The effects of the Kyoto Protocol on the carbon trade balance

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Abstract

This study presents estimates of the magnitude of carbon leakage as a consequence of emission reduction commitments under the Kyoto Protocol using gravity model-style regression analysis on data from the WIOD project. The carbon trade balance between 2002 and 2009 was reduced by 705 megatons of carbon dioxide due to Kyoto and carbon leakage amounts to slightly above 4% of traded carbon dioxide emissions. We highlight four previously neglected issues: First, we control for multilateral trade resistance in the estimation of a unilateral policy by using a two-stage procedure. Second, we control explicitly for the effect of Eastern European countries on leakage estimates. We show that this country group strongly affects the baseline estimates in the framework introduced by Aichele and Felbermayr (Rev Econ Stat 97(1):104–115, 2015). Third, we introduce an alternative specification of the Kyoto variable. Fourth, this is the first study to present econometric evidence for the magnitude of carbon leakage from services sectors. While service elasticities are estimated to be sizable, strong leakage is limited to transport sectors as well as renting of machinery. The manufacturing sectors of metals, machinery and transport equipment are responsible for three quarters of observed leakage.

Keywords Carbon leakage · Kyoto Protocol · Climate policy · Trade and environment · Gravity model

JEL Classification F18 · F53 · F64 · Q56

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1 Introduction

In the process of international negotiations that led to the agreement in Kyoto,¹ fears about possible carbon leakage effects² from the Protocol were widespread (Barrett 1998). The United States, the major emitter of greenhouse gas at the time of negotiating, motivated its refusal to participate with leakage concerns (Hagel 1997). Models of international trade (Copeland and Taylor 2005) and computable general equilibrium models (Babiker 2005) were used to study the issue and predicted widely varying leakage rates. Predicted leakage was shown to be very sensitive to the choice of parameters (Burniaux and Oliveira Martins 2012).

Studies by Aichele and Felbermayr (2012, 2015) presented the first econometric evidence for carbon leakage via international trade. Their second paper examines leakage on a sectoral level. The authors argue that Kyoto ratification caused an increase of sectoral imports from non-member countries and a decrease of exports to non-members of 7.8%. Their estimation strategy derives from the building blocks of structural gravity models. Trade flows of embodied CO₂ are explained by a variable that captures the between-country difference in Kyoto ratification status. Regressions are conducted on pooled data of sectoral trade flows (40 countries, 12 sectors).

The aim of the present study is to estimate the partial equilibrium carbon leakage caused by the Kyoto Protocol while controlling for multilateral trade resistance.³ More specifically, we are asking how Kyoto affected the global carbon trade balance of ratifiers versus non-ratifiers, i.e. the difference between exports and imports of embodied carbon dioxide. The concept of the carbon trade balance is also known in the literature as ‘CO₂ trade balance’ or ‘balance of embodied emissions in trade’ (Munksgaard and Pedersen 2001; Muradian et al. 2002) and was used to study emission transfers via international trade between Kyoto ratifiers and non-ratifiers (Peters et al. 2011). Examining carbon leakage using the concept of the carbon trade balance is a direct consequence of the ‘strict’ definition of carbon leakage we employ [see the discussion in Peters and Hertwich (2008)]. Essentially the decision to ratify commitments under the Kyoto Protocol is a unilateral environmental policy even if the negotiating process was multilateral. The decision to ratify engages a country relative to its trading partners. At the same time, the decision to not ratify also amounts to a change of *relative* domestic environmental policy. The ratifying country will increase relative production costs and therefore substitute foreign for domestic products, while the non-ratifying country will decrease relative production costs

¹ In the Kyoto Protocol member states of the United Nations Framework Convention on Climate Change (UNFCCC) decided in 1997 on emission reduction targets for industrial nations. The ratification process in the individual member states started in 2001, with most countries ratifying in 2002. Some countries still ratified in the following years—see Tables 9 and 10 in “Appendix 1”. The emission reduction target amounted to an average of − 5.2% in the period 2008–2012 against the base year level (typically 1990).

² The term *carbon leakage* refers to increases in foreign CO₂ emissions as a direct consequence of domestic regulation of CO₂. What is typically called the *leakage rate* measures the increase in foreign emissions relative to the decrease in domestic emissions. Leakage can be interpreted as a phenomenon in the realm of the pollution haven hypothesis (Copeland and Taylor 1994; Zhang et al. 2017).

³ On multilateral trade resistance, see e.g. the work by Anderson and van Wincoop (2003)

Fig. 1 Carbon Trade Balance of Kyoto ratifiers with non-ratifiers. *Notes* The carbon trade balance consists of exports minus imports of embodied CO₂. This graph is from the viewpoint of Kyoto ratifiers in the sample, where trading partners are all non-ratifiers in the sample

and substitute domestic for foreign products. Thus we need to look at both exports and imports of Kyoto ratifiers (and non-ratifiers) to determine the amount of carbon leakage caused by the Protocol.

Looking at Fig. 1, we observe a noticeable kink in the development of the carbon trade balance between Kyoto ratifiers and non-ratifiers around the year 2002. Most member countries ratified their commitments in national parliaments that year. Committed countries increased their net imports of embodied carbon dioxide from around 100 to around 600 megatons. Several explanations for this development are possible, among them leakage effects, China joining the WTO,⁴ an increasing number of regional trade agreements between members and non-members of Kyoto and so on. We follow the methodology of Aichele and Felbermayr (2015) of effectively treating the Protocol as influencing domestic production costs which will result in changes to domestic mill prices and consequently to multilateral trade resistance. Under the leakage hypothesis, the Kyoto Protocol leads to an increase in the effective price of carbon dioxide. This in turn will lead to a partial substitution of goods and services from non-ratifiers for those from ratifiers.

In order to meaningfully relate estimated leakage to the carbon trade balance we need to take into account sectoral differentiation of the effects and apply the estimated elasticities to sectoral emission trade flows. This is especially important if trade flows are very unequally distributed across sectors as is the case with services. While several studies have presented evidence on traded emissions including services sectors (Fernández-Amador et al. 2016, is one example), the use of the World Input–Output Database (WIOD) in combination with multi-regional input–output analysis allows us to present the first econometric evidence for leakage effects from

⁴ See also the discussions on whether China became a pollution haven after 2002 (Zhang et al. 2014).

the Kyoto Protocol through services trade. Carbon leakage from services turns out to be quite substantial in percentage terms, although less so in absolute terms.

Besides the estimation of Kyoto's impact on the carbon trade balance, including the first estimates of services' role in that, this study makes four further contributions. First, we estimate the treatment effect from Kyoto ratification via a two-stage procedure suggested by Head and Mayer (2014) in order to control for multilateral trade resistance while estimating the carbon trade impact of a unilateral policy. Second, we suggest an alternative specification of the Kyoto treatment variable that allows us to estimate asymmetric effects on Kyoto ratifiers' imports and exports. Third, we allow for time-varying effects of ratification. Fourth, we take into account the special role of Eastern Europe, a previously neglected issue. These countries are shown to significantly influence the results, however, we will raise some doubts about the estimates in their case.

The average annual estimated effect of the Kyoto Protocol on the carbon trade balance amounts to 88 megatons of CO₂, summing up to a total of 705 megatons in the period 2002–2009. Kyoto ratification is associated with an increase of 4.4% of total emissions embodied in imports, and 4.2% of total emissions embodied in exports from ratifiers to non-ratifiers. Depending on the years, between 11 and 54% of the negative carbon trade balance of Kyoto countries can thus be explained. We can quantify major sources of carbon leakage in transport sectors such as water or inland transport. The effect of services remains somewhat limited due to the low level of trade in these sectors. Energy-intensive manufacturing sectors such as metals, machinery and transport equipment exhibit the highest levels of leakage and are responsible for 76% of the total estimated effect on the carbon trade balance.

2 Data and construction of the carbon trade balance

The carbon trade balance consists of exports minus imports of carbon dioxide, i.e. flows of emissions embodied in the traded goods and services. To construct a data set of emission trade flows we use the World Input–Output Database (WIOD). WIOD offers annual multiregional input–output (MRIO) tables from 1995 to 2009.⁵ These tables are needed in order to approximate average sectoral CO₂ emission intensities that include the upstream emissions from other sectors and countries.⁶ The world in WIOD consists of 40 countries and one rest of the world category. Each economy is split into 34 sectors, 17 of which are services sectors. At the same harmonized country-sector resolution, this database also provides information on

⁵ For detailed information on the construction, structure and use of WIOD, a project funded by the European Commission in order to study the effects of globalization on production processes, see Dietzenbacher et al. (2013), Timmer (2012) and Timmer et al. (2015). Available online at: <http://www.wiod.org/database/wiots13> (last accessed: Apr 23, 2019). Newer releases of WIOD offer also longer time series, although not for the environmental accounts.

⁶ Kitzes (2013) provides a concise introduction to environmentally extended input–output analysis.

carbon dioxide emissions from fossil fuel combustion and non-energy usage.⁷ This informs us about direct sectoral emissions. We use the MRIO tables to include indirect emissions (emissions from previous production stages) in the calculation of emission intensities of traded goods and services.⁸ Bilateral sectoral trade flows are implicit in the MRIO tables and can be extracted thereof. For more details on the data and some descriptive statistics, consult “Appendix 1”.

The database is well-suited for our analysis due to the inclusion of the major Kyoto committed countries (with Switzerland and Norway being the most prominent missing ones) as well as the most important non-Kyoto countries.⁹ The sample covers 85% of world GDP, slightly less of global carbon dioxide emissions (81–82%) and between 82–87% of total world trade in value terms. WIOD also carefully corrects problems in relation to re-exports and export-processing zones.¹⁰

The world vector of emission intensities Γ_t with representative element $\gamma_{j,s,t}$ in sector s of country j in year t is obtained by pre-multiplying the World Leontief inverse with the vector of direct emissions per unit of a sectors output R_t .¹¹

$$\Gamma_t = R_t(I - A_t)^{-1} \quad (1)$$

We combine the information in Γ_t with the value of imports $M_{i,j,s,t}$ of importer i from exporter j to obtain the CO₂ emissions embodied in an import flow $M_{i,j,s,t}^c$.¹²

$$M_{i,j,s,t}^c = M_{i,j,s,t} \gamma_{j,s,t} \quad (2)$$

We define the carbon trade balance $CTB_{i,j,t}$ of country i with country j as the sum of sectoral exports $E_{i,j,s,t}^c = M_{j,i,s,t}^c$ minus imports $M_{i,j,s,t}^c$ of carbon dioxide.

$$CTB_{i,j,t} = \sum_{s \in S} M_{j,i,s,t}^c - \sum_{s \in S} M_{i,j,s,t}^c \quad (3)$$

In Fig. 1 we presented the carbon trade balance for all Kyoto countries with all non-Kyoto countries in WIOD. The picture would look mirror-inverted for non-Kyoto countries. Figure 2 depicts the carbon trade balances for individual countries. The core observation from the upper panel of these graphs is that the carbon trade balance with non-members decreased for all of the most important Kyoto ratifiers

⁷ Details on the construction of the environmental satellite accounts of WIOD are provided by Genty et al. (2012).

⁸ Another approach to obtain sectoral emission intensities would be single-regional input–output (SRIO) analysis. This would again account for the substantial differences in within-country intermediate trade (Zhang and Zhang 2017). The difference is that SRIO assumes that imported intermediate inputs were produced using the domestic technology. Especially when dealing with North–South trade flows we typically observe strong technology differences.

⁹ WIOD covers 29 out of 37 Annex-B parties to the Kyoto Protocol. The following Kyoto ratifiers with reduction commitments are missing: CRO, ISL, LIE, MON, NOR, NZL, CHE, UKR.

¹⁰ For some of the basic results, we conduct robustness checks using the data from Aichele and Felbermayr (2015).

¹¹ A more detailed treatment of the MRIO procedure can be found in “Appendix 2”.

¹² Equivalently, we could write the relation for the domestic country as exporter using the domestic country’s emission intensity: $E_{i,j,s,t}^c = E_{i,j,s,t} \gamma_{i,s,t}$.

Fig. 2 Country carbon trade balances: Largest CO₂ traders. Notes. Vertical axis: Megatons CO₂. Each panel shows the eight largest carbon dioxide traders among Kyoto ratifiers (upper panel) and non-ratifiers (lower panel). Each country is shown twice, its carbon trade balance with the group of ratifiers and non-ratifiers

after 2002.¹³ At the same time the carbon trade balance with other member countries does not show a clear pattern: decreasing for some (RUS, CAN), increasing for some (DEU, JPN, ITA), relatively constant for some (FRA, GBR, NLD). For all of these countries, except Russia, the carbon trade balance with other Kyoto members developed more positively compared to non-members. However, the difference between the development of member and non-member trade differs considerably across countries. The leakage hypothesis is consistent with developments like in Germany: The carbon trade balance with Kyoto non-members develops more negatively than with members.

¹³ This result holds even more strongly for the Eastern European ratifiers that were joining the European Union in 2004 and 2007. Figure 8 in “Appendix 3” depicts their country carbon trade balances. This is especially interesting with respect to Sect. 5.

For the most important non-ratifiers, we observe that on average the carbon trade balance increased by more for trade with Kyoto members. Interestingly, the largest emitter of carbon dioxide, China, exhibits no difference in the development of Kyoto and non-Kyoto trading patterns. The second largest emitter, the United States, displays the pattern we would expect under the leakage hypothesis: The carbon trade balance with Kyoto members develops more positively than with non-members.

3 Methodology

3.1 Estimating emission trade elasticities

In order to identify the effect of the Kyoto Protocol on the carbon trade balance we follow and extend the methodology proposed by Aichele and Felbermayr (2015). The logarithmic transformation of bilateral CO₂ trade flows $M_{i,j,s,t}^c$ will act as the dependent variable in our regressions. We explain them by a measure of differential Kyoto treatment and control for time-varying pair-specific policy variables $P_{i,j,t}$ (common membership in trade agreements, the European Union and the World Trade Organization). We control for country-pair idiosyncratic sectoral carbon trade levels $v_{i,j,s}$, i.e. capturing path dependencies of particularly strong sectoral relations that are time-independent within our sample (Baltagi et al. 2003). Additionally, and in contrast to Aichele and Felbermayr, we control for multilateral resistance by including importer and exporter-specific time effects on carbon trade $\theta_{i,s,t}$ and $\zeta_{j,s,t}$. Thereby we capture if a country increases or decreases CO₂ imports or exports with all other countries in the sample over time.

Treatment (Kyoto participation) of importer i is modeled using an indicator variable $K_{i,t}$ taking the value 1 if i has ratified binding emission constraints under Kyoto in year t . We propose two ways of including the difference in bilateral Kyoto status in our regression. Specification (i) uses the Aichele and Felbermayr formulation $\Delta K_{i,j,t} = K_{i,t} - K_{j,t}$. Here, differential Kyoto treatment $\Delta K_{i,j,t}$ can take the values $\{-1, 0, 1\}$, with 1 if only the importer is treated and -1 if only the exporter is treated. In specification (ii), we include two indicator variables: $\bar{K}_{i,j,t}^m$ has value 1 whenever only the importer is treated, $\bar{K}_{i,j,t}^x$ has value 1 whenever only the exporter is treated.

In a structural gravity framework one way to control for the multilateral resistance terms lies in the inclusion of importer- and exporter-specific time fixed effects $\theta_{i,s,t}$ and $\zeta_{j,s,t}$. As is well known in the gravity literature, the effects of unilateral policies cannot be directly estimated in most structural gravity models as importer and exporter-specific time fixed effects would wipe out all the variation with respect to the policy of interest (Yotov et al. 2016). From the viewpoint of each country the ratification of commitments under the Kyoto Protocol is a unilateral decision not varying over trading partners. This would lead to perfect collinearity between $K_{i,t}$ and $\theta_{i,t}$. Head and Mayer (2014) suggest a two-stage approach to estimate unilateral effects while controlling for multilateral resistance. In the first stage, a regression of logarithmic trade flows on all bilateral policy variables, standard trade cost variables and multilateral resistance terms is estimated.

Standard trade costs (e.g. distance, contiguity, language, cross-border trade, colonial history) are captured by $v_{i,j,s}$ and multilateral resistance is captured by $\theta_{i,s,t}$ and $\zeta_{j,s,t}$. In the second stage, the estimates $\widehat{\theta}_{i,s,t}$ and $\widehat{\zeta}_{j,s,t}$ from the first stage are regressed on all the i , t - and j , t -specific variables including controls for importer carbon expenditure levels $e_{i,s,t}$ and exporter carbon output levels $y_{j,s,t}$.¹⁴

(1st stage)

$$\ln M_{i,j,s,t}^c = \alpha_0 + \delta P_{i,j,t} + \theta_{i,s,t} + \zeta_{j,s,t} + v_{i,j,s} + e_{i,j,s,t} \quad (4)$$

(2nd stage)

$$(i) \widehat{\theta}_{i,s,t} + \widehat{\theta}_{j,s,t} = \alpha + \sum_{g \in G} \sum_{s \in S} \sum_{t \in T} [\beta_{g,s,t} \Delta K_{i,j,t}] + \alpha_e \ln e_{i,s,t} + \alpha_y \ln y_{j,s,t} + \varepsilon_{i,j,s,t} \quad (5)$$

$$(ii) \widehat{\theta}_{i,s,t} + \widehat{\theta}_{j,s,t} = \dots + \sum_{g \in G} \sum_{s \in S} \sum_{t \in T} [\beta_{g,s,t}^m \overline{K}_{i,j,t}^m + \beta_{g,s,t}^x \overline{K}_{i,j,t}^x] + \dots \quad (6)$$

The motivation for specification (ii) is that we want to allow for asymmetric treatment effects on treated countries' imports and exports. Specification (i) amounts to imposing the restriction $\beta_{g,s,t}^m = -\beta_{g,s,t}^x$. This restriction might not be warranted a priori. As an example take a country that raises the environmental standard on some product group to a level that domestic producers would already fulfill but foreign producers would not. In this case effective trade costs for importing would increase while they would stay unaffected for exporting.

Generally, we allow treatment effects $\beta_{g,s,t}$ to vary over time, sectors and countries/country groups. The set T contains all years between 2001 (first countries ratified Kyoto) and 2009 (last year in our sample). S contains all 34 sectors in the sample. G contains three country groups for which we expect differing effects (see discussion in Sect. 5). In addition we also report estimates with the restriction $\beta_{g,s,t} = \bar{\beta} \forall g, s, t$ to get the average sectoral time-constant effect of Kyoto, as well as the estimates restricted by $\beta_{g,s,t} = \bar{\beta}_t \forall g, s$ to get the average sectoral treatment effect over time.

Following the tradition of the gravity literature, we estimate Eqs. 4 and 5 by pooled OLS. We perform several robustness checks in Sect. 7. With respect to omitted variable bias and consistency of the estimated treatment effect we trust that the

¹⁴ The inclusion of $e_{i,s,t}$ and $y_{j,s,t}$ follows directly from the derivation of the theoretical gravity model which can be summarized as

$$M_{i,j,s,t} = \frac{e_{i,s,t}}{R_{i,s,t}^m} \frac{y_{j,s,t}}{R_{j,s,t}^x} T_{i,j,s}$$

where $R_{i,s,t}^m$ are the $R_{j,s,t}^x$ are the importer and exporter multilateral resistance terms and $T_{i,j,s}$ is a general trade cost variable. See Feenstra (2016, p. 168ff).

included fixed effects take care of most of the unexplained variation in emission trade.¹⁵ The cross-sectional importer–exporter-sector fixed effect $v_{i,j,s}$ controls for time-invariant bilateral trade relations and thereby for the specialization of each economy which might affect selection into ratifying.¹⁶

For a causal interpretation of the Kyoto effect, we need the common trend assumption: In the absence of Kyoto, treated country pairs would behave as their untreated counterparts. Some of the most important non-ratifiers are emerging economies (EECs) like China, India, Brazil, Mexico, Turkey and Indonesia, while most of the ratifiers are high-income economies (HECs). Sectoral trade growth of the EECs with all other countries is controlled for by $\theta_{i,s,t}$ and $\zeta_{j,s,t}$. Asymmetric trade growth of the EECs with the HECs might cause a bias to our estimate if it is timely correlated with Kyoto ratification. However, as Aichele and Felbermayr (2015) point out, the construction of their treatment variable $\Delta K_{i,j,t}$ mitigates this potential bias. If asymmetric trade growth between EECs and HECs were solely the result of non-Kyoto related factors, this would bias $\hat{\beta}_{g,s,t}$ downwards in specification (i).¹⁷ This is not necessarily true for $\hat{\beta}_{g,s,t}^m$ and $\hat{\beta}_{g,s,t}^x$ in specification (ii).¹⁸ Thus specification (i) is preferable if we have reason to believe that trade growth between Kyoto ratifiers and non-ratifiers behaves significantly different from trade growth within each group (ratifiers, non-ratifiers) even in the absence of the Protocol.

3.2 Calculate effects on the carbon trade balance

Ultimately we are interested in the change of the carbon trade balance between Kyoto ratifiers (*rat*) and non-ratifiers (*non*). In the style of Eq. 3, we define

$$CTB_{rat,non,t} = \sum_{i \in non} \sum_{j \in rat} \sum_{s \in S} M_{j,i,s,t}^c - \sum_{i \in rat} \sum_{j \in non} \sum_{s \in S} M_{i,j,s,t}^c \quad (7)$$

$$= \sum_{s \in S} M_{non,rat,s,t}^c - \sum_{s \in S} M_{rat,non,s,t}^c \quad (8)$$

The estimated change in the carbon trade balance follows from applying the elasticities to actual emission trade flows.

¹⁵ “As long as the fixed effects do not wipe out all of the variation of interest, it will likely remove most sources of inconsistency” (Baltagi et al. 2014, p. 632)

¹⁶ See also the selection model in Aichele and Felbermayr (2015).

¹⁷ Each country couple is observed twice, once with HEC as importer, once with EEC as importer. Both, under a general trade boom and under a hypothetical Kyoto effect, $\hat{\beta}_{g,s,t} \uparrow$ for $M_{HEC,EEC,s,t}^c$. However for $M_{EEC,HEC,s,t}^c$ under a general trade boom $\hat{\beta}_{g,s,t} \downarrow$, while under a hypothetical Kyoto effect $\hat{\beta}_{g,s,t} \uparrow$. In sum, under a general trade boom $\hat{\beta}_{g,s,t}$ would exhibit no effect, while a hypothetical Kyoto effect would show up in $\hat{\beta}_{g,s,t} \neq 0$.

¹⁸ Under specification (ii), only one observation per country couple feeds into the estimation of $\hat{\rho}_{g,s,t}^m$ as well as $\hat{\rho}_{g,s,t}^x$. The reason lies in the construction of the treatment variables: When observing $M_{HEC,EEC,s,t}^c$ it follows that only $\bar{K}_{i,j,t}^m = 1$ while $\bar{K}_{i,j,t}^x = 0$. On the other hand, for $M_{EEC,HEC,s,t}^c$, $\bar{K}_{i,j,t}^m = 0$ and $\bar{K}_{i,j,t}^x = 1$. Compare this to specification (i), where $\Delta K_{i,j,t} = 1$ in the first case and $\Delta K_{i,j,t} = -1$ in the second case, thus both country couple observations feeding into the estimation of $\hat{\beta}_{g,s,t}$.

$$\Delta \widehat{CTB}_{rat,non,t} = \sum_{g \in G} \sum_{s \in S} M_{non,g,s,t}^c \widehat{\beta}_{g,s,t}^x - \sum_{g \in G} \sum_{s \in S} M_{g,non,s,t}^c \widehat{\beta}_{g,s,t}^m \quad (9)$$

When estimating specification (i) we would just use $-\widehat{\beta}_{g,s,t}^x = \widehat{\beta}_{g,s,t}^m = \widehat{\beta}_{g,s,t}$.

4 Restricted estimates of Kyoto treatment

Estimating Eqs. 4 and 5 generates a large amount of output. The most important results are presented in Sect. 6. In the current section we discuss some of the results under relatively strict restrictions on the coefficient estimates. We start by looking at the coefficients under the constraint that one and the same estimate is applying to the whole sample.

Table 1 presents the estimates for time-, sector- and group-invariant Kyoto treatment effects. Columns 1–3 display results for specification (i), while columns 4–6 display results for specification (ii). For the full sample and specification (i), Kyoto ratification implies on average increasing sectoral imports and decreasing sectoral exports of 11.2%. Aichele and Felbermayr (2015) find a baseline estimate of 7.8%. What explains the difference? The latter study uses only twelve sectors, most of them manufacturing sectors. It also uses a slightly different sample of countries and a slightly shorter time span. If we exclude all tertiary sectors (services sectors 18–34) from the estimation the estimate is reduced to 6.4% (see column 2). The result from the pooled sample in column 1 is thus considerably driven by services sectors. Looking at column 4, specification (ii) reveals that on average the effect on exports is larger than that on imports. This is driven by primary (agriculture,

Table 1 Kyoto treatment effects: time-, sector- and group-invariant

	All	w/o	Only	All	w/o	Only
	sec.	serv.	serv.	sec.	serv.	serv.
	(1)	(2)	(3)	(4)	(5)	(6)
$\Delta K_{i,j,t}$	0.112*** (0.005)	0.064*** (0.006)	0.165*** (0.009)			
$\overline{K}_{i,j,t}^m$				0.086*** (0.009)	0.031*** (0.009)	0.155*** (0.015)
$\overline{K}_{i,j,t}^x$				– 0.136*** (0.008)	– 0.097*** (0.008)	– 0.175*** (0.013)
Adj. R^2	0.966	0.971	0.949	0.966	0.971	0.949
$\beta_t^m = -\beta_t^x$ (F)				16.413	24.626	0.851
Obs.	754,955	397,824	357,131	754,955	397,824	357,131

Restriction: $\beta_{g,s,t} = \tilde{\beta} \forall g, s, t$. Dependent variable: $\ln M_{i,j,s,t}^c$. Standard errors in parentheses. Regressions include fixed effects for country-year and importer–exporter-sector, as well as controls for common WTO, EU, or RTA membership. Standard errors are clustered by importer–exporter-sector (53,040 clusters)

Significance: * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

mining) and secondary sectors (manufacturing), where imports from ratifiers increase by only 3.1% while exports to ratifiers decrease by 9.7%. For tertiary sectors, the difference between imports and exports is not statistically significant at the 5% level as the F-value of 0.85 confirms.

In Table 2 we examine the time-dimension of the effects. We can reject the hypothesis that coefficients are the same for all years at the 5% level. In specification (i), variation is relatively limited and there is no clear trend of growing or shrinking influence. Interestingly, the same is not true for specification (ii). The coefficients are presented graphically in Fig. 3. In the first years after ratification the negative effect on exports seems dominant. The F-tests in Table 2 inform us that for most of the years, effects on imports and exports are indeed significantly different. In the years after 2007 importer effects become dominant.

A further refinement of the estimates concerns the role of country groups, specifically the role of the Eastern European countries. In our main results we will distinguish estimates for three groups of Kyoto ratifying countries: old EU-15, new EU-10 from Eastern Europe and Non EU countries. In the following section we will discuss the motivation for doing so.

Table 2 Kyoto treatment effects: time-varying

	2002	2003	2004	2005
Specification (i)				
$\tilde{\beta}_t$	0.103*** (0.005)	0.147*** (0.005)	0.156*** (0.006)	0.126*** (0.006)
Specification (ii)				
$\tilde{\beta}_t^m$	0.093*** (0.008)	0.096*** (0.009)	0.107*** (0.009)	0.081*** (0.011)
$\tilde{\beta}_t^x$	-0.113*** (0.007)	-0.195*** (0.008)	-0.203*** (0.009)	-0.170*** (0.009)
$\tilde{\beta}_t^m = -\tilde{\beta}_t^x(\text{F})$	2.93** 2006	57.99*** 2007	45.58*** 2008	32.98*** 2009
Specification (i)				
$\tilde{\beta}_t$	0.082*** (0.007)	0.094*** (0.007)	0.143*** (0.008)	0.115*** (0.008)
Specification (ii)				
$\tilde{\beta}_t^m$	0.018 (0.011)	0.066*** (0.012)	0.168*** (0.013)	0.128*** (0.014)
$\tilde{\beta}_t^x$	-0.143*** (0.010)	-0.121*** (0.011)	-0.119*** (0.011)	-0.101*** (0.011)
$\tilde{\beta}_t^m = -\tilde{\beta}_t^x(\text{F})$	57.35***	10.12***	6.72***	1.92

Restriction: $\beta_{g,s,t} = \tilde{\beta}_t \forall g, s$. Dependent variable: $\ln M_{i,j,s,t}^c$. Standard errors in parentheses. Regressions include fixed effects for country-year and importer-exporter-sector, as well as controls for common WTO, EU, or RTA membership. Standard errors are clustered by importer-exporter-sector (53,040 clusters). We perform Wald-tests for equality of the Kyoto coefficients over time (in the period 2002–2009), the resulting F-statistics are non-significant at the 0.10 level, F-stat: 104.09 (β_t), 78.80 (β_t^m), 53.58 (β_t^x)

Significance: * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Fig. 3 Kyoto treatment effects: Time-varying. *Notes.* Coefficients from Table 2. Coefficient for β_t^k is sign-inverted

5 The role of Eastern Europe

The fact that Kyoto ratification meant widely varying constraints for individual countries is depicted in Fig. 4. It compares the emission target for each country with its actual emission growth rates before ratification. To the left of the graph we find countries facing relatively strict targets like Canada, Spain and Portugal. The more we move to the right end of the graph, the less binding are the emission targets. We should underline two main points here: First, the distribution of emission targets is much narrower than the distribution of the actual emission growth rates before

Fig. 4 Country emission growth targets under Kyoto. *Notes.* For each country, the darker left bar shows the necessary average annual growth rate of emissions from 1990–2010 to stay below the binding emission target. The right bar shows the actual average annual growth rate of emissions from 1990 until the ratification of Kyoto. The difference (actual–target) indicates how strict a country’s target is, i.e. by how much would a country have to reduce its pre-ratification emission growth rate in order to achieve the target

ratification. Second, especially the Eastern European countries faced targets that meant almost no restrictions on their emission path. All countries with a particularly large negative difference of at least two percentage points are from that region. Even if we account for the fact that pre-ratification emissions are an imperfect measure of expected future business-as-usual emissions, the size of the differences is striking.

Of the ten countries with a negative trend-versus-target difference of more than two percentage points, nine joined the European Union either in 2004 (Poland, Hungary, Czech Republic, Slovakia, Lithuania, Estonia, Latvia) or 2007 (Bulgaria, Romania). The only missing countries from this wave of EU enlargement are Cyprus and Malta—both of them without an emission target under Kyoto—, as well as Slovenia which faced a stricter Kyoto target being also the economically most developed Eastern European nation.

These observations lead us to allow for varying estimates of the Kyoto treatment effect over country groups. One group (*NewEU*) consists of the ten Eastern European EU accession countries with emission targets. We split the rest of the Kyoto committed countries into the group of the fifteen members of the European Union prior to 2004 (*OldEU*) and a third group that combines the Kyoto ratifiers outside of the European Union (*NonEU*), i.e. Russia, Canada, Australia and Japan. For each group we create an indicator variable that takes value 1 whenever a group member is either the importer or the exporter. We interact these dummies with our treatment variable to estimate the average sectoral time-constant effect of Kyoto for each country group. In terms of Eqs. 4 and 5 this amounts to imposing a restriction $\beta_{g,s,t} = \hat{\beta}_g \forall s, t$. A priori we would expect to find low leakage estimates for countries with non-binding targets. These countries would not be forced to undertake particularly strong measures in order to change their emission path.

Column 1 in Table 3 shows that, contrary to that expectation, the new Eastern European EU members exhibited the strongest effect on the baseline leakage estimate. The carbon trade balance of these countries is affected by 20.1%. Specification (ii) suggests a highly significant differentiation of this effect: We estimate that emission imports from non-Kyoto countries increased by 32.5% after the ratification while exports declined by only 8.7%. On the other hand, treatment effects for the Old- and Non-EU groups are estimated at 2.7 and 4.8% respectively and seem to be the result of decreases of emission exports with slightly negative leakage on the import side. Results are similar if we conduct the same exercise with the data used by Aichele and Felbermayr (2015). The treatment effect in the Old EU and Non-EU group is estimated at 5 respectively 3% while Eastern European countries' carbon trade balance is affected by 16.5%. Again the major impact on Eastern European countries is an increase in CO₂ imports.

As Eastern Europe is found to be the main driver of leakage in our sample we should expect that a strong increase in domestic environmental regulation took place in Eastern Europe in the beginning of the 2000s. There is evidence for such a boost in regulation, however, the driving force behind this boost is more likely the accession to the European Union instead of the ratification of Kyoto. As we observed, Kyoto did not incentivize immediate environmental regulation for Eastern Europeans. On the other hand, environmental regulations as specified in the *acquis communautaire* were a prerequisite for joining the EU. As we proceed to estimate the

Table 3 Kyoto treatment effects by country groups

	All sec.	w/o serv.	Only serv.	A/F (2015)
Specification (i)				
$\check{\beta}_{OldEU}$	0.027*** (0.007)	− 0.020*** (0.008)	0.081*** (0.013)	0.050*** (0.009)
$\check{\beta}_{NewEU}$	0.201*** (0.009)	0.132*** (0.009)	0.277*** (0.015)	0.165*** (0.014)
$\check{\beta}_{NonEU}$	0.048*** (0.010)	0.076*** (0.011)	0.012 (0.016)	0.030*** (0.011)
Specification (ii)				
$\check{\beta}_{OldEU}^m$	− 0.026** (0.011)	− 0.145*** (0.012)	0.123*** (0.021)	0.050*** (0.021)
$\check{\beta}_{NewEU}^m$	0.325*** (0.013)	0.325*** (0.014)	0.316*** (0.024)	0.388*** (0.041)
$\check{\beta}_{NonEU}^m$	− 0.078*** (0.014)	− 0.033** (0.014)	− 0.131*** (0.025)	− 0.066*** (0.029)
$\check{\beta}_{OldEU}^x$	− 0.075*** (0.010)	− 0.102*** (0.010)	− 0.043** (0.018)	− 0.048*** (0.019)
$\check{\beta}_{NewEU}^x$	− 0.087*** (0.012)	0.056*** (0.012)	− 0.241*** (0.020)	0.045*** (0.044)
$\check{\beta}_{NonEU}^x$	− 0.168*** (0.013)	− 0.185*** (0.015)	− 0.143*** (0.020)	− 0.127*** (0.027)
$\check{\beta}_{OldEU}^m = -\check{\beta}_{OldEU}^x(F)$	40.20***	416.92**	5.71**	0.01
$\check{\beta}_{NewEU}^m = -\check{\beta}_{NewEU}^x(F)$	179.17***	229.93***	8.12***	264.16***
$\check{\beta}_{NonEU}^m = -\check{\beta}_{NonEU}^x(F)$	172.52***	106.60***	71.79***	72.13***

Restriction: $\beta_{g,s,t} = \check{\beta}_g \forall s, t$. Dependent variable: $\ln M_{i,j,s,t}^c$. Standard errors in parentheses. Regressions include fixed effects for country-year and importer–exporter-sector, as well as controls for common WTO, EU, or RTA membership. Standard errors are clustered by importer–exporter-sector (53,040 clusters). A/F(2015) refers to the use of data from Aichele and Felbermayr (2015). Regressions in the fourth column do not control for importer expenditure and exporter production (not in the data). Countries (not) included in their data: *Old EU*: -LUX; *New EU*: -LAT, -LTU, -BGR; *Non EU*: +CHE, +NOR, +NZL; *Non-Kyoto*: -TWN, -CYP, -MLT, +CHL, +ISR, +ZAF

Significance: * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

disaggregated effects of Kyoto in the next section, we must control for the specific effects of Kyoto in Eastern Europe. Restricting $\beta_{g,s,t}$ to be constant across groups would lead to an overestimation of the Kyoto effect for the Old EU and Non-EU countries, which would be particularly problematic given that these countries exhibit much higher trade volumes with the non-ratifiers. This would bias the magnitude of the leakage estimates upwards.

6 Kyoto's impact on the carbon trade balance

We use Eq. 9 to calculate the effect of Kyoto ratification on the carbon trade balance between Kyoto ratifiers and non-ratifiers. The results presented here are obtained using specification (i) of the Kyoto treatment variable. This is our preferred specification as we might have reason to believe that trade between non-ratifiers and ratifiers would have grown by more than trade growth within each group due to long-run changes in specialization patterns.^{19,20} We use a significance level of 1% for the treatment effect. Figure 5 presents the overall development of the carbon trade balance between Kyoto ratifiers and non-ratifiers, indicating the estimated effect that the Kyoto Protocol exerted. Committed countries carbon trade deficit rises from 101.2 megatons in 2002 to 607.2 megatons in 2008. Kyoto is estimated to have affected the carbon trade balance negatively, with an absolute value of 76.9 megatons in 2002 and 152.9 megatons in 2008. Figure 5 also indicates that the dominant part of this effect originates from the Old EU and Non-EU countries. The Old EU countries experience the strongest leakage in the years after most members joined the Protocol between 2003 and 2005. Similarly the non-EU group experiences strong leakage after 2006, when Russia and Australia ratified the Protocol. The New EU countries display comparatively modest levels of net leakage across all years with around 14% of total leakage.

Figure 6 disaggregates these net leakage estimates according to sectors. The two sectors with the single largest impact on the overall effect are machinery (13) and basic and fabricated metals (12). Leakage from the machinery sector explains 30.5% of total net leakage between 2002 and 2009. Leakage from the basic and fabricated metals sector explains 26.4% of total net leakage between 2002 and 2009. A third substantial source of leakage is the transport equipment sector (15). The remaining primary and secondary sectors taken together exhibit a neutral effect on net leakage with -0.9% of the total. Service sectors (18–34) play a minor role compared to manufacturing, although exhibiting substantial leakage considering their overall lower volume of trade. Their share of net leakage lies at 24.7% of the total in the period 2002–2009, most of which is accounted for by the transport sectors (inland, water and air) as well as the renting of machinery and equipment sector.

Table 4 summarizes the main results from the viewpoint of Kyoto ratifiers. The Kyoto-induced increase in imports from non-committed countries lies at 4.4% of total carbon imports while the corresponding decrease of exports amounts to 4.2% of total carbon exports. Summing up exports and imports of carbon dioxide and comparing them with leakage yields an Kyoto leakage share in total carbon dioxide trade of 4.3% in the period 2002–2009, varying between 2.4% (2006/07) and 5.2% (2008/09). The corresponding Kyoto leakage share in total CO₂ emissions varies between 0.1% (2006) and 0.6% (2008), with a mean of 0.4%.

The sectoral structure of leakage yields some further interesting insights. Figure 7 depicts the country group-specific impact of the Kyoto Protocol on single sectors

¹⁹ Recall that many non-ratifiers in the sample are big emerging economies.

²⁰ We present the results for specification (ii) in “Appendix 3”.

Fig. 5 Effect of the Kyoto Protocol on the carbon trade balance, by country groups. *Notes.* The carbon trade balance of Kyoto ratifiers with non-ratifiers. Specification (i). Significance level 1%. The effects for three country groups of ratifiers ('Non-EU', 'Old EU' and 'New EU') are stacked

Fig. 6 Effect of the Kyoto Protocol on the carbon trade balance, by sectors. *Notes.* The carbon trade balance of Kyoto ratifiers with non-ratifiers. Specification (i). Significance level 1%. The effects for different sectors (and groups of sectors) are stacked. Group 'Other Manufacturing/Agriculture': sectors 1–11, 14–17. Group 'Services': sectors 18–34. See sector list in Table 11, "Appendix 1"

and sector groups. We present average annual leakage values for two time spans, the early period between 2002 and 2005 (upper panel) and the later period between 2006 and 2009 (lower panel). We observe a relatively constant leakage level on average. Average annual sectoral leakage from the Kyoto Protocol across all sectors decreases from 2.7 megatons for the early period to 2.5 megatons for the later period, a decrease of roughly 10%. At the same time the growth of overall CO_2 trade amounted to 20%.

Three sectors with a predominantly positive net impact on the carbon trade balance, especially in the period after 2005, are sectors 1, 2 and 8. On the one hand

Table 4 Kyoto treatment effects: summary table

	Carbon trade balance				CO ₂ imports				CO ₂ exports			
	2002/03	2004/05	2006/07	2008/09	2002/03	2004/05	2006/07	2008/09	2002/03	2004/05	2006/07	2008/09
CO ₂ trade	-154.96	-355.14	-514.76	-583.22	910.83	1189.63	1401.23	1367.59	755.87	834.49	886.47	784.36
Leakage	-83.69	-101.53	-55.52	-111.99	47.13	60.43	31.04	76.10	-36.57	-41.10	-24.49	-35.89
Leakage share	0.54	0.29	0.11	0.19	0.05	0.05	0.02	0.06	-0.05	-0.05	-0.03	-0.05
<i>Shares of country groups (in percent of leakage)</i>												
Old EU	0.42	0.52	-0.03	0.41	0.47	0.56	-0.14	0.36	0.34	0.46	0.10	0.51
New EU	0.09	0.13	0.27	0.12	0.07	0.11	0.24	0.09	0.12	0.17	0.32	0.16
Non-EU	0.50	0.35	0.76	0.48	0.46	0.34	0.90	0.54	0.54	0.37	0.58	0.33
<i>Shares of sectors, overview (in percent of leakage)</i>												
Primary (1–2)	0.15	0.00	-0.03	-0.17	0.14	0.00	-0.05	-0.09	0.17	0.00	-0.02	-0.34
Secondary (3–17)	0.63	0.77	0.80	0.88	0.58	0.72	0.76	0.78	0.68	0.84	0.86	1.10
Tertiary (18–34)	0.22	0.24	0.23	0.29	0.27	0.29	0.28	0.31	0.15	0.16	0.16	0.24
<i>Shares of sectors (in percent of leakage)</i>												
Agri./min. (1–2)	0.15	0.00	-0.03	-0.17	0.14	0.00	-0.05	-0.09	0.17	0.00	-0.02	-0.34
Petroleum (8)	0.02	-0.02	-0.30	0.00	0.02	-0.01	-0.15	0.00	0.01	-0.03	-0.48	0.00
Metals (12)	0.14	0.20	0.68	0.21	0.13	0.19	0.79	0.21	0.15	0.21	0.53	0.21
Machinery (13)	0.13	0.21	0.55	0.40	0.11	0.18	0.57	0.37	0.16	0.25	0.53	0.45
Elec./opt. equ. (14)	0.07	0.10	-0.42	-0.06	0.07	0.11	-0.62	-0.08	0.06	0.07	-0.16	-0.02
Transp. equ. (15)	0.06	0.13	0.41	0.25	0.04	0.11	0.37	0.20	0.08	0.18	0.45	0.36
Oth. manufct.	0.22	0.15	-0.12	0.08	0.22	0.14	-0.21	0.07	0.22	0.17	-0.01	0.10
Transp. serv. (23–26)	0.12	0.11	0.14	0.18	0.15	0.15	0.22	0.21	0.09	0.05	0.04	0.11
Rent. of mach. (30)	0.03	0.07	0.16	0.12	0.03	0.08	0.20	0.12	0.04	0.06	0.11	0.11
Oth. serv.	0.06	0.06	-0.07	-0.01	0.08	0.06	-0.14	-0.02	0.03	0.05	0.02	0.03

Specification (i). The table exhibits means of biannual values. Row 'CO₂ Trade' refers to CO₂ trade from the viewpoint of Kyoto countries with Non-Kyoto countries in the sample, in megatons of CO₂. Row 'Leakage' refers to the estimated treatment effect of Kyoto on emission trade flows. Row Other Manufacturing summarizes sectors 3–7, 9–11, 16–17. Row Other Services summarizes sectors 18–22, 27–29, 31–34

Fig. 7 Group-specific sectoral effects on the carbon trade balance. *Notes.* Kyoto-induced change in the carbon trade balance of Kyoto ratifiers with non-ratifiers. Specification (i). Group ‘Other Manufacturing’ (oth. manfct.) summarizes sectors 3–7, 9–11, 16–17. Group ‘Other Services’ (oth. serv.) summarizes sectors 18–22, 27–29, 31–34

the coke, petroleum and petroleum products sector (8), which experiences decreasing imports and increasing exports to non-committed countries, with the latter effect dominating. These effects are especially pronounced in the Old EU countries and the Non-EU countries. On the other hand the primary sectors agriculture (1) and mining (2) also influence the carbon trade balance positively in the later period. This results from export increases in mining in the Non-EU group. Both of these observations would be consistent with a decrease in Kyoto-countries’ domestic demand for inputs of energy-intensive industries.

6.1 Manufacturing sources of carbon leakage

The four major sources of the Kyoto-induced decrease of the carbon trade balance are sectors 11, 12, 13 and 15. We discuss what is driving the results for each of them in the following listing, ordered by size of total leakage (in detail presented in Table 5).

- The machinery sector (13) explains 30.5% of total net leakage between 2002 and 2009. Both the Old EU and Non-EU countries are mostly affected. The machin-

Table 5 Kyoto treatment effects: manufacturing summary table

	13-mach		12-meta		15-treq		11-nmmp	
	2002– 2005	2006– 2009	2002– 2005	2006– 2009	2002– 2005	2006– 2009	2002– 2005	2006– 2009
<i>Carbon trade balance</i>								
Total	– 16.08	– 37.67	– 15.83	– 30.70	– 9.13	– 25.08	– 5.71	– 5.48
Old EU	0.62	0.42	0.70	0.79	0.18	0.00	0.47	0.48
New EU	0.05	0.06	0.20	0.21	0.07	0.03	0.16	0.29
Non-EU	0.33	0.52	0.09	0.00	0.76	0.97	0.37	0.23
<i>CO₂ imports</i>								
Total	8.08	23.09	8.75	20.43	4.03	13.20	3.27	3.38
Old EU	0.59	0.39	0.80	0.83	0.23	0.00	0.45	0.48
New EU	0.06	0.07	0.13	0.17	0.09	0.04	0.14	0.29
Non-EU	0.35	0.54	0.08	0.00	0.68	0.96	0.41	0.23
<i>CO₂ exports</i>								
Total	– 8.00	– 14.58	– 7.07	– 10.27	– 5.10	– 11.89	– 2.44	– 2.09
Old EU	0.64	0.47	0.58	0.72	0.13	0.00	0.49	0.47
New EU	0.05	0.05	0.30	0.28	0.05	0.02	0.19	0.30
Non-EU	0.31	0.48	0.11	0.00	0.82	0.98	0.32	0.23

Specification (i). Δ Carbon Trade Balance = Δ CO₂ Exports – Δ CO₂ Imports. Rows 'Total' show megatons of embodied CO₂. Rows 'Old EU', 'New EU', 'Non-EU' show the share of row 'Total' that is accounted for by a particular country group. As an example: The carbon trade balance in the metals sector between ratifiers and non-ratifiers decreases annually by 15.83 megatons between 2002 and 2005. 70% of this effect is accounted for by the Old EU countries. If a share value is negative, this indicates a country group-specific effect opposed to the total effect

ery sector significantly affects the carbon trade balance on both the export and the import side equally in the early period while the import increase dominates in the later period. This is strongly driven by an average annual import increase of 12.5 megatons by the Non-EU group in the later period after 2.8 megatons in the early period. The effect for the New EU group is moderate with an average annual carbon trade balance decrease of 0.8 megatons (early period) respectively 2.3 megatons (later period).

- The basic metals and fabricated metals sector (12) explains 26.4% of total net leakage between 2002 and 2009. It is the major source of leakage for the Old EU group throughout the 2000s. Emission imports from metals increase by 7 megatons annually in the early period, and 17 megatons in the later period. In contrast, emission exports from the Old EU group decrease by 4 megatons (early period) respectively 7.4 megatons (later period). In comparison moderate levels of leakage from this sector are observed for the New EU group, and even more moderate for the Non EU group.
- The transport equipment sector (15) explains 19.4% of total net leakage between 2002 and 2009. The negative effect on the carbon trade balance in this sec-

tor stems almost entirely from the Non-EU group. In the early period, average annual emission imports increase by 2.7 megatons, while they increase by 12.7 megatons in the later period. Conversely, average annual emission exports decrease by 4.2 megatons in the early period and by 11.7 megatons in the later period.

- The non-metallic mineral products sector (11) explains 6.3% of total net leakage between 2002 and 2009. All country groups experience negative impacts on their carbon trade balance. In the early period, average annual net emission imports increase by 2.7 megatons for the Old EU, 2.1 megatons for the Non-EU and 0.9 megatons for the New EU group. In the later period, the corresponding annual decrease in the carbon trade balance amounts to 2.6 megatons for the Old EU, 1.3 megatons for the Non-EU and 1.6 megatons for the New EU group.

With respect to the other manufacturing sectors sizable leakage effects in the early period are found in the electrical and optical equipment sector (14), the chemicals and chemical product sector (9), the manufacturing n.e.c. sector (16) as well as the textiles and textile products sector (4). In the later period many of these sectors experience a reversal, e.g. the electrical and optical equipment sector, with leakage coming to a halt or even reversing towards a positive effect on the carbon trade balance.

6.2 Services sources of carbon leakage

The two most important sources of leakage in services are sectors 23, 24, 25 and 30, which are presented in detail in Table 6.

- The renting of machinery and equipment sector (30) explains 9.1% of total net leakage between 2002 and 2009. The most important source region of leakage is the Old EU group, and here in particular the emission import side of the carbon trade balance. In the early period, average annual emission imports increase by 2.8 megatons while exports decrease by 1.6 megatons. In the later period, average annual emission imports increase by 7.4 megatons while exports decrease by 2.8 megatons. The remaining change in the carbon trade balance is accounted for by the New EU group.
- The inland transport sector (23) explains 6.8% of total net leakage between 2002 and 2009. Average annual emission imports increase by 3.2 megatons in the early period and 7 megatons in the later period for the group of Old EU countries. Emission exports stay comparatively relatively unaffected. Again the groups of Non-EU and New EU countries play (almost) no role.
- The water transport sector (24) explains 4.4% of total net leakage between 2002 and 2009. The picture is very similar to the inland transport sector. Almost the entire leakage effect is due to the Old EU countries increasing their average annual emission imports, in this case by 3.1 megatons (early period) respectively 3.3 megatons (later period).

Table 6 Kyoto treatment effects: services summary table

	30-rent		23-itra		24-wtra		25-atra	
	2002– 2005	2006– 2009	2002– 2005	2006– 2009	2002– 2005	2006– 2009	2002– 2005	2006– 2009
<i>Carbon trade balance</i>								
Total	– 4.96	– 11.04	– 3.90	– 8.09	– 2.47	– 5.20	– 3.06	– 0.70
Old EU	0.89	0.92	0.92	0.98	1.45	0.87	1.17	0.00
New EU	0.11	0.08	0.08	0.02	0.11	0.13	0.10	1.00
Non-EU	0.00	0.00	0.00	0.00	– 0.56	0.00	– 0.27	0.00
<i>CO₂ imports</i>								
Total	3.08	7.84	3.24	7.08	2.06	3.93	1.63	0.51
Old EU	0.92	0.94	0.98	0.98	1.50	0.84	1.25	0.00
New EU	0.08	0.06	0.02	0.02	0.11	0.16	0.10	1.00
Non-EU	0.00	0.00	0.00	0.00	– 0.61	0.00	– 0.35	0.00
<i>CO₂ exports</i>								
Total	– 1.88	– 3.19	– 0.66	– 1.02	– 0.41	– 1.28	– 1.43	– 0.18
Old EU	0.85	0.87	0.59	0.93	1.23	0.96	1.08	0.00
New EU	0.15	0.13	0.41	0.07	0.11	0.04	0.10	1.00
Non-EU	0.00	0.00	0.00	0.00	– 0.34	0.00	– 0.18	0.00

Specification (i). Δ Carbon Trade Balance = Δ CO₂ Exports – Δ CO₂ Imports. Rows ‘Total’ show megatons of embodied CO₂. Rows ‘Old EU’, ‘New EU’, ‘Non-EU’ show the share of row ‘Total’ that is accounted for by a particular country group. As an example: The carbon trade balance in the inland transport sector between ratifiers and non-ratifiers decreases annually by 3.9 megatons between 2002 and 2005. 92% of this effect is accounted for by the Old EU countries. If a share value is negative, this indicates a country group-specific effect opposed to the total effect, i.e. Non-EU countries increased their carbon trade balance in sector 24 by 1.4 megatons (– 56% of – 2.5)

- The air transport sector (25) explains 2.1% of total net leakage between 2002 and 2009. Leakage is mostly restricted to the early period, when the Old EU group increased its average annual emission imports by 2 megatons and decreased its average annual emission exports by 1.5 megatons.

7 Robustness checks

To test the robustness of our methodological approach we perform several checks and compare the resulting restricted estimates on the Kyoto treatment variable. Table 7 summarizes the time-, sector- and group-invariant estimates on the Kyoto effect while Table 8 tests robustness for the country group-specific estimates. The baseline model proves to be robust to methodological changes. The Kyoto effect is found to be of very similar magnitude in the extended Aichele/Felbermayr model (R3) as well as in the Baier/Bergstrand (R4) model.

7.1 “Naive” gravity

We estimate a model without controlling for the unobserved fraction of bilateral trade costs and without controlling for multilateral resistance, i.e. excluding bilateral, importer- and exporter-specific fixed effects $\nu_{ij,s}$, $\theta_{i,s,t}$ and $\zeta_{j,s,t}$. Instead we control for bilateral trade costs by including the observable variables distance, contiguity, language, cross-border trade, colonial history, summarized as vector T_{ij} in Eq. 10. To capture time trends of emission trade at the sectoral level we allow for a sectoral time trend $\tau_{s,t}$. We call this model a “naive” gravity model.

$$\ln M_{ij,s,t}^c = \bar{\beta}^{na} \Delta K_{ij,t} + \alpha_e \ln e_{i,s,t} + \alpha_y \ln y_{j,s,t} + \delta_1^{na} P_{ij,t} + \delta_2^{na} T_{ij} + \tau_{s,t} + \varepsilon_{ij,s,t}^{na} \quad (10)$$

Row R1 of Table 7 depicts the resulting estimates for $\bar{\beta}^{na}$. The “naive” model would lead us to conclude falsely that Kyoto resulted in inverse leakage.

7.2 Aichele/Felbermayr (2015)

We test two specifications based on the work by Aichele and Felbermayr (2015). While the model in Eqs. 4–6 controls for importer- and exporter-specific sectoral time trends $\theta_{i,s,t}$ and $\zeta_{j,s,t}$, the model in Eq. 11 employs country-specific time trends $\vartheta_{i,t}$ and $\psi_{j,t}$. The latter capture the mean development of a country’s aggregate carbon trade as both importer *and* exporter.²¹ While this allows for estimation of the model in one stage, the implication is that multilateral resistance is not fully controlled for. We estimate two versions of Aichele and Felbermayr’s model, the first being their original formulation, the second including additionally importer carbon expenditure levels $e_{i,s,t}$ and exporter carbon output levels $y_{j,s,t}$.

$$\ln M_{ij,s,t}^c = \bar{\beta}^{AF} \Delta K_{ij,t} + \alpha_e \ln e_{i,s,t} + \alpha_y \ln y_{j,s,t} + \delta_1^{AF} P_{ij,t} + \vartheta_{i,t} + \psi_{j,t} + \nu_{ij,s} + \varepsilon_{ij,s,t}^{AF} \quad (11)$$

Rows R2 and R3 of Table 7 depict the resulting estimates for $\bar{\beta}^{AF}$. The estimates under the original Aichele and Felbermayr formulation (R2) are roughly 3 to 4 percentage points above those of the baseline model while including expenditure and output (R3) leads to similar results as in the baseline model. The same observations are true for the model allowing for country group variations of the Kyoto treatment effect, presented in Table 8. The differences between (R2) and the baseline model as well as (R3) suggest that taking into account sectoral differentiation of carbon output and expenditure trends is important.

7.3 Baier/Bergstrand (2009)

A further robustness check employs the methodology of Baier and Bergstrand (2009) in the context of carbon trade. These authors suggested using exogenous

²¹ Aichele and Felbermayr (2015) in addition do not allow for sectoral differences in their country-time effects. In the terminology of Eq. 4, their country-time fixed effects amount to assuming $\theta_{i,s,t} = \zeta_{j,s,t} \forall i = j$ as well as $\theta_{i,s,t} = \bar{\theta}_{i,t} \forall s$ and $\zeta_{j,s,t} = \bar{\zeta}_{j,t} \forall s$.

Table 7 Robustness checks on $\bar{\beta}$

	All sec. (1)	w/o serv. (2)	Only serv. (3)
Baseline	0.112*** (0.005)	0.064*** (0.006)	0.165*** (0.009)
Adj. R^2	0.966	0.971	0.949
R1:			
Naive gravity	-0.168*** (0.007)	-0.215*** (0.007)	-0.124*** (0.011)
Adj. R^2	0.590	0.629	0.488
R2:			
Aichele/Felbermayr (1)	0.151*** (0.009)	0.109*** (0.011)	0.207*** (0.015)
Adj. R^2	0.929	0.918	0.925
R3:			
Aichele/Felbermayr (2)	0.106*** (0.009)	0.061*** (0.011)	0.163*** (0.015)
Adj. R^2	0.932	0.921	0.927
R4:			
Baier/Bergstrand	0.106*** (0.009)	0.090*** (0.011)	0.118*** (0.015)
Adj. R^2	0.912	0.897	0.914

Restriction: $\beta_{g,s,t} = \bar{\beta} \forall g, s, t$. Standard errors in parentheses. Baseline refers to the estimates in Table 1

Significance: * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

multilateral resistance terms MRT_{ij} based on observable trade cost characteristics. We model trade costs as being determined by distance, contiguity, common language, colonial history and a dummy capturing within-country trade.²²

$$\ln \frac{M_{ij,s,t}^c}{e_{i,s,t} y_{j,s,t}} = \bar{\beta}^{BB} \Delta K_{i,j,t} + \delta_1^{BB} P_{i,j,t} + \delta_2^{BB} MRT_{ij} + \tau_{s,t} + \epsilon_{ij,s,t}^{BB} \quad (12)$$

Row R4 of Table 7 depicts the resulting estimates for $\bar{\beta}^{BB}$. The estimates are very close to the baseline model as well as the extended Aichele/Felbermayer model (R3), albeit with higher estimates for the manufacturing subsample and lower estimates for the service subsample. These same observations are true for the country group-specific estimates, see the estimates in Table 8.

²² Baier and Bergstrand (2009) model each element of the multilateral resistance term vector according to $MRT_{ij} = \left[\left(\sum_{k=1}^N \theta_k^{BB} T_{i,k} \right) + \left(\sum_{m=1}^N \theta_m^{BB} T_{m,j} \right) - \left(\sum_{k=1}^N \sum_{m=1}^N \theta_k^{BB} \theta_m^{BB} T_{k,m} \right) \right]$, where θ_i^{BB} denotes a country's sectoral emission output as a share of world sectoral emission output, $\theta_i^{BB} = \frac{y_{i,s,t}}{y_{WORLD,s,t}}$.

Table 8 Robustness checks on $\check{\beta}$

	All sec.	w/o serv.	Only serv.
Baseline			
$\check{\beta}_{OldEU}$	0.027*** (0.007)	− 0.020* (0.008)	0.081*** (0.013)
$\check{\beta}_{NewEU}$	0.201*** (0.009)	0.132*** (0.009)	0.277*** (0.015)
$\check{\beta}_{NonEU}$	0.048*** (0.010)	0.076*** (0.011)	0.012 (0.016)
R2:			
Aichele/Felbermayr (1)			
$\check{\beta}_{OldEU}$	0.053*** (0.012)	0.025* (0.014)	0.099*** (0.021)
$\check{\beta}_{NewEU}$	0.249*** (0.016)	0.159*** (0.020)	0.354*** (0.024)
$\check{\beta}_{NonEU}$	0.062*** (0.016)	0.095*** (0.018)	0.020 (0.027)
R3:			
Aichele/Felbermayr (2)			
$\check{\beta}_{OldEU}$	0.022* (0.012)	− 0.011 (0.013)	0.069*** (0.020)
$\check{\beta}_{NewEU}$	0.196*** (0.015)	0.106*** (0.020)	0.297*** (0.023)
$\check{\beta}_{NonEU}$	0.056*** (0.016)	0.089*** (0.018)	0.017 (0.027)
R4:			
Baier/Bergstrand			
$\check{\beta}_{OldEU}$	0.022* (0.012)	0.011 (0.014)	0.031 (0.021)
$\check{\beta}_{NewEU}$	0.195*** (0.016)	0.149*** (0.021)	0.241*** (0.024)
$\check{\beta}_{NonEU}$	0.059*** (0.016)	0.082*** (0.018)	0.029 (0.026)

Restriction: $\beta_{g,s,t} = \check{\beta}_g, \forall s, t$. Standard errors in parentheses. Significance: * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. Baseline refers to the estimates in Table 3

8 Conclusion

In this study, we estimated carbon leakage as a consequence of the Kyoto Protocol by looking at the effects of ratification on the carbon trade balance. We argued that taking into account regional and sectoral disaggregation is essential in order to deal with very unequally distributed trade flows. The findings hint towards non-negligible leakage effects from unilateral environmental policy actions and underline the need to improve international coordination of climate change policies. In the

absence of such coordination, border carbon adjustment might be a possible remedy to overcome the disincentive for unilateral climate policies resulting from evidence for carbon leakage.²³

An important shortcoming of the gravity methodology used in this and other studies is its partial equilibrium nature. Third-country effects are by construction ruled out. In general equilibrium, the change in the carbon trade balance between Germany and China after Germany ratified and China did not ratify would be expected to also affect their carbon trade balance with the United States. Future research will be directed towards incorporating these effects in the estimation of carbon leakage.

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Appendix

Appendix 1: Discussion of the data and descriptive statistics

The WIOD database²⁴ provides national input–output tables, a linked worldwide input–output table (in current prices and previous years' prices) as well as various socio-economic and environmental accounts, among them data on sectoral emissions of carbon dioxide. It covers a total of 40 countries, among them all EU members except Croatia, over a period of currently 17 years from 1995 to 2011. Compared to other available sources—such as the International Energy Agency (IEA), Global Trade Analysis Project (GTAP) or the Statistical Database of the Organization for Economic Co-operation and Development (OECD)—the WIOD was chosen for its internal consistency between input–output tables and environmental accounts and its free availability online. A drawback is that some countries are missing from the database, such as South Africa, Chile and many important OPEC states (Tables 9, 10).

We use current 1995 US Dollars as the reference currency for our analysis. Data in the WIOD is grouped in 35 sectors corresponding to ISIC Rev.3. As for the last of these sectors, Private Households with Employed Persons, we do not have information for most countries, let alone trade data, we exclude it from our analysis. We use the sectoral classification listed in Table 11 with 34 sectors. They consist of two primary sectors (1–2), 15 secondary sectors (3–17) and 17 tertiary sectors (18–34) (Table 12).

²³ Opponents point to the risk “that these measures would serve purely protectionist or retaliatory purposes” (Droege et al. 2018).

²⁴ This study uses Release 2013 of WIOD. A newer release covers the period 2000–2014.

Table 9 Countries in our sample: no reduction commitments*Non-ratifiers/no emission commitments*

Brazil
 China
 Cyprus
 India
 Indonesia
 Malta
 Mexico
 South Korea
 Taiwan
 Turkey
 United States of America

All countries in our sample that did not ratify the Kyoto Protocol or that ratified without emission commitments

The researchers of the WIOD compiled the information on sectoral emissions of CO₂ from data by the IEA, Eurostat and the UNFCCC (Timmer 2012, p. 47f.). National input–output tables are mainly based on national statistical reporting—National Accounts and annual international trade data (ibid., p. 17).

A third data requirement are bilateral trade flows. There are again a number of sources providing information on this. Again, we use the information provided in the WIOD. They spent much effort on harmonizing the trade data from other sources, such as UN, OECD, WTO or IMF. In addition they are dealing with country-specific problems present in the data. Some problems with the trade statistics lie in unequal mirror statistics. Mirror statistics are the result of trade reporting by both trading partners: Country A's exports to B are reported by country B as its imports from A. Unfortunately, the numbers that country A reports for its exports and country B reports for its imports rarely match well. For a thorough discussion on the causes of these differences, see Guo et al. (2009, 8ff.).

Re-exports are a significant source of error also in the data required for my analysis. These errors are especially prominent in countries with important maritime ports. In my analysis this is the case most notably for China, the Netherlands and Belgium (Guo et al. 2009, p. 11). In the case of China, many goods are exported via Hongkong or Macao, which are reported separately in trade statistics. Often it is the case that the US declares the imports as Chinese, whereas China declares its exports as going to Hongkong, and therefore giving a biased information on its exports to the United States (Ferrantino and Wang 2008, p. 503). The size of the distortions is the subject of extensive research among trade economists (Mellens et al. 2007; Fung and Lau 2003).

In the WIOD, researchers corrected for re-exports and harmonized mirror trade statistics. In Chinese data, they also included information for Hongkong and Macao. For Belgium, they separated values for Luxembourg which were reported together with Belgium (Timmer 2012, p. 26f.).

Concerning trade in services, it is still very difficult to obtain reliable data on bilateral trade flows on a sectoral basis. This is true for the high-income countries in

Table 10 Countries in our sample: reduction commitments

	Year of ratification	Target	Actual
<i>Ratifiers of emission commitments</i>			
Czech Republic	2001	− 0.0042	− 0.0289
Romania		0.0029	− 0.0595
Austria	2002	− 0.0069	0.0070
Belgium		− 0.0039	0.0014
Bulgaria		0.0013	− 0.0495
Canada		− 0.0031	0.0173
Denmark		− 0.0117	0.0020
Estonia		− 0.0042	− 0.0735
Finland		0.0000	0.0051
France		0.0000	0.0004
Germany		− 0.0117	− 0.0151
Greece		0.0112	0.0179
Hungary		0.0049	− 0.0198
Ireland		0.0061	0.0220
Italy		− 0.0034	0.0065
Japan		− 0.0031	0.0058
Latvia		− 0.0042	− 0.0788
Luxembourg		− 0.0163	− 0.0206
Netherlands		− 0.0031	0.0011
Poland		0.0070	− 0.0155
Portugal		0.0120	0.0297
Slovakia		− 0.0042	− 0.0316
Slovenia		0.0004	0.0066
Spain		0.0070	0.0262
Sweden		0.0020	− 0.0043
United Kingdom		− 0.0067	− 0.0089
Lithuania	2003	− 0.0042	− 0.0669
Russian Federation	2004	0.0000	− 0.0349
Australia	2007	0.0039	0.0154

All countries in our sample that ratified the Kyoto Protocol under emission commitments. 'Target' is the average annual emission growth rate needed to achieve the binding emission constraint by 2010. 'Actual' is the average annual emission growth rate recorded between 1990 (Kyoto default base year) and country-specific date of ratification

this study but even more so for the BRICs. In the documentation of the WIOD the researchers included a word of warning:

[T]he quality of trade data in services is still far away from being comparable to trade data for merchandise goods. Due to the long tradition of tariff revenues, trade data for goods have been collected with quite high quality and

Table 11 Economic sectors in the world input–output database (WIOD)

	Sector	ISIC
1 agri	Agriculture, hunting, forestry and fishing	01–05
2 minq	Mining and quarrying	10–14
3 fopr	Food, beverages and tobacco	15–16
4 text	Textiles and textile products	17–18
5 leat	Leather, leather and footwear	19
6 wood	Wood and products of wood and cork	20
7 papp	Pulp, paper, paper, printing and publishing	21–22
8 petr	Coke, refined petroleum and nuclear fuel	23
9 chem	Chemicals and chemical products	24
10 rupl	Rubber and plastics	25
11 nmmf	Other non-metallic mineral	26
12 meta	Basic metals and fabricated metal	27–28
13 mach	Machinery, nec	29
14 elop	Electrical and optical equipment	30–33
15 treq	Transport equipment	34–35
16 manr	Manufacturing, nec; recycling	36–37
17 elgw	Electricity, gas and water supply	40–41
18 cons	Construction	45
19 mott	Sale, maintenance and repair of motor vehicles and motorcycles; retail sale of fuel	50
20 whot	Wholesale trade and commission trade, except of motor vehicles and motorcycles	51
21 rett	Retail trade, except of motor vehicles and motorcycles; repair of household goods	52
22 hore	Hotels and restaurants	55
23 itra	Inland transport	60
24 wtra	Water transport	61
25 atra	Air transport	62
26 otra	Other supporting and auxiliary transport activities; activities of travel agencies	63
27 pote	Post and telecommunications	64
28 fina	Financial intermediation	65–67
29 real	Real estate activities	70
30 rent	Renting of M&Eq and other business activities	71–74
31 publ	Public admin and defence; compulsory social security	75
32 educ	Education	80
33 heal	Health and social work	85
34 csps	Other community, social and personal services	90–93

Sector 35 (private households with employed persons) omitted. Sectoral classification according to ISIC Rev.3

accuracy. Due to intangibility and nonstorability of services, at-the-border duties cannot be applied to services, thus having resulted in much weaker compilation practices with considerable less accuracy. Thus, services statistics has ample space for improvement in terms of measurement. [...] The WIOD Trade in Services Database should be seen in this light as the best currently

Table 12 Summary statistics: committed versus non-committed countries

Kyoto status	Mean			Median			Standard deviation		
	All	0	1	All	0	1	All	0	1
GDP per capita (10^3 USD)	18.82	10.57	21.95	17.08	4.96	22.90	16.02	10.53	16.76
GDP (10^{11} USD)	8.46	13.61	6.51	2.89	4.26	1.95	17.90	28.65	11.77
Real GDP growth rate (%)	3.58	4.05	3.41	3.31	3.74	3.00	2.10	2.24	2.06
Population (10^8 persons)	1.03	3.02	0.28	0.18	1.06	0.10	2.62	4.53	0.37
Population growth rate (%)	0.44	1.04	0.21	0.45	1.22	0.25	0.73	0.45	0.68
CO ₂ emissions, total (10^5 kiltons)	5.11	11.20	2.80	1.69	3.29	1.07	10.35	17.87	3.87
CO ₂ emissions, intermediate (10^5 kiltons)	4.39	9.86	2.31	1.36	2.69	0.90	9.11	15.72	3.32
CO ₂ emissions embodied in imports (10^5 kiltons)	1.57	2.32	1.29	0.80	1.11	0.55	2.32	3.64	1.56
CO ₂ intensity of imports (kiltons per USD)	0.82	0.89	0.80	0.81	0.89	0.78	0.24	0.26	0.23
Imports (10^5 USD)	2.00	2.71	1.74	1.00	0.93	1.08	2.63	4.05	1.88
EU membership (member = 1)	0.44	0.05	0.59	0.25	0.00	1.00	0.45	0.10	0.44
WTO membership (member = 1)	0.97	0.98	0.97	1.00	1.00	1.00	0.16	0.08	0.19
Energy use (10^{13} Megajoule)	1.36	2.88	0.79	0.47	1.07	0.25	2.66	4.54	1.11
Emission relevant energy use (10^{13} Megajoule)	0.96	2.02	0.56	0.32	0.72	0.19	1.88	3.20	0.80
Energy intensity of output (MJ per USD)	12.99	12.34	13.24	8.57	8.87	7.49	11.95	5.90	13.65
Emiss. rel. energy int. of output (MJ per USD)	9.45	8.89	9.66	5.82	6.38	5.69	8.60	4.65	9.75

Average values for the years 2001–2004. Kyoto Status ‘1’ encompasses all countries that ratified emission commitments under the Kyoto Protocol at some point in our sample, group ‘0’ the opposite. US dollar are in real 1995 terms

available approximation to a comprehensive picture of global trade flows in services (Timmer 2012, p.30).

Following this warning, we can expect a higher probability of inaccuracy in the results of embodied CO₂ in services trade.

Appendix 2: Multi-regional input–output approach

It is not possible to obtain a precise image of the actual flows of embodied CO₂ with the available data. Our investigation is performed on a national level where we work with average, country-wide emission intensities. It is clear that these intensities will not be homogeneous within a country. Particularly problematic is this for a large country like China, where Meng et al. (2011) have shown that variation in emissions between regions can be quite fundamental. As Bartleet et al. (2010) show for New Zealand, there is also a large variation of emission intensities within manufacturing

sectors, and even within subsectors. So any result can necessarily only be considered a reasonably good approximation of the actual flows.

To determine the embodied emissions in trade between two countries we multiply sectoral exports with sectoral emission intensities.

$$E_{ij,s,t}^c = E_{ij,s,t} \gamma_{i,s,t} \quad (13)$$

Equation (13) gives us a formula for the embodied carbon emissions $E_{ij,s,t}^c$ of exports from country i to country j in sector s in year t . Embodied emissions are obtained by multiplying the exports $E_{ij,s,t}$ in this sector by this sectors emission intensity $\gamma_{i,s,t}$, i.e. country i 's emission intensity in sector s in year t .

The only basic data requirements we have for these calculations are sectoral trade flows $E_{ij,s,t}$ and emission intensities $\gamma_{i,s,t}$. We have bilateral sectoral trade flows in the data described in Sect. 2. Emission intensities are a bit more tricky. One straightforward approach would be to just take the vector of total sectoral emissions and divide it by the vector of sectoral gross output. By using this strategy we would, however, obtain biased results that relatively overestimate the emission intensity of sectors performing highly emission generating production processes and relatively underestimate it in the reverse case. The reason for this is that we are neglecting inter-sectoral relations within a country. To use an example, energy generation may be highly emission generating but it is used as an input for almost all other sectors of an economy. Therefore, we should ascribe part of the CO₂ emitted during energy generation to other sectors' emission balances.

The popular method to include inter-sectoral relations within an economy is input–output analysis, first introduced by Leontief (1936). The heart of the input–output analysis is the inter-industry transaction table. Table 13 shows a reduced-form example economy with only three sectors (industries): agriculture, manufacturing and services. In the upper block of this table we find the inter-industry transactions. They are to be read as follows: The rows show the supply (output) of the sectors to other sectors as well as to final demand (which is equal to household consumption plus exports). The columns show the use (inputs) of other sectors products for the production process.²⁵ In each row we can sum up total intermediate supplies and deliveries for final demand to reach gross output.

Suppose there are $s = 1, \dots, S$ sectors in our economy. In matrix notation we can describe the input–output system using the following variables (Perman et al. 2003, p. 272ff.):

$$X = \begin{pmatrix} X_1 \\ X_2 \\ \dots \\ X_S \end{pmatrix} \quad Y = \begin{pmatrix} Y_1 \\ Y_2 \\ \dots \\ Y_S \end{pmatrix} \quad A = \begin{pmatrix} a_{11} & a_{12} & \dots & a_{1S} \\ a_{21} & a_{22} & \dots & a_{2S} \\ \dots & \dots & \dots & \dots \\ a_{S1} & a_{S2} & \dots & a_{SS} \end{pmatrix}$$

$$R = (r_1 \ r_2 \ \dots \ r_S) \quad \Gamma = (\gamma_1 \ \gamma_2 \ \dots \ \gamma_K)$$

²⁵ Imports, factor payments and value added would appear at the bottom of the transaction table but are omitted here for reasons of simplicity.

Table 13 Input–output analysis: example table

	A	M	S	Households	Exports	Gross output
Inter-industry transaction table						
A	0	400	0	500	100	1000
M	350	0	150	800	700	2000
S	100	200	0	250	50	600
Intermediate input coefficients a_{ij}						
A	0.00	0.20	0.00			
M	0.35	0.00	0.25			
S	0.10	0.10	0.00			
$(I - A)$						
A	1.00	− 0.20	0.00			
M	− 0.35	1.00	− 0.25			
S	− 0.10	− 0.10	1.00			
$(I - A)^{-1}$						
A	1.08	0.22	0.06			
M	0.42	1.11	0.28			
S	0.15	0.13	1.03			
Sectoral CO ₂ emissions z_i	50.00	400.00	60.00			
Emission output coefficients r_i	0.05	0.20	0.10			
Emission intensities γ_i	0.15	0.25	0.16			
Embodied emissions in exports f_i	15.25	172.67	8.08			

Read the inter-industry transaction table as follows: In row 1, sector A (Agriculture) delivers intermediate inputs worth 400 to sector M (Manufacturing) and 0 to sector S (Services). A also delivers 500 to households for consumption and 100 to foreign demand

X is a $S \times 1$ vector of sectoral gross output. Each element of this vector (corresponding to output of one specific sector) can be written as the sum of the intermediate inputs X_{sl} this sector produces for the other sectors l plus the sectoral final demand. Y is a $S \times 1$ vector of sectoral final demand. Thus, $X_s = X_{s1} + X_{s2} + \dots + X_{sS} + Y_s$. A is a $S \times S$ matrix of intermediate input coefficients $a_{sl} = \frac{X_{sl}}{X_l}$. These coefficients allow us to write total sectoral output in sector s as

$$X_s = a_{s1}X_1 + a_{s2}X_2 + \dots + a_{sS}X_S + Y_s \quad (14)$$

The matrix formulation of (14) is found below in Eq. (15). R is a $1 \times S$ vector of sectoral emission output coefficients $r_s = \frac{z_s}{X_s}$, where z_s are total sectoral emissions. The coefficient r_s tells us the amount of CO₂ emitted for the production of one (value) unit of good s . Finally, Γ is a $1 \times S$ vector of sectoral emission intensities for final demand deliveries γ_s . The emission intensity γ_s captures the actual emission content of goods that are either domestically consumed or exported. Γ is the aim of our use of input–output analysis.

The inter-sectoral relations captured by input–output analysis can be expressed as follows:

$$X = AX + Y \quad (15)$$

Equation (15) states the fact that each sector's gross output can be expressed in terms of its deliveries to other sectors' production (intermediate inputs) and to final demand (households and exports). Subtracting AX on both sides of (15), factoring out X and bringing $(I - A)$ to the other side yields the so-called "Leontief inverse" $(I - A)^{-1}$, which gives a direct correspondence between gross output and final demand.

$$X = (I - A)^{-1}Y \quad (16)$$

Premultiplying both sides of (16) with R introduces sectoral emissions into the system.

$$RX = R(I - A)^{-1}Y \quad (17)$$

Note that the expression we obtain on the left-hand side of (17), RX , equals the sum of total economy-wide emissions Z . This is a result of the construction of R , the vector of sectoral emission output coefficients.²⁶ Thus, we can rewrite (17) as

$$Z = \Gamma Y \quad (18)$$

In (18) we define $\Gamma = R(I - A)^{-1}$. Note that Γ is exactly what we need, the vector of sectoral emission intensities for final demand. It creates a link between the final demand for each sector's output (the elements of Y) and the total emissions in the economy Z . Total economy-wide emissions are distributed to the sectors according to their sectoral emission share which is corrected for the distribution of intermediate inputs as represented by the Leontief inverse.

For our empirical analysis, we have data on total sectoral production X , on final demand for household consumption and exports and on total sectoral emissions z_s (from which we can find R). Therefore we can calculate the vector of emission intensities Γ from (18).

Returning to our example economy in Table 13, the second block shows the intermediate input coefficients matrix, obtained by dividing a sector's intermediate inputs by its gross output. In the fourth block we obtain the Leontief inverse, which we multiply by the emission output coefficient vector R to arrive at the emission intensity vector Γ .

Appendix 3: Tables and Figures

See Figs. 8, 9, 10 and 11.

²⁶ $RX = r_1X_1 + r_2X_2 + \dots + r_sX_s = z_1 + z_2 + \dots + z_s$, where r_s is the average emission output in sector s per monetary unit of output and X_s is the monetary value of gross output. Thus we obtain the sum of sectoral emission output, $Z = \sum z_s$.

Fig. 8 Country Carbon Trade Balances: Eastern European Kyoto ratifiers. *Notes.* The ten Eastern European EU countries among Kyoto ratifiers. Each country is shown twice, its carbon trade balance with the group of ratifiers and non-ratifiers

Fig. 9 Effect of the Kyoto Protocol on the carbon trade balance, by country groups. *Notes.* The carbon trade balance of Kyoto ratifiers with non-ratifiers. Specification (ii). The effects for three country groups of ratifiers ('Non-EU', 'Old EU' and 'New EU') are stacked

Fig. 10 Effect of the Kyoto Protocol on the carbon trade balance, by sectors. *Notes.* The carbon trade balance of Kyoto ratifiers with non-ratifiers. Specification (ii). The effects for different sectors (and groups of sectors) are stacked. Group ‘Other Manufacturing/Agriculture’: sectors 1–11, 16, 17. Group ‘Transport Services’: sectors 23–26. Group ‘Other Services’: sectors 18–22, 27–34. See sector list in Table 11, “Appendix 1”

Fig. 11 Group-specific sectoral effects on the carbon trade balance. *Notes.* Kyoto-induced change in the carbon trade balance of Kyoto ratifiers with non-ratifiers. Specification (ii). Group ‘Other Manufacturing’ summarizes sectors 3–7, 9–11, 16–17. Group ‘Other Services’ summarizes sectors 18–22, 27–29, 31–34

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