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## CO<sub>2</sub> Embodied in International Trade with Implications for Global Climate Policy

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The flow of pollution through international trade flows has the ability to undermine environmental policies, particularly for global pollutants. In this article we determine the CO<sub>2</sub> emissions embodied in international trade among 87 countries for the year 2001. We find that globally there are over 5.3 Gt of CO<sub>2</sub> embodied in trade and that Annex B countries are net importers of CO<sub>2</sub> emissions. Depending on country characteristics—such as size variables and geographic location—there are considerable variations in the embodied emissions. We argue that emissions embodied in trade may have a significant impact on participation in and effectiveness of global climate policies such as the Kyoto Protocol. We discuss several policy options to reduce the impact of trade in global climate policy. If countries take binding commitments as a part of a coalition, instead of as individual countries, then the impacts of trade can be substantially reduced. Adjusting emission inventories for trade gives a more consistent description of a country's environmental pressures and circumvents many trade related issues. It also gives opportunities to exploit trade as a means of mitigating emissions. Not least, a better understanding of the role that trade plays in a country's economic and environmental development will help design more effective and participatory climate policy post-Kyoto.

### 1. Introduction

International trade causes a geographic separation of consumers and the pollution emitted in the production of consumable items. This gives a mechanism for consumers to shift environmental pollution associated with their consumption to distant lands. For local pollutants this may be viewed as a rational option for consumers, but for global pollutants—such as greenhouse gases (GHG)—consumers will bear the costs regardless of where production occurs. Consequently one would expect the optimal policy for global pollutants to consider the implications of international trade. Interestingly, the only reference to international trade in the Kyoto Protocol is that “Parties. . . shall strive to implement policies and measures. . . in such a way as to minimize adverse effects. . . on international trade”. Many of the debated problems of the Kyoto Protocol are manifested in international trade—costs, competitiveness, carbon leakage, and so on—and perhaps ironically, restructuring international

trade may help mitigation and accelerate sustainable development.

Historically, international trade has played a significant role in economic development by giving a mechanism to efficiently allocate resources, typically labor and capital (1). However, without fully and uniformly costing externalities, production may occur in regions with poor environmental performance or weak environmental legislation. This separation of consumption and production has instigated many studies on the pollution embodied in international trade—primarily air pollutants (2, 3), but also water (4), land (5), materials (6), and even forest products (7). These studies have highlighted the magnitude and policy importance of pollution embodied in trade for individual countries or small groups of countries. Despite this, there is a clear need for more comprehensive global studies to provide input for climate policy analysis.

Given the political rhetoric associated with trade and competitiveness issues in climate policy (8–10), there has been little research on how trade may impact climate policy. If a country has a large share of its exports in pollution-intensive production, then there may be large—real or perceived (11)—economic cost associated with participating in a global climate regime (12). If the climate regime has inadequate participation, then there is a risk that production will increasingly shift to nonparticipating countries. Either industries may close down and move to nonparticipating countries, or more problematic, expanded production may occur in nonparticipating countries (13) as is clearly demonstrated by the rapid growth of production in China (14, 15). Further, with increasingly global production, most low-cost mitigation options may be located outside the country of consumption. As an example, since Norway has almost 100% hydropower, it would make economic sense for Norway to focus emission reductions on coal power electricity generation in its important trading partners (16). The Kyoto Protocol attempts to address this through the Clean Development Mechanism (CDM), but evidence suggests that the CDM has not been effective at meeting its goals (17).

There have been many proposals for climate policy in the post-Kyoto period (18, 19) with many considering issues such as equity, flexibility, economic costs, and environmental effectiveness. Very few proposals have assessed whether international trade may be underlying some of the concerns with the Kyoto Protocol. International trade has been discussed as a way to enforce climate policy (20) and there is increasing interest in using trade-based mechanisms such as border-tax adjustments (21–23). National emission inventories can also be adjusted for trade (24, 25) which has the potential to avoid issues such as carbon leakage, but has received little attention in climate policy debates (12). Given the importance of trade in most aspects of modern economies, it is certainly beneficial to investigate the role trade has in climate policy.

The main focus of this article is a quantitative comparison of how the emissions embodied in international trade shape a country's environmental profile and discuss the implications for global climate policy. We perform detailed analyses on the emissions embodied in exports and imports, the carbon leakage between Annex B and non-Annex B countries, and compare different methods for constructing GHG inventories. Finally, we discuss the implications of anthropogenic carbon flows for global climate policy.

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## 2. Background and Methodology

Often, the most polluting aspect of a consumable product is the pollution emitted in production. The emissions occur either directly through the production processes or indirectly in the global supply chain due to acquisitions such as electricity, transportation, manufacturing, and so on. The accumulated emissions emitted in the production of the product are said to be “embodied” emissions (other authors have used “virtual” or “hidden”). For global climate policy the “emissions embodied in trade” (EET) between countries are of most interest.

We consider three aspects of EET relevant for global climate policy. First, a direct analysis of EET provides a better understanding of the environmental separation between domestic consumption and global production. Second, an analysis of carbon leakage reveals to what extent pollution is shifted rather than abated. Third, trade-adjusted GHG emission inventories eliminate carbon leakage and attempt to exploit trade to mitigate emissions.

**2.1. Emissions Embodied in Trade (EET).** Calculating the EET can become complex due to the need to enumerate the unique production systems in individual countries to a reasonable level of sectorial detail and then to link this to consumption systems through international trade data. The most common methodology for this type of analysis is a generalization of environmental input–output analysis (IOA) (26) to a multiregional setting.

Using IOA there are two main approaches to modeling EET at a national level (27). The simplest approach is to determine the domestic CO<sub>2</sub> emissions in each country to produce the bilateral trade with another country. This method is the most transparent, but does not assess the imports required to produce the bilateral trade. A more complex approach uses a multiregional input–output (MRIO) model to determine the global emissions for an exogenous final consumption with global trade determined endogenously. Both methods give the same global emissions, but the national emissions differ in the method of allocating intermediate consumption (27). In this article we employ the simplified version that we find is more transparent and appropriate for quantitative analysis of EET in global climate policy.

To explicitly model the EET requires a decomposition of the standard IOA framework into domestic and traded components. The total CO<sub>2</sub> emissions occurring in each region are

$$f_r = F_r(I - A_{rr})^{-1} \left( y_{rr} + \sum_s e_{rs} \right) \quad (1)$$

where  $F_r$  is a row vector with each element representing the CO<sub>2</sub> emissions per unit industry output,  $A_{rr}$  are the inter-industry requirements of domestically produced products demanded by domestic industries,  $y_{rr}$  are the products produced and consumed domestically,  $e_{rs}$  are the bilateral exports from region  $r$  to region  $s$ , and  $I$  is the identity matrix. Summing over all regions gives the total global emissions since bilateral trade is considered. In the full MRIO model the bilateral trade,  $e_{rs}$ , is decomposed into components for intermediate and final consumption (27).

The linearity assumption of IOA allows eq 1 to be decomposed into components for domestic demand on domestic production

$$f_{rr} = F_r(I - A_{rr})^{-1} y_{rr} \quad (2)$$

and the EET from region  $r$  to region  $s$

$$f_{rs} = F_r(I - A_{rr})^{-1} e_{rs} \quad (3)$$

Summation gives the total emissions occurring in the country  $f_r = f_{rr} + \sum_s f_{rs}$ . Direct household and government emissions—such as personal car use—can be included in  $f_{rr}$ . The total emissions embodied in exports (EEE) from region  $r$  to all other regions are

$$f_r^e = \sum_s f_{rs} \quad (4)$$

and the total emissions embodied in imports (EEI) are obtained by reversing the summation

$$f_r^m = \sum_s f_{sr} \quad (5)$$

Another quantity that is often discussed in the literature is the Balance of Emissions Embodied in Trade (BEET)

$$f_r^{BEET} = f_r^e - f_r^m \quad (6)$$

which represents a trade balance for pollution.

**2.2. Carbon Leakage.** Carbon leakage is an issue that has been discussed quite extensively in the economics literature on climate change (28). In this article we deviate from the notion of carbon leakage used in Computable General Equilibrium (CGE) modeling. The CGE literature takes a very “strong” definition of carbon leakage (13) defined as the increase in non-Annex B emissions divided by the reduction in Annex B emissions (28). Under this definition, the analyst seeks to determine the production that *shifts* from an Annex B to a non-Annex B country *in response to a GHG mitigation policy in an Annex B country*. Theoretical studies of strong carbon leakage find the leakage to range between 0 and 130%, but it is highly dependent on the modeling assumptions (28). Empirically, there is little evidence that production shifts due to environmental legislation (29, 30).

The weakness of the IPCC definition of carbon leakage is that it ignores the fact that production may increase in non-Annex B countries for reasons totally disconnected to climate mitigation in Annex B countries—“weak” carbon leakage (13). From 1990 to 2006 global GHG emissions have increased 35% despite stabilizing in Annex B countries (31) and it is important to quantify what portion of this increase is directly or indirectly due to consumption in Annex B countries. This gives rise to an alternative notion of “weak carbon leakage”, defined as the CO<sub>2</sub> EEI from non-Annex B countries to Annex B countries

$$f_r^* = \sum_{s \notin \text{Annex B}} f_{sr} \quad (7)$$

where the summation includes only non-Annex B countries.

This weaker definition of carbon leakage is typically employed in the EET literature and considers the total aggregated CO<sub>2</sub> flows from non-Annex B to Annex B countries. The distinct advantage of “weak carbon leakage” is that it quantifies how much production in non-Annex B countries is to meet consumption in Annex B countries; for instance, how much of China’s emissions are exported. In terms of the global climate system, it is irrelevant if a policy change in an Annex B country caused production to increase in non-Annex B countries (“strong carbon leakage”). It is more important to quantify how much Annex B consumption is produced in countries without binding mitigation policies in place (“weak carbon leakage”).

**2.3. Production and Consumption Inventories.** There are several ways to allocate responsibility for anthropogenic emissions to countries (32). Of particular interest for climate policy is the allocation of production-based and consumption-based emissions (25, 12, 27). We define the production-

based emission inventory as the total domestic emissions occurring from economic production within a country

$$f_r^{prod} = f_r \quad (8)$$

The production-based inventory is related to, but different from the IPCC definition. In the IPCC definition, emission inventories are allocated according to “national (including administered) territories and offshore areas over which the country has jurisdiction” (33), while our production-based inventories are based on the economic activities of *residential institutions* as defined in the System of National Accounts (SNA) (34) and used in the NAMEA (35, 36). Generally the underlying source data are the same, but the production-based inventories include international economic activities—primarily, international transportation and tourism—as defined in the Gross Domestic Product (GDP) (12). Further, the NAMEA are allocated to economic sectors, while the IPCC data are allocated to technologies.

We define the consumption-based emission inventory as the total global emissions occurring from economic consumption within a country

$$f_r^{cons} = f_r^{prod} - f_r^e + f_r^m = f_r - f_r^{BEET} \quad (9)$$

and can thus be considered a trade-adjusted version of the production-based inventory. The consumption-based inventory takes the production-based inventory, but deducts the EEE and adds the EEI. According to our definitions of EEE and EEI, the consumption-based inventory is based on *total* consumption—intermediate and final—using bilateral trade data. If using the full MRIO model a slightly different definition would be used which considers the global emissions from *final* consumption in each region (27).

### 3. Data

The data requirements for a multiregional IOA are considerable, but most developed countries and many developing countries collect the necessary data. However, converting the country data to a consistent global data set is a considerable task. The Global Trade Analysis Project (GTAP) has constructed the necessary data for the purposes of CGE modeling and this data set can be applied for multiregional IOA. The GTAP provides data for 87 countries and 57 industry sectors covering IOA, trade, protection, energy, and CO<sub>2</sub> emissions (37). Version 6 represents the world economy in 2001. We only consider CO<sub>2</sub> emissions which covers over 70% of global GHG emissions (38).

While the GTAP database has impressive coverage, care needs to be taken with its consistency and accuracy. Generally, original data are supplied by the members of the GTAP in return for free subscription. The data are often from reputable sources such as national statistical offices. Unfortunately, due to the voluntary nature of data submissions, the data are not always the most recently available. Further, once the original data has been received “[GTAP] make[s] further *significant* adjustments to ensure that the I–O table matches the external macroeconomic, trade, protection, and energy data” (37). These adjustments (or calibrations) are made for internal consistency in computable general equilibrium modeling and are of unknown magnitude. The key data challenges and adjustments we perform on the GTAP data in preparation for our analysis are described in the Supporting Information.

### 4. Results

**4.1. Emissions Embodied in Trade.** Table 1 shows the EEE and EEI for key Annex B and developing countries. The Supporting Information contains the full data set in both absolute and percentage quantities. For each region we show

the production-based emissions,  $f_r^{prod}$ , the consumption-based emissions,  $f_r^{cons}$ , the percentage EEE,  $f_r^e/f_r^{prod}$ , the percentage EEI,  $f_r^m/f_r^{prod}$ , the percentage BEET,  $f_r^{BEET}/f_r^{prod}$ , the percentage carbon leakage normalized with respect to the total production-based emissions,  $f_r^*/f_r^{prod}$ , and the percentage carbon leakage with respect to the EEI,  $f_r^*/f_r^m$ . We have cross checked our numbers with another study (39) and found that our values generally lie between their lower and upper bounds (see Supporting Information). Figure 1 gives a graphic representation of the EEE and EEI for the 15 countries in the data set with the highest domestic emissions.

Table 1 shows that 5.3 Gt (21.5%) of global CO<sub>2</sub> emissions are embodied in international trade. This number increases to 5.7 Gt (23.0%) if all international transportation is allocated to EEE (see Supporting Information). The Annex B countries export 2.8 Gt (18.9%) of their domestic CO<sub>2</sub> emissions and the non-Annex B countries export 2.6 Gt (25.3%). For individual countries the EEE can vary considerably. Over half of the countries have more than 25% CO<sub>2</sub> EEE with many countries around 50% EEE. The range of values is between 7.4% and 59.7%. This increases to 7.8% and 71.5% if all international transportation is included (see Supporting Information).

Due to symmetry, the global EEI is the same as the global EEE. The Annex B countries import 3.6 Gt (24.5%) of their domestic CO<sub>2</sub> emissions, while the non-Annex B countries import 1.7 Gt (17.2%). Consequently, Annex B countries are net importers of CO<sub>2</sub> emissions and non-Annex B countries are net exporters. For individual countries the CO<sub>2</sub> EEI ranges from 5.9% (Russian Federation) to 219.3% (Hong Kong). Their are 9 of 87 countries which have an EEI of more than 100% (that is, the CO<sub>2</sub> EEI are greater than their domestic emissions). These are generally small, trade-exposed countries. When interpreting the EEI it is important to note that we normalize the EEI (numerator) with the domestic emissions (denominator). This implies that if a country has a cleaner electricity mix then its trading partners, then it is likely that it will have a higher value of EEI compared to a country with a dirtier electricity mix.

Table 1 also shows the “Balance of Emissions Embodied in Trade” (BEET). Annex B countries are net importers of CO<sub>2</sub> emissions, while non-Annex B countries are net exporters. Some authors have placed emphasis on the BEET in the literature (25), but we feel that care is needed in its interpretation. The tendency is to argue that it is better to export more pollution than you import (positive BEET). From a global climate change perspective we argue that it is more desirable to have production occur where it is environmentally preferable and then trade the products internationally. Based on this, some countries may have a large positive or negative BEET depending on their environmental comparative advantage (12).

Given the possible importance of EET in shaping a countries environmental profile we performed regressions between EET and various country characteristics (see Supporting Information). We found that generally large countries—GDP, population, area—have smaller EET. This could be interpreted as large countries being more self-sufficient (11). In terms of the Kyoto Protocol, this suggests that the policy implications of trade will differ depending on the size of the country. Small, trade exposed countries (e.g., Belgium, EEE 45.5%, EEI 89.4%) may face greater economic impacts if climate policy affects trade, compared to a bigger country (e.g., United States, EEE 8.3%, EEI 15.6%) that has a relatively large and independent domestic economy. This suggests that if countries act in coalitions to increase their effective size then they may negate some of the negative consequences of trade.

Currently the United States has not ratified the Kyoto Protocol (Croatia ratified May 2007 and Australia ratified



**TABLE 1. Emissions Embodied in Trade for Selected Countries (Complete List in Supporting Information)<sup>a</sup>**

	production Mt CO <sub>2</sub>	consumption Mt CO <sub>2</sub>	embodied emissions			carbon leakage	
			exports %	imports %	BEET %	total %	share %
United States	6006.9	6445.8	8.3	15.6	-7.3	9.6	61.7
Russian Federation	1502.8	1178.0	27.5	5.9	21.6	2.7	46.6
Japan	1291.0	1488.8	14.5	29.8	-15.3	20.4	68.5
Germany	892.2	1032.1	25.3	41.0	-15.7	13.7	33.4
United Kingdom	618.6	721.3	21.3	37.9	-16.6	14.5	38.2
Canada	547.7	532.2	31.7	28.8	2.8	7.7	26.7
France	509.9	591.9	22.7	38.8	-16.1	12.8	33.0
Italy	475.1	547.6	26.5	41.8	-15.3	16.4	39.2
Belarus/Ukraine	363.3	314.8	28.5	15.1	13.3	3.1	20.3
Australia	351.6	293.7	31.4	14.9	16.5	8.6	57.6
Poland	309.8	280.6	21.9	12.5	9.4	3.0	24.1
Spain	305.7	336.7	26.4	36.6	-10.1	14.5	39.8
Netherlands	204.5	243.4	39.1	58.1	-19.0	21.1	36.3
Belgium	126.4	181.9	45.5	89.4	-43.9	29.4	32.9
Czech Republic	117.4	99.8	40.2	25.3	14.9	4.5	17.7
Greece	101.4	107.3	29.6	35.5	-5.8	14.8	41.8
Finland	94.9	86.3	44.6	35.5	9.1	6.3	17.7
Denmark	74.8	85.0	34.1	47.8	-13.7	13.0	27.2
Portugal	70.0	79.7	25.5	39.4	-13.9	10.7	27.2
Sweden	59.7	83.4	34.1	73.7	-39.7	18.1	24.5
Rest of Annex B	593.1	708.7	34.0	53.5	-19.5	12.7	23.7
Annex B	14616.7	15438.9	18.9	24.5	-5.6	10.8	44.3
China	3289.2	2703.7	24.4	6.6	17.8	3.2	48.2
Rest of Middle East	1199.9	1042.2	28.2	15.1	13.1	8.7	57.8
India	1024.8	953.9	13.1	6.2	6.9	4.3	69.7
Korea	397.7	443.1	27.6	39.1	-11.4	23.1	59.2
Mexico	389.9	407.5	19.4	23.9	-4.5	5.9	24.8
Rest of Former Soviet	350.6	303.8	28.5	15.1	13.3	3.1	20.3
South Africa	323.7	200.2	44.6	6.4	38.2	3.4	52.1
Brazil	321.0	318.5	19.7	18.9	0.8	9.2	48.7
Indonesia	305.4	247.3	31.4	12.4	19.0	7.9	64.3
Taiwan	247.9	240.2	40.0	36.9	3.1	20.2	54.8
Turkey	196.3	188.0	27.5	23.3	4.2	8.6	36.9
Thailand	178.7	154.3	41.8	28.1	13.7	16.6	59.2
Venezuela	155.8	124.0	29.3	8.9	20.4	4.7	53.2
Argentina	120.4	118.4	18.4	16.7	1.7	9.8	58.5
Malaysia	116.8	93.3	59.7	39.5	20.1	23.5	59.6
Rest of non-Annex B	1520.9	1778.4	22.3	39.3	-16.9	26.0	66.3
Non-Annex B	10138.9	9316.7	25.3	17.2	8.1	9.7	56.3
Total	24755.6	24755.6	21.5	21.5	0.0	10.4	48.2

<sup>a</sup> The first columns show the production-based and consumption-based emission inventories. The EEI, EEI, and BEET are expressed as a percentage of the production-based emissions. The carbon leakage is expressed as a percentage of the production-based emissions (first column) and EEI (second column). Production-based totals differ from UNFCCC values since we allocate emissions according to economic activity and not territory (see text).

December 2007). Since the United States represents around one-third of Annex B emissions (38) the Annex B EET varies substantially. Table 2 shows that the ratified countries are significantly more trade exposed than the United States, Table 1. The United States (8) and, previously Australia (9), both cited competitiveness concerns as their rationale for not ratifying the Kyoto Protocol. Based on EET arguments, our results suggest that the United States and Australia have considerably less competitiveness concerns compared to many other Annex B countries.

**4.2. Carbon Leakage.** If an international climate regime has limited participation, such as in the Kyoto Protocol, the problem of carbon leakage arises. Increased carbon leakage can be caused by two factors. First, industries close down in a participating country and migrate to a nonparticipating country with lax environmental regulations (strong Pollution Haven Hypothesis, PHH). Evidence for the strong PHH is poor (29, 30). Second, increased consumption in a participating country is met by increased production in a nonparticipating country (weak PHH) (13). Given dynamic economic development the weak PHH would be sufficient

to cause substantial concerns for the effectiveness of a climate regime with limited participation.

Table 1 shows the carbon leakage from Annex B countries for CO<sub>2</sub> in 2001, and Figure 2 gives a graphical representation for key countries. We use two measures of carbon leakage. The first gives the carbon leakage compared to total domestic emissions which indicates the magnitude of the leakage. The second measure (shown in brackets below), normalizes carbon leakage relative to EEI which indicates the share of EEI coming from non-Annex B countries and is a maximum of 100%. We estimate the carbon leakage from the Kyoto Protocol for CO<sub>2</sub> as 10.8% (44.3%). The leakage varies considerably among countries. It is as high as 29.4% (32.9%) for Belgium and decreases to 2.7% (46.6%) for the Russian Federation. The general trend is for countries with high EEI to have high carbon leakage, although geographic location is important. For instance, Japan and the United States are located far away from other Annex B countries and so normalized to their EEI they have high carbon leakage (68.5% and 61.7%, respectively). On the other hand, countries within the EU have high absolute carbon leakage, but since most

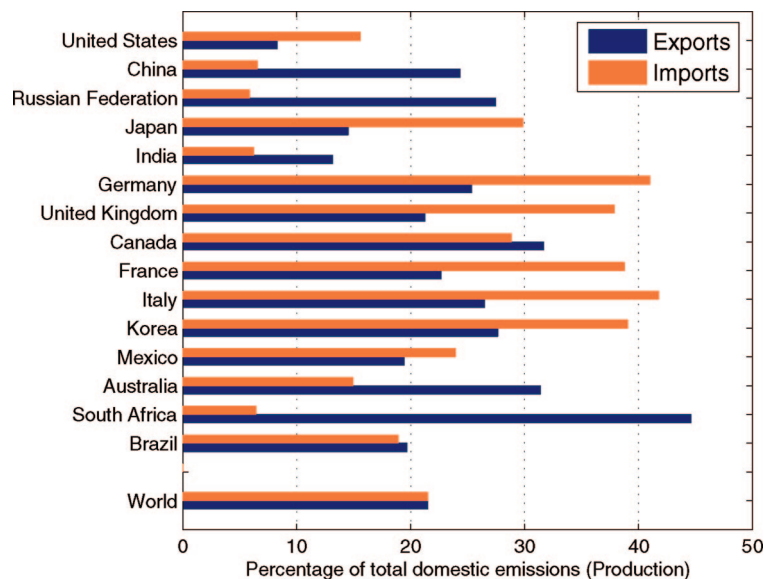


FIGURE 1. Percentage EEE and EEI compared to total production-based emissions for selected countries.

TABLE 2. Emissions Embodied in Trade for the Ratified Annex B Countries (As of December 2007 the US was the only non-ratified Annex B country)

	production Mt CO <sub>2</sub>	consumption Mt CO <sub>2</sub>	embodied emissions		
			exports %	imports %	BEET %
Annex B	14616.7	15438.9	18.9	24.5	-5.6
ratified	8609.8	8993.1	26.2	30.7	-4.5
U.S.	6006.9	6445.8	8.3	15.6	-7.3
non-Annex B	10138.9	9316.7	25.3	17.2	8.1
total	24755.6	24755.6	21.5	21.5	0.0

of the trade is with surrounding Annex B countries their carbon leakage normalized to total EEI is low.

**4.3. Production versus Consumption Inventories.** The current approach to construct GHG emission inventories is to use national borders as a system boundary. Due to international trade, this production-based approach does not reflect what a country consumes. Some authors have argued that GHG inventories should be based on consumption, mainly to circumvent issues with carbon leakage (24, 25, 12). A GHG inventory based on consumption is compiled by taking the production-based GHG inventory, adding the EEI and subtracting the EEE (eq 9). Since the consumption-based approach considers the environmental pressures arising from a product it can be considered as a generalization of life-cycle assessment to the aggregated consumption of a country and is similar conceptually to the ecological footprint (27).

Table 1 shows the production-based and consumption-based GHG inventories for 2001. We do not compare with the UNFCCC territorial-based GHG inventories since, first, we allocate emission by economic activity and not territory, and second, the GTAP emissions data are less accurate making comparisons misleading. Globally the total emissions from consumption and production are the same. However, the allocation among countries varies depending on the BEET. If we consider Annex B countries then the emissions coverage is 822 Mt CO<sub>2</sub> greater (5.6%) based on consumption compared to production. This reflects the negative BEET between Annex B and non-Annex B countries. For non-Annex B countries the consumption-based CO<sub>2</sub> emissions are 822 Mt (-8.1%) lower compared to production. A distinct advantage of the consumption-based inventories is that they eliminate carbon

leakage, as all emissions associated with consumption are connected to the consuming country.

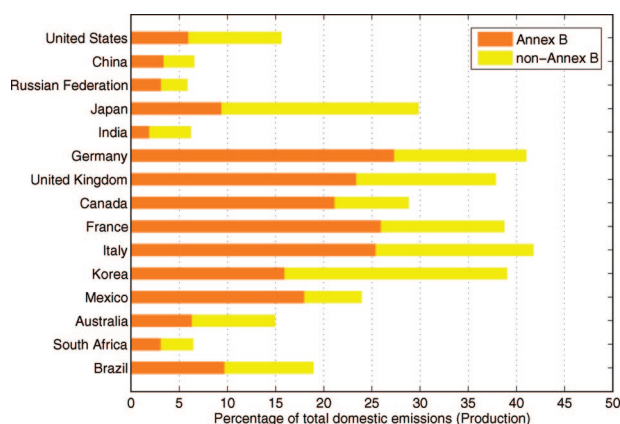
Of the 35 Annex B countries in our data set, only 9 have lower emissions based on consumption rather than production. These nine countries generally have large exports of natural resources (e.g., Australia, Canada, Poland, Russian Federation, and so on). The remaining countries have increased reported emissions, indicating that in terms of CO<sub>2</sub> they consume more than they produce. Most EU countries have a large increase in emissions with consumption, particularly the smaller countries as they are highly dependent on trade. For the EU27 as a whole there is a 564 Mt CO<sub>2</sub> (12.8%) increase in emissions using a consumption-based approach. The United States has a 439 Mt (7.3%) increase and this is rapidly increasing over time (3). To put these magnitudes into context, a country emitting 500 Mt CO<sub>2</sub> annually would be the tenth biggest emitter in the database.

## 5. Discussion

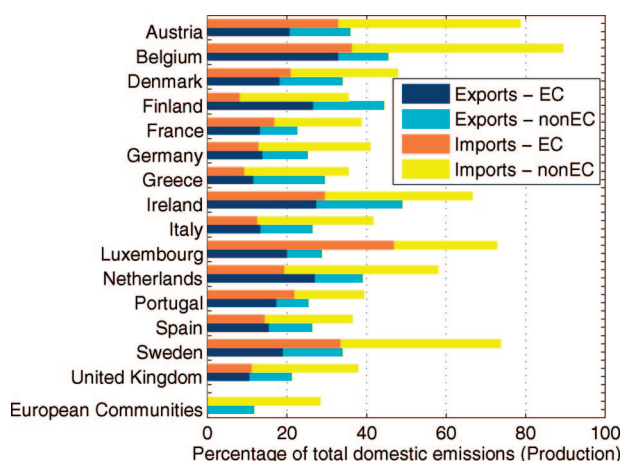
Our results highlight that there are considerable embodied flows of anthropogenic carbon in international trade. We found a total of over 5.3 Gt of CO<sub>2</sub> emissions embodied in international trade flows, and Annex B countries were found to be net imports of CO<sub>2</sub> emissions. As a percentage of production-based emissions we found considerable variation in the EET and this relates back to various country characteristics such as size variables and geographic location. We found the carbon leakage from non-Annex B to Annex B countries was heavily dependent on geographic location.

In terms of policy we claim that a high share of EEE affects competitiveness and hence participation in binding emission reductions since deep emissions cuts would ultimately affect export industries. This effect is greater for small and trade-exposed countries. While it is desirable for countries to clean up production, it is not necessarily desirable for them to stop producing and to shift production elsewhere. As long as there is trade some countries will specialize in pollution-intensive production. In this regard, the challenge for policy is to ensure that countries that specialize in pollution-intensive exports do so with clean technology, rather than moving production elsewhere (assuming production can be relocated) or not taking part in a global climate regime.

With limited participation to binding commitments, EEI can significantly undermine the effectiveness of the Kyoto Protocol through carbon leakage. This is arguably already an



**FIGURE 2. EEI of selected countries showing the EEI from Annex B countries and non-Annex B countries (carbon leakage). Relative to total EEI, EU countries have a larger share of EEI originating in Annex B countries since EU countries are surrounded by other Annex B countries. The carbon leakage for non-Annex B countries is defined the same as for Annex B countries.**



**FIGURE 3. EEE and EEI of selected EC members showing the EET originating inside the coalition (left bar) and outside the coalition (right bar). Generally, the EET are reduced if countries act in a coalition since only the EET originating outside the coalition is considered.**

issue in the Kyoto Protocol where the ratified Annex B countries only account for one-third of global GHG emissions (38). Further, from 1990 to 2006 global CO<sub>2</sub> emissions have increased by 35% (31), even though Annex B countries are still on target for a 5% reduction in 1990 GHG emissions by 2008–2012 (40). This highlights a major challenge in the Kyoto framework. To achieve global coverage and avoid carbon leakage high participation is needed, but this runs the risk of reducing effectiveness to encourage participation (41). We claim these issues are inseparable from international trade.

Within the context of the Kyoto Policy one way to reduce the impact of trade on individual countries may be to encourage coalition formation (42). The EET is generally lower for a coalition compared to individual members of the coalition and this may reduce competitiveness concerns and encourage participation. As an example, within the European Communities (EC)—EU15 in the Kyoto Protocol—a significant share of the EET are between EC members and so the EET of individual countries are larger and more variable compared to the EC as a whole, Figure 3. The coalition limits trade impacts to products and services that leave the EC. It is also possible that groupings of countries with similar environmental objectives could form coalitions with binding

commitments; see Supporting Information for examples with the Asia-Pacific Partnership on Clean Development and Climate (AP6), Association of South East Asian Nations (ASEAN), and the South American Community of Nations (CSN). A further advantage of regional approaches is that many geo-political and economic organizations are already well-established and many of these bodies have already implemented environmental initiatives. Negotiations among regions with established dialogue and policies may face fewer political obstacles and may be a more effective method of designing an optimal global framework (42).

Another approach to reduce the impact of trade on climate policy is to adjust emission inventories for trade. Currently, emission inventories are production-based and this causes a separation between a country's consumption and the global production system. Arguably, it is this separation that causes the competitiveness concerns in the Kyoto Protocol. With consumption-based emission inventories consistency is returned between a country's consumption (which occurs domestically) and the production system required for the consumption (which occurs globally). Consumption-based inventories eliminate carbon leakage and encourage mitigation to occur where the costs are lowest (16, 12). In the very least, trade-adjusted emission inventories may offer a more systematic approach for allocating differentiated commitments (43, 44) if the Kyoto Protocol structure is retained post-2012.

Another interesting feature of consumption-based inventories in the context of the Kyoto Protocol is the connection with Border Tax Adjustments (BTA). BTA have been suggested as a way of addressing competitiveness concerns and encouraging participation (20–23). BTA are related to consumption-based inventories in two ways. First, since the consumption-based inventory includes a share of emissions from trading partners it indirectly places a cost of carbon in those trading partners. Second, the methodology used to construct consumption-based inventories is also a consistent method to determine the value of border taxes for aggregated sectors.

As negotiations for a post-Kyoto climate protocol intensify, it is important to not only strive for participation from developing countries, but also to improve the structure of the Kyoto Protocol. Arguably, the Kyoto Protocol has many good features which should remain, but small improvements may greatly increase its effectiveness (44). One potential hole in the Kyoto Protocol is that global emissions can seemingly increase unabated despite emissions reductions in Annex B countries (40). While the Kyoto Protocol may be hailed as a success in international political negotiations, it is yet to be seen whether it will be successful in meeting its environmental goals. In this article, we have argued that international trade underlies many of the debated issues in the Kyoto Protocol—economic costs, competitiveness, participation, carbon leakage—and trade issues should play a much stronger role in post-Kyoto negotiations.

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## Supporting Information Available

Supplementary Methods, Data, Comparisons, Results, and Discussion; the complete list of all 87 countries analyzed shown in both absolute and percentage terms; three additional figures on coalition formation. This information is available free of charge via the Internet at <http://pubs.acs.org>.

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