationally tradable fossil fuel resource. National factor markets are assumed to clear, i.e. $V_f^i = V_{Sf}^i + \sum_{l \in \mathcal{L}} V_{lf}^i + V_{Ef}^i$, determining the factor prices v_f^i. Countries can charge a national carbon tax λ^i on the use of fossil fuels in order to fulfill specific emission reduction targets and the fossil fuel price r is determined on the world market by global market clearing:

$$r = \frac{1}{R^W} \sum_{i \in \mathcal{N}} \left(\frac{1}{1 + \lambda^i} \right) \xi_R^i \left(\alpha_{SE}^i Y_S^i + \sum_{l \in \mathcal{L}} \alpha_{lE}^i Y_l^i \right), \tag{8}$$

where $Y_S^i = q_S^i p_S^i$ and $Y_l^i = q_l^i p_l^i$ are the sectoral values of production. Following Boeters and Bollen (2012), a change in the fossil fuel price is translated into a change in the global supply of the fossil fuel with a constant elasticity of fossil fuel supply function:

$$\widehat{R^W} = (\widehat{r})^{\eta}, \tag{9}$$

where η denotes the supply elasticity and the hat notation (introduced into the structural gravity literature by Dekle, Eaton, and Kortum, 2007, 2008) indicates the change of the respective variables, i.e. $\widehat{R^W} = \frac{R^{W\prime}}{R^W}$ and $\widehat{r} = \frac{r'}{r}$, where the prime indicates a counterfactual value in response to a policy shock and values without a prime correspond to the baseline equilibrium. The total fossil fuel supply R^W stems from the different countries according to their varying fossil fuel endowment shares ω^i (with $\sum_{i \in \mathcal{N}} \omega^i = 1$).

A change in the fossil fuel world market price further leads to an adjusted national energy price:

$$\widehat{e}^i = \left(\widehat{(1+\lambda^i)}\widehat{r}\right)^{\xi^i_R} \prod_{f\in\mathcal{F}} \left[\frac{(\alpha^i_{Sf}+\xi^i_f\alpha^i_{SE})Y^{i\prime}_S + \sum_{l\in\mathcal{L}}(\alpha^i_{lf}+\xi^i_f\alpha^i_{lE})Y^{i\prime}_l}{(\alpha^i_{Sf}+\xi^i_f\alpha^i_{SE})Y^i_S + \sum_{l\in\mathcal{L}}(\alpha^i_{lf}+\xi^i_f\alpha^i_{lE})Y^i_l}\right]^{\xi^i_f}. \tag{10}$$

Note that the adjustment of the energy price in response to a policy shock further depends on the endogenously adjusted, counterfactual production values. Subsection 2.5 will lay out the full system of equations that can – for a given counterfactual policy shock – be solved for the values of a sufficient set of endogenous variables from which all variables of interest can then be obtained.

2.3 Income

Countries generate income from (i) the expenditure on their national production factors, (ii) their share of the global supply of the fossil fuel, and (iii) the carbon tax charged on its fossil fuel use:

$$\begin{aligned} Y^i = &\sum_{f\in\mathcal{F}} \left[(\alpha^i_{Sf}+\xi^i_f\alpha^i_{SE})Y^i_S + \sum_{l\in\mathcal{L}}(\alpha^i_{lf}+\xi^i_f\alpha^i_{lE})Y^i_l\right] \\ &+ \omega^i \sum_{j\in\mathcal{N}} \left(\frac{1}{1+\lambda^j}\right)\xi^j_R \left(\alpha^j_{SE}Y^j_S + \sum_{l\in\mathcal{L}}\alpha^j_{lE}Y^j_l\right) + \left(\frac{\lambda^i}{1+\lambda^i}\right)\xi^i_R\left(\alpha^i_{SE}Y^i_S + \sum_{l\in\mathcal{L}}\alpha^i_{lE}Y^i_l\right). \end{aligned} \tag{11}$$

2.4 Trade Flows

Introducing iceberg trade costs T^{ij}_l (with $T^{ij}_l = T^{ji}_l \geq 1$ and $T^{ii}_l = 1$) and defining sectoral scaled equilibrium prices as $\psi^i_l \equiv \left(\beta^i_l p^i_l\right)^{1-\sigma_l}$, the exports of country i to country j in sector l can be obtained from the bilateral demand given in (3) as:

$$X^{ij}_l = \left(\frac{\psi^i_l T^{ij}_l}{P^j_l}\right)^{1-\sigma_l} \mathfrak{X}^j_l. \tag{12}$$

This gravity equation links bilateral trade flows to bilateral trade costs, the importer's market size and overall openness (captured by the price index which is equivalent to Anderson and van Wincoop (2003)'s inward multilateral resistance), as well as the overall exporting capability of country j (summarized by ψ^i_l which implicitly captures the exporter's size in terms of production and its outward multilateral resistance).

Assuming balanced trade and market clearing, as well as using the sectoral price index given by (4), from (12) we can obtain an expression which links the sectoral production to the international trade cost matrix:

$$Y_l^i = \psi_l^i \sum_{j=1}^{N} \frac{(T_l^{ij})^{1-\sigma_l}}{\sum_{k=1}^{N} \psi_l^k (T_l^{kj})^{1-\sigma_l}} \gamma_l^j Y^j. \tag{13}$$

2.5 Comparative Statics

Equation (8) for the world market price of fossil fuels, equation (9) depicting the constant elasticity of fossil fuel supply function, equation (10) that captures the response in energy prices, equation (11) which describes total national income, and equation (13) linking sectoral production values and scaled equilibrium prices to the trade cost matrix (or the counterfactual equilibrium counterparts of these equations) describe a system of equations that can almost be solved for a given policy shock. Cost minimization in production allows to derive the second last necessary equation which captures the change in factory-gate prices (or equivalently in scaled equilibrium prices):

$$\left(\widehat{\psi}_l^i\right)^{\frac{1}{\sigma_l-1}} = \left(\widehat{e}^i\right)^{\alpha_{lE}^i} \prod_{f\in\mathcal{F}} \left(\frac{(\alpha_{Sf}^i + \xi_f^i \alpha_{SE}^i) Y_S^i + \sum_{m\in\mathcal{L}} (\alpha_{mf}^i + \xi_f^i \alpha_{mE}^i) Y_m^i}{(\alpha_{Sf}^i + \xi_f^i \alpha_{SE}^i) Y_S^{i\prime} + \sum_{m\in\mathcal{L}} (\alpha_{mf}^i + \xi_f^i \alpha_{mE}^i) Y_m^{i\prime}} \right)^{\alpha_{lf}^i}. \tag{14}$$

The last equation needed to solve the model for the counterfactual equilibrium stems from the specific policy scenario under investigation. We will run different scenarios in all of which all countries around the world will fulfill the emission reduction targets specified in their NDCs, except for one country that decides to withdraw from the agreement. We can link this scenario to the choice of the carbon tax λ^i in the model. Denoting the set of committed (or cooperating) countries by *cop*, the country that is not part of the agreement chooses a zero carbon tax, while all other countries choose their carbon tax exactly at the required level to ensure that their realized emissions are equal to their targetted emission level (denoted by $\overline{R^{i\prime}}$):

$$\lambda^i = \begin{cases} 0 \quad \text{if } i \notin cop, \\ \frac{\xi_R^i \left(\alpha_{SE}^i Y_S^{i\prime} + \sum_{l \in \mathcal{L}} \alpha_{lE}^i Y_l^{i\prime}\right)}{\overline{R^{i\prime}} r'} - 1 \quad \text{if } i \in cop. \end{cases} \tag{15}$$

2.6 Decomposition of Emission Changes

As emissions are proportional to a country's fossil fuel use, emissions in country i can be written as:

$$R^i = \frac{\xi_R^i \left(\alpha_{SE}^i Y_S^i + \sum_{l \in \mathcal{L}} \alpha_{lE}^i Y_l^i\right)}{(1+\lambda^i) r} = \xi_R^i \bar{\alpha}_E^i \frac{\tilde{Y}^i}{P^i} \left((1+\lambda^i)\frac{r}{P^i}\right)^{-1}, \tag{16}$$

where $\tilde{Y}^i \equiv Y_S^i + \sum_{l \in \mathcal{L}} Y_l^i$ denotes total production, $\kappa_S^i = Y_S^i / \tilde{Y}^i$, $\kappa_l^i = Y_l^i / \tilde{Y}^i$ are sectoral production shares, and $\bar{\alpha}_E^i \equiv \alpha_{SE}^i \kappa_S^i + \sum_{l \in \mathcal{L}} \alpha_{lE}^i \kappa_l^i$ is the production-share-weighted average energy cost share. Intuitively, the level of emissions in a country depends on (i) how much is spend for energy inputs in production, (ii) which share of the energy input expenditure is paid for fossil fuel inputs in energy production, and (iii) how expensive fossil fuels are (both in terms of the world market price and the national carbon tax).

Following Grossman and Krueger (1993) and Copeland and Taylor (1994) (as well as Larch and Wanner, 2017, in a structural gravity context), the change in emissions can then be decomposed into three parts:

$$dR^i = \underbrace{\frac{\partial R^i}{\partial(\tilde{Y}^i/P^i)} d(\tilde{Y}^i/P^i)}_{\text{scale effect}} + \underbrace{\frac{\partial R^i}{\partial \bar{\alpha}_E^i} d\bar{\alpha}_E^i}_{\text{composition effect}} + \underbrace{\frac{\partial R^i}{\partial(r/P^i)} d(r/P^i) + \frac{\partial R^i}{\partial \lambda^i} d\lambda^i}_{\text{technique effect}},$$

Scale Effect. A country's resource use (and hence emissions) increases proportionally with the size of the economy (measured as the real value of production):

$$\frac{\partial R^i}{\partial(\tilde{Y}^i/P^i)} = \frac{\xi_R^i \bar{\alpha}_E^i}{(1+\lambda^i) r/P^i} > 0 \quad \text{and} \quad \frac{\partial R^i}{\partial(\tilde{Y}^i/P^i)} \frac{(\tilde{Y}^i/P^i)}{R^i} = 1.$$

Composition Effect. An increase in the average energy intensity of production in a country (measured by the weighted average energy cost share) proportionately increases the country's carbon emissions:

$$\frac{\partial R^i}{\partial \bar{\alpha}_E^i} \quad = \quad \frac{\xi_R^i \tilde{Y}^i}{(1+\lambda^i)r} > 0 \quad \text{and} \quad \frac{\partial E^i}{\partial \bar{\alpha}_E^i}\frac{\bar{\alpha}_E^i}{E^i} = 1.$$

Technique Effect. An increase in the fossil fuel resource price – either due to a higher world market price or due to a higher national carbon tax – proportionately *lowers* a country's carbon emissions:

$$\begin{aligned} \frac{\partial R^i}{\partial (r/P^i)} &= -\frac{\xi_R^i \bar{\alpha}_E^i \tilde{Y}^i / P^i}{(1+\lambda^i)(r/P^i)^2} < 0 \quad \text{and} \quad \frac{\partial R^i}{\partial (r/P^i)}\frac{r/P^i}{R^i} = -1, \\ \frac{\partial R^i}{\partial (1+\lambda^i)} &= -\frac{\xi_R^i \bar{\alpha}_E^i \tilde{Y}^i}{r(1+\lambda^i)^2} < 0 \quad \text{and} \quad \frac{\partial R^i}{\partial (1+\lambda^i)}\frac{1+\lambda^i}{R^i} = -1. \end{aligned}$$

3 Data and Estimation

3.1 Data Sources

Our main data source is the Global Trade Analysis Project (GTAP) 9 database (Aguiar, Narayanan, and McDougall, 2016). From GTAP, we take the data on carbon emissions, sectoral production, trade flows, factor expenditures, and expenditure for and income from fossil fuels. GTAP also provides estimates for the sectoral elasticities of substitution of which we make use. Unfortunately, no estimate is available for the fossil fuel supply elasticity. We therefore choose a value which is in line with the range of values reported by Boeters and Bollen (2012) for different specific fossil fuels, namely $\eta = 2$.

The GTAP 9 data is given for the base year 2011. We hence construct our whole data set for this year. It captures 139 countries (some of which are in fact aggrerates of several countries) covering the whole world. We aggregate the sectoral structur to one non-tradable and 14 tradable sectors.

For the gravity estimation of bilateral trade costs, we rely on a set of standard gravity variables from the CEPII dataset by (Head, Mayer, and Ries, 2010), namely bilateral distance, an indicator variable for whether two countries share a common border, and a second indicator variable for a common official language. We complement these variables by an indicator variable for joint regional trade agreement (RTA) membership taken from Mario Larch's RTA database (Egger and Larch, 2008).

The (I)NDCs of the signatory states of the Paris Agreement are collected and made available online by the World Resources Institute.[4] In order to translate the different emission targets into 2030 BAU reduction targets, we additionally use GDP and carbon emission projections by the US Energy Information Administration's (EIA) International Energy Outlook 2016. Where the combination of NDCs and GDP and emission projections imply a target that represents an increase over the BAU emission path, we assume that the respective Paris member countries commit to not emitt more CO_2 than in the BAU case.

3.2 Selected Descriptive Statistics

Given the critical role of initial emission levels for the importance of the different national reduction targets (and, as will turn out, for the leakage potential), figure 3 displays the national levels of carbon emissions. China and the US stand out as the strongest emitters, followed by other large developed or emerging economies, such as India, Russia, Japan, Germany, and Canada.

Table 2 additionally summarizes the gravity variables used in the trade cost estimation: country pairs are on average 7600 km apart, 2% share a common border, 11% share a common official language, and 23% are joint members of a regional trade agreement.

Variable	Obs	Mean	Std. Dev.	Min	Max
Distance (in km)	19,321	7568.75	4334.84	8.45	19781.39
Contiguiuty	19,321	0.02	0.14	0	1
Common Language	19,321	0.11	0.31	0	1
RTA	19,321	0.23	0.42	0	1

Table 2: Gravity Variables

[4]https://cait.wri.org/indc/

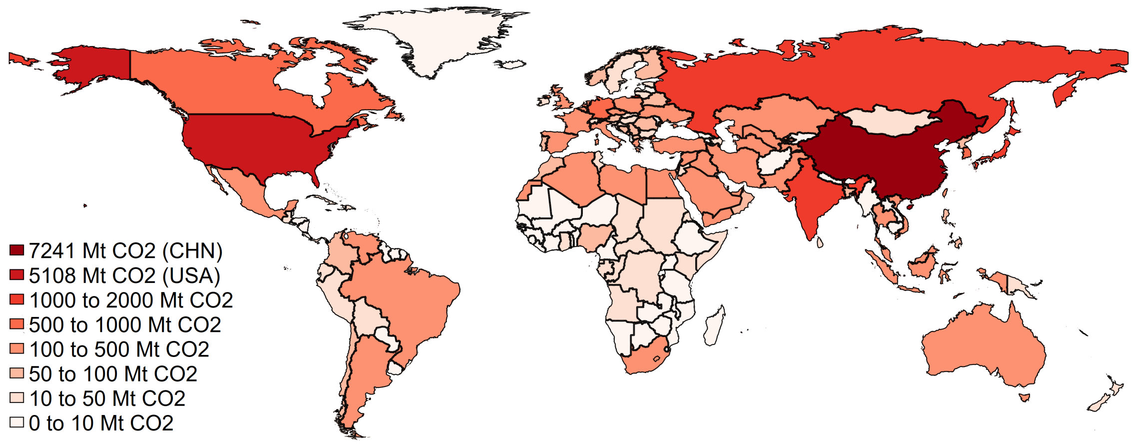

Figure 3: National Carbon Emissions in 2011

3.3 Gravity Estimation

Estimates of bilateral trade costs can be obtained based on the gravity equation (12) derived above. Approximating trade costs by a function of observable bilateral characteristics (captured by the vector $\mathbf{z}_{ij}$), collecting all (partly unobservable) importer- and exporter-specific terms and introducing an error term yields the following regression equation:

$$X_l^{ij} = \exp(\pi_i + \chi_j + \mathbf{z}'_{ij}\boldsymbol{\beta}) \times \varepsilon_{ij}. \tag{17}$$

Following the suggestions by Feenstra (2004) and Santos Silva and Tenreyro (2006), respectively, we capture π_i and χ_j by the inclusion of exporter and importer fixed effects and estimate the model in its multiplicative form (avoiding problems due to heteroskedasticity and zero trade flows) with the Poisson Pseudo Maximum Likelihood (PPML) estimator. The estimation results for all sectors are shown in table 3. Based on these coefficient estimates, we can construct an estimated trade cost matrix.

	(1) agricult.	(2) apparel	(3) chemical	(4) equipm.	(5) food	(6) machin.	(7) metal
$\ln DIST$	-1.202	-0.789	-0.885	-0.563	-0.920	-0.768	-0.865
	(0.127)***	(0.137)***	(0.073)***	(0.129)***	(0.093)***	(0.076)***	(0.083)***
$CONTIG$	0.331	0.361	0.187	0.660	0.474	0.204	0.550
	(0.166)**	(0.177)**	(0.138)	(0.216)***	(0.152)***	(0.127)	(0.119)***
$LANG$	-0.078	0.455	0.208	0.064	0.375	0.077	-0.000
	(0.211)	(0.209)**	(0.181)	(0.134)	(0.127)***	(0.178)	(0.235)
RTA	0.113	0.154	0.263	0.670	0.461	0.169	0.084
	(0.136)	(0.210)	(0.106)**	(0.166)***	(0.129)***	(0.143)	(0.223)
N	19182	19182	19182	19182	19182	19182	19182

	(8) mineral	(9) mining	(10) other	(11) paper	(12) service	(13) textile	(14) wood
$\ln DIST$	-1.233	-1.331	-0.810	-1.006	-0.352	-0.994	-0.872
	(0.124)***	(0.224)***	(0.292)***	(0.084)***	(0.053)***	(0.091)***	(0.194)***
$CONTIG$	0.553	0.087	-0.058	0.619	0.256	0.147	0.735
	(0.214)***	(0.360)	(0.280)	(0.152)***	(0.094)***	(0.147)	(0.210)***
$LANG$	-0.050	0.199	0.106	0.259	0.255	0.297	0.062
	(0.194)	(0.355)	(0.316)	(0.184)	(0.071)***	(0.180)*	(0.284)
RTA	0.005	0.026	-0.162	0.227	0.006	0.337	0.389
	(0.168)	(0.244)	(0.420)	(0.145)	(0.077)	(0.182)*	(0.252)
N	19182	19182	19182	19182	19182	19182	19182

Notes: All regressions include importer and exporter fixed effects. Standard errors clustered by exporter and im-importer are given in parentheses. * $p < 0.10$, ** $p < .05$, *** $p < .01$.

Table 3: Gravity Estimation Results

3.4 Model Validation

In this subsection, we briefly discuss how our model fits the data from the baseline equilibrium, as well as how its global emission reactions to a policy shock compare to other models in the literature.

As structural gravity models always do, our model perfectly replicates the national (sectoral) production values. Unsurprisingly, the workhorse model in international trade also fits the sectoral bilateral trade flows very well, indicated by an average Pseudo-R^2 from the gravity regressions of 0.83. Importantly, national carbon emissions are also perfectly fitted in our framework. The sectoral distribution of a country's carbon emissions is closely proxied by the perfectly replicated distribution of sectoral energy expenditures.

In order to investigate whether the model predicts credible reactions to policy shocks (not only in terms of trade effects that are well established in the trade literature, but also in terms of emission changes), we simulate a counterfactual scenario in which all Annex I countries of the Kyoto Protocol reduce their emissions by 20% while all other countries undertake no climate policy and calculate the resulting leakage rate. This specific scenario has been investigated intensively in the literature and therefore can be compared nicely. Using 2011 baseline data, we find a leakage rate of 24.6%. Böhringer, Balistreri, and Rutherford (2012) implement the same scenario in a number of CGE models using data for 2004 and find a range of leakage rates from 5 to 19%. Larch and Wanner (2017) obtain a leakage rate of 12.5% for the base year 2007. While the prediction of our model appears to fall out of a typical range of results on first sight, it has to be taken into account that the Annex I countries covered a larger share of global emissions in 2004 than in 2011. Given the implied smaller coalition size in our case, leakage is expectedly higher and our model hence seems to generate leakage predictions that are at the higher end of the range, rather than actually outside of it.

4 Counterfactual Analysis: Unilateral Withdrawals from the Paris Agreement

We use the model framework developed in section 2 to investigate the effects of unilateral withdrawals from the Paris Agreement. We consider each of the 139 countries in our data set in turn, i.e. we run 139 different model simulations in all of which *all countries but one* fulfill the targets specified in their NDCs while one country does not undertake any policies towards its reduction aim and instead endogenously adjusts to the policies undertaken by the committed countries. We start this section off by discussing the results for two particularly important and illustrative examples, the US and China, before comparing results across the world.

4.1 The US Withdrawal

As discussed in the introduction, the mere erasure of the US target would cut the overall emission reduction of the Paris Agreement by one fourth. But the calculation of this direct effect did not allow for an endogenous adjustment of the US to the climate policies of the Paris member countries, as the US were assumed to follow a BAU emission path rather than fulfill their NDC target. Simulating a US withdrawal as a counterfactual scenario in which all countries introduce carbon taxes that are sufficient to fulfill their reduction targets while the US introduces no carbon tax at all, we find that the US emissions *increase* by 5.4%. This implies a leakage rate of 9.3%, i.e. almost every tenth ton of CO_2 saved in the committed countries is offset by increased emissions in the US. Putting together the loss of the US target and the partial offset of the remaining countries' targets via leakage, we find that a US withdrawal from the Paris Agreement lowers the achieved global emission reduction by a third (33.7%). As shown in section 2.6, we can decompose the US emission increase into three components. It could stem from an overall increase in production (scale effect), a shift towards the production of more energy-intensive goods (composition effect), or the use of more fossil fuel intensive production techniques for a given scale and composition of the economy (technique effect). We find a zero scale effect, a very small composition effect (0.3%) and a very strong technique effect

(4.8%).[5] As explained above, the technique effect can occur either due to a carbon tax or due to changes in the world fossil fuel price. As the withdrawing country does not introduce a carbon tax, we can fully attribute the strong positive technique effect to a decline in the fossil fuel price in response to lower fossil fuel demand in the committed countries. US producers make use of this fall in the price to switch towards a more fossil fuel intensive production technique. These findings indicates that the leakage of carbon emissions into the US is almost entirely driven by the energy-market leakage channel. This insight relates to a strand of literature that stresses the role of the supply side in climate policies (cf. e.g. Sinn, 2008; Harstad, 2012; Jensen, Mohlin, Pittel, and Sterner, 2015). If achieving the reduction targets in the rest of the world via carbon taxes (i.e. a demand-side climate policy) induces strong leakage towards the US, climate policies that try to directly limit the *supply* of fossil fuels might be offset to a smaller extent.

4.2 A Potential Chinese Withdrawal

China has ratified the Paris Agreement and – different than the US – has not expressed an intention to withdraw. The scenario of a Chinese withdrawal is therefore a much more hypothetical one. Given China's role as the world's largest emitter and its very different economic structure compared to highly developed countries (as the US), we think it is nevertheless an illustrative example that is worth a closer look before moving on to comparing results across the world.

Given China's mild reduction target, we showed in the introduction that the direct effect of removing the Chinese NDC had a far less detrimental effect on the global emission reduction (5.4%) than the US case. But again, this number was based on China following its BAU emission path. In fact, we find that Chinese emissions increase by 6.6% in response to the other countries' carbon taxes if China does not introduce a climate policy of its own. Due to the very high level of Chinese emissions, this is equivalent to a 12.1% leakage rate, i.e. an even higher share of the rest of the world's emission reductions is offset than in the US withdrawal case. Putting the direct loss and the leakage effect together results in a total global emission reduction loss of 17.5% for

[5] Note that the decomposition relies on a total differential and therefore is a linear approximation around the baseline equilibrium. The three effects hence do not necessarily (and typically) exactly add up to the overall emission change.

a Chinese withdrawal from the Paris Agreement. Taking into account an endogenous reaction to the other countries' policies hence more than triples the overall harm done to the effectiveness of the agreement in this case. As in the US case, the increase in Chinese emissions is almost entirely driven by the fall in the international price for fossil fuels (5.9%, compared to 0.1% scale and a 0.3% composition effect).

4.3 Results Across the World

We now turn to comparing the effects of unilateral withdrawals of all countries in our data set. Figure 4 shows the emission changes in every country if the rest of the world fulfills its targets and the respective country takes no climate policy action. Unsurprisingly, all countries endogenously react by increasing their emissions. As it turns out, the two examples considered so far (China and the US) are the countries with the smallest percentage emission increases. All other countries experience higher carbon emissions in the range of 7.5 to almost 11%. Comparing the pattern to figures 1 and 3, countries with a high overall level of emissions and/or very ambitious reduction targets appear to have lower increases of their emission levels.

To dig a little deeper into the differences in national emission effects, we can again make use of the decomposition. Two characteristics of our exemplary considerations hold up as global patterns: the almost complete absence of a scale effect (0.01% on average) and the predominant role of the technique effect (accounting for 86% of the emission increase on average). Different from the Chinese and US cases, the composition effects are non-negligible for many other countries (1.2% on average, ranging up to 3.7%). Figures 5 and 6 depict the technique and composition effects in the withdrawing countries, respectively.

Just as for the overall emission effect, the technique effect is smallest in the US and China. If one of these major emitters of carbon emissions is absent from the Paris Agreement, the fall in the demand for fossil fuels is strongly attenuated. This implies less pressure on the international fossil fuel price and hence a smaller incentive to shift towards more fossil fuel intensive production techniques. On the other hand, if a small country with a mild reduction target drops out of the agreement, almost the complete sum of national targets is still in place. Therefore, the fossil fuel

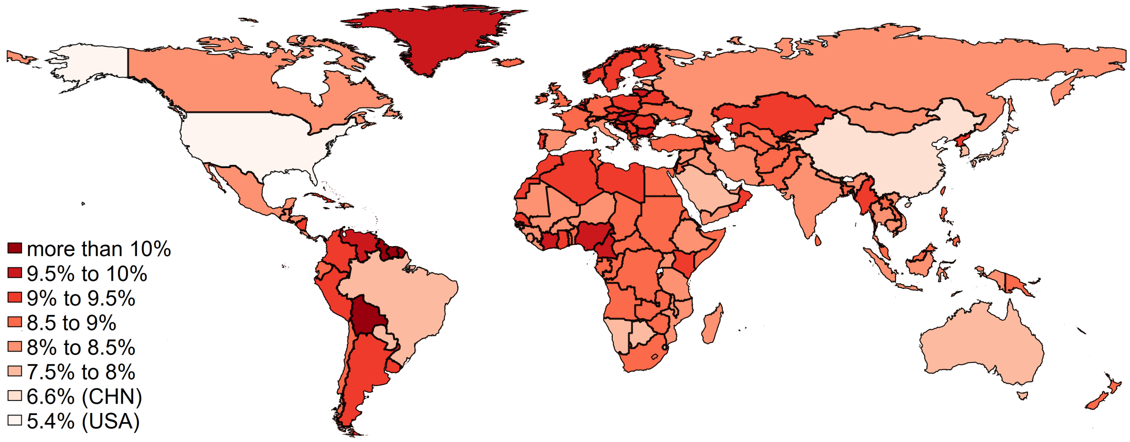

Figure 4: National Emission Effects

Notes: This figure shows the emission change in each country if the respective country withdraws from the Paris Agreement while the rest of the world fulfills its emission reduction targets. Emissions go up by 8.7% on average, ranging from 5.4% in the US to 11.0% in Trinidad and Tobago.

price goes down by almost the full extent by which it would have been lowered in the case of full global compliance with the Paris Agreement and therefore the withdrawing country faces a very strong incentive towards "dirtier" production techniques induced by the lower fossil fuel price.

More fossil fuel intensive production *techniques* for all goods are one reason why emissions in the withdrawing country can go up, another one is the possibility to specialize in the supply of goods from particularly emission-intensive *sectors*. This source of higher emissions is captured by the composition effect. While we found almost no compositional changes in China and the US in case of their withdrawals, it is evident from figure 6 that the same is not true for many other countries. Even though the composition effects are not as strong as the technique effects, most countries make use to a noticeable extent of the possibility to shift production towards emission intensive sectors and then exports these products to Paris member countries who partly pulled out of these sectors in order to achieve their emission reduction targets.

After this closer look on how the national emission increases of withdrawing countries come about, let us focus on the implications of these endogenous adjustments for the global emissions.

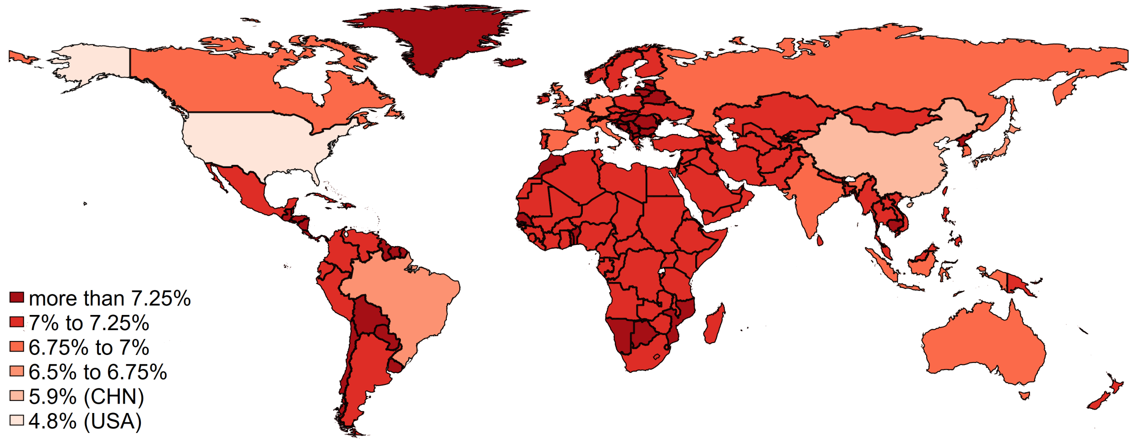

Figure 5: Technique Effects

Notes: This figure shows the technique effect in each country if the respective country withdraws from the Paris Agreement while the rest of the world fulfills its emission reduction targets. The technique effect increases the withdrawing country's emissions by 7.2% on average, ranging from 4.8% in the US to 7.3% in Croatia.

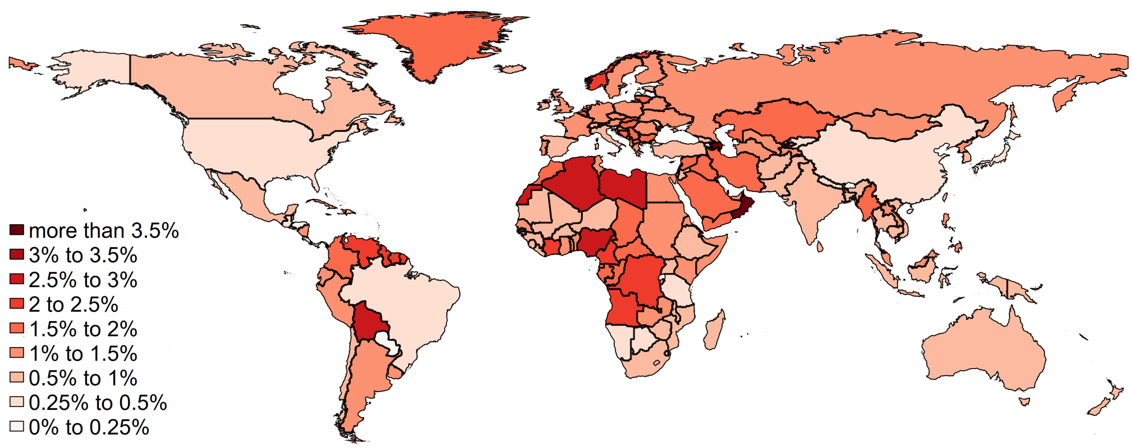

Figure 6: Composition Effects

Notes: This figure shows the composition effect in each country if the respective country withdraws from the Paris Agreement while the rest of the world fulfills its emission reduction targets. The composition effect increases the withdrawing country's emissions by 1.2% on average, ranging from 0.04% in Luxembourg to 3.7% in Trinidad and Tobago.

As illustrated above for the Chinese and US case, the emission increase in the withdrawing country partly offsets the global emission reduction from the remaining reduction targets, a phenomenon that is captured by the leakage rate. Figure 7 displays the different leakage rates that occur in the 139 withdrawal scenarios. Even though the US and China experience the lowest percentage emission increase, their very high levels of carbon emissions translates these comparatively small increases into the by far highest leakage rates. Already the withdrawals from the group of countries with the highest leakage rates after those two leading emitters (India, Russia, Japan, and Germany) offsets far lower shares of the world emission reduction (3.5, 3.1, 2.2, and 1.8%, respectively). As was illustrated by the consideration of the technique and composition effects above, leakage appears to be primarily driven by the energy market leakage channel, while leakage via the production shift and international trade channel plays a second-order role. For most countries, leakage is very small as their emissions make up only a small fraction of global emissions (the median leakage rate is 0.07%).

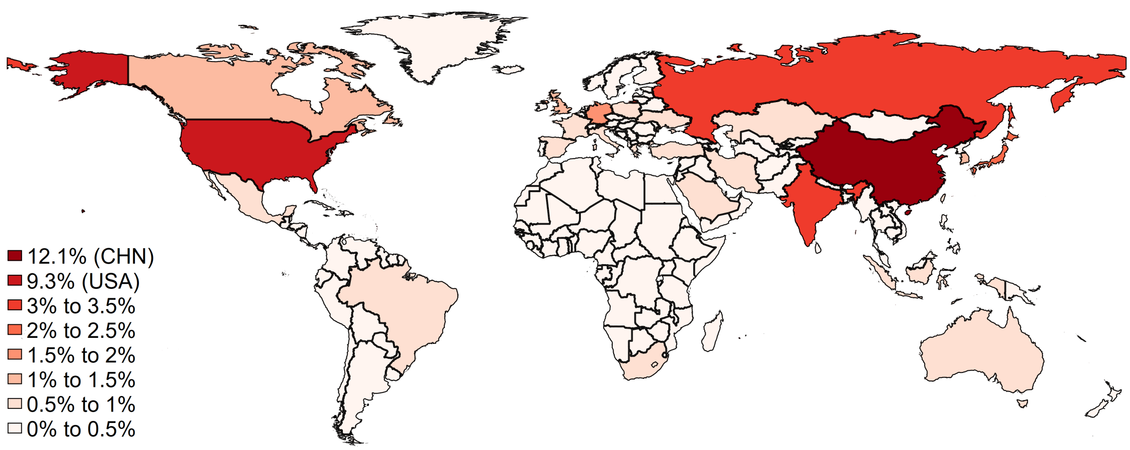

Figure 7: Leakage Rates

Notes: This figure shows the leakage rates that occur in the 139 different unilateral withdrawal scenarios from the Paris Agreement. On average, 0.4% of the rest of the world's emission reduction is offset by emission increases in the withdrawing country. The leakage rates range between 0.0% for a number of very small countries and 12.1% for China.

Putting together the direct emission reduction losses from removing a withdrawing country's reduction target and the additional leakage losses due to endogenous adjustment towards higher emissions in the withdrawing country, we can obtain total loss in the global emission reduction of the Paris Agreement induced by unilateral withdrawals. These total reduction losses are shown in figure 8 and (for the five countries with the strongest effects) in table 4. The announced US withdrawal has by far the worst impact on the Paris Agreement's effectiveness to lower global emissions, followed by the also previously discussed Chinese case. All other unilateral withdrawals are significantly less harmful to the agreement's capacity to lower world emissions. Nevertheless, a group of countries including e.g. several European countries (Germany, Italy, Spain, France, the United Kingdom, Greece, and Poland), other large developed countries (Japan, South Korea, Canada, and Australia), as well as three of the four remaining BRICS states (Brazil, Russia, and India) would still perceptibly lower the overall reduction (all in the range of 3 to 7.5%). Two particularly noteworthy cases are India (3.6%) and Russia (3.2%) for both of which the zero target (i.e. the target to not do worse than the BAU path) implied a zero direct effect. Taking into account their endogenous adjustment, it becomes evident that a Russian or Indian withdrawal would indeed harm the effectiveness of the Paris Agreement significantly. For all African countries, as well as for smaller and/or poorer European, Asian, or South American countries, even the total effect remains rather small, pulling down the average across all countries to a 1.1% reduction loss.

Withdrawing country	USA	CHN	BRA	JPN	DEU
World reduction lost (total effect)	33.7%	17.5%	7.5%	7.4%	5.8%

Table 4: Top Five Total Reduction Losses

Table 5 summarizes the results for all major variables of interest across the 139 different withdrawal scenarios that have been graphically shown above.

5 Conclusion

In spite of potential problems of enforceability and an overall lack of ambition in the NDCs, the Paris Agreement has an important strength: its global coverage. This strength is currently at stake as not all signatory states have moved forward to ratification of the agreement and one major

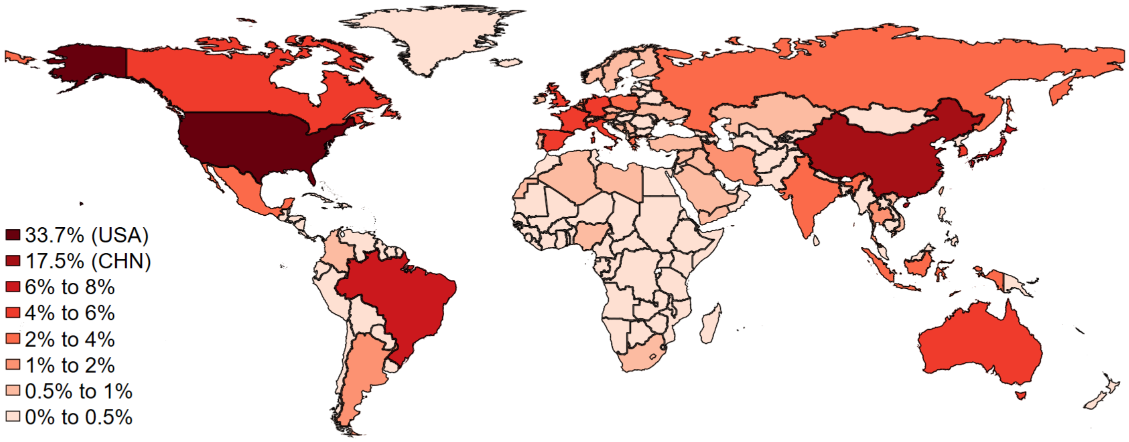

Figure 8: Total Emission Reductions Lost

Notes: This figure shows the shares of the global emission reduction due to the Paris Agreement that is lost due to a unilateral withdrawal in the 139 different scenarios. On average, 1.1% of the global emission reduction are forgone. The loss shares range from 0.0% for a number of very small countries to 33.7% for the US.

Variable	Obs	Mean	SD	Min	Max
Direct global reduction loss (in %)	139	0.72	2.47	0	25.52
Total global reduction loss (in %)	139	1.15	3.49	0.00	33.69
Leakage rate (in %)	139	0.41	1.36	0.00	12.11
Emission effect* (in %)	139	8.69	0.71	5.36	10.98
Scale effect* (in %)	139	0.01	0.04	-0.09	0.16
Composition effect* (in %)	139	1.16	0.72	0.04	3.71
Technique effect* (in %)	139	7.16	0.26	4.81	7.32

Table 5: Unilateral Withdrawal Results

Notes: For the variables marked by an asterisk, the national values of the withdrawing countries are shown.

party – namely the US – has ratified, but already announced its withdrawal. In this paper, we analyze the consequences of unilateral withdrawals from the Paris Agreement on the achieved global emission reduction. To be able to account for both the direct effect of removing the withdrawing country's reduction target and the indirect effect of additionally offset emission reductions due to carbon leakage, we develop an extended multi-sector structural gravity model featuring emissions from fossil fuel use, carbon taxes, and a constant elasticity fossil fuel supply function. We find that single countries leaving the Paris Agreement can severely hurt the effectiveness of the treaty, the worst case being a US withdrawal which would eliminate one third of the overall emission reduction. Taking into account the endogenous emission adjustments beyond the mere absence of an emission target turns out to be of major importance, most notably in the Chinese case, in which the reduction loss more than triples if carbon leakage is added to the direct effect. Using a decomposition of emission changes into scale, composition, and technique effects, we find that emission increases in withdrawing countries are mainly driven by a shift towards emission-intensive production techniques in response to a fall in the international fossil fuel price.

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