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Trade in 'Virtual Carbon'

Empirical Results and Implications for Policy

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Abstract

The fact that developing countries do not have carbon emission caps under the Kyoto Protocol has led to the current interest in high-income countries in border taxes on the "virtual" carbon content of imports. The authors use Global Trade Analysis Project data and input-output analysis to estimate the flows of virtual carbon implicit in domestic production technologies and the pattern of international trade. The results present striking evidence on the wide variation in the carbon-intensiveness of trade across countries, with major developing countries being large net exporters of virtual carbon. The analysis suggests that tax rates of $50 per ton of virtual carbon could lead to very substantial effective tariff rates on the exports of the most carbon-intensive developing nations.

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Trade in 'Virtual Carbon': Empirical Results and Implications for Policy

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1. Introduction

A key provision of the Kyoto Protocol is that signatories take on legally binding caps on their carbon emissions if they are in ‘Annex 1’ to the protocol (essentially all high income and transition economies), while non-Annex 1 countries (developing countries) do not have caps. This has potential consequences for trade competitiveness and carbon leakage, and countries with caps may consider taxing the carbon content of imports from countries without caps to level the playing the field – indeed, the Waxman-Markey and Boxer-Kerry bills currently before the US Congress, aimed at instituting a system of cap and trade for climate policy in the US, both include border taxation as a key provision.[1]

Taxing carbon content at the border is potentially trade-distorting, with associated losses in efficiency and welfare for trading countries. Moreover, *unilateral* carbon taxation at the border may invite retaliation and could damage the multilateral trading system under the WTO. This motivates our study: we measure the bilateral flows of carbon implicit in international trade, and then calculate how large the effective tariff rate associated with a border tax on embodied carbon – or *virtual carbon* to borrow a term used by the water community[2] – could be for major high income and developing countries.

Our main findings are that the carbon intensiveness of exports is very high in many large developing countries, that there is wide variation in intensiveness across countries and sectors, and that imposition of a border tax could lead to substantial effective tariff rates on imports from developing countries – for example an average tariff rate of 10.3% on Chinese imports to the US if carbon is taxed at \$50 per ton of CO_2.

Our analysis extends recent work, in particular Peters and Hertwich (2008), by (i) constructing a country-by-country matrix of flows of carbon embodied in international trade, (ii) disaggregating carbon intensities to the sector and country level, (iii) linking the analysis of carbon flows in international trade to the literature on border tax adjustments, and (iv) estimating how large the taxes could be if virtual carbon were taxed at the border in major economies. Ours is a partial equilibrium analysis, and it is worth noting recent work by Mattoo *et al.* (2009a, 2009b) which employs a general equilibrium framework to analyze the impacts of taxing carbon, including border taxes, on exports of manufactured goods by large developing countries.

The remainder of the paper is organized as follows. We first review the concept of embodied or virtual carbon and discuss previous efforts to estimate the amount of carbon that is (implicitly) traded between countries. We then outline the basic input-output framework that is used to model the carbon flows implicit in trade. Section 4 details the data employed. Section 5 lays out the relevant trade theory, as well considerations of

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[1] Note that in the current climate negotiations some countries have questioned whether carbon should be taxed where it is emitted or where it is consumed. Our analysis of the trade literature below shows this to be a non-issue – the logic of taxing consumption of carbon is that taxes would need to be imposed on all consumption, including on the carbon content of imports.

[2] See, for example, Velázquez (2006), Chapaquin *et al*. (2006) and Guan and Hubuecek (2007).

WTO compatibility and ethical concerns, followed by presentation of the empirical results in Section 6. The final section assesses policy implications and concludes.

2. Virtual Carbon and Its Measurement

A growing number of anlayses have sought to examine the extent to which carbon is embodied in the international trade of goods and services either with an emphasis on a single country, notably China, trading with the rest of the world (Helm *et al*. 2007; Pan *et al*. 2008; Peters *et al*. 2008; Andrews *et al*. 2008) or all countries (with some aggregation for blocs of smaller countries) trading with one another (Ahmad and Wyckoff, 2003; Peters and Hertwich, 2008). Typically, these papers employ some form of input-output (IO) analysis (see, Miller and Blair, 1985; Førsund, 1985) to examine not only how economic sectors that comprise individual economies buy from and sell goods to one another but also how these sectors (or economies) then trade with the rest of the world. Importantly, embodied within these goods is the carbon that was released or emitted in the course of their production. The idea then, in existing studies, is to track this virtual carbon as the goods wend their way through the global economy, and ultimately in some shape or form are consumed.

Studies differ as to how detailed a carbon trail is analyzed. Delgado (2007) provides an assessment of the carbon intensity of the *export mix* of European Union (EU) members. Peters and Hertwich (2008) look at both sides of the coin by examining the carbon embodied in the imports of a country (or regional trading bloc) as well as its exports (see, in addition, Ahmad and Wyckoff, 2003). This bilateral trade input-output (BTIO) approach can be contrasted with the multi-regional input-output approach (MRIO) (Peters, 2008; Wiedmann *et al*. 2008). In essence, the BTIO approach only accounts for emissions in the exporting country. By contrast, the MRIO allocates to the consuming country all of the virtual carbon produced over the entire chain of production (across sectors and across countries) for a final consumption good. It is, of course, an empirical question as to how crucial this distinction is in practice. Ultimately, however, a critical consideration may be the specific analytical use of the different approaches. This is an issue to which we return later in this paper.

How large are these flows of virtual carbon? What is the difference between the amount of carbon that countries such as the US and China, or trading blocs such as the European Union, *produce* and *consume*? On the one hand, Peters and Hertwich (2008) find that (taken as group) the production emissions of those countries which make up Annex B of the Kyoto Protocol are roughly 5 percent less than consumption emissions. Ahmad and Wyckoff (2003) reach a similar conclusion for OECD countries (circa 1995) taken as a bloc. On the other hand, these findings mask considerable variation between countries (within these highly aggregated groupings). Furthermore, captured within this calculation of net difference is a process whereby the majority of countries are exporting embodied emissions in substantial quantities. However, these same countries are also importing considerable amounts of carbon embodied in other goods that they consume. Looking at the overall carbon balance for a country masks a considerable amount of ebb and flow. Ahmad and Wyckoff (2003) note that the *total* amount of internationally traded carbon is comparable in size to (and in many cases greater than) the production emissions in many individual countries.

Calculating the balance of trade in virtual carbon has been focal to many of these contributions. In this context it is worth noting that the broader idea of an 'ecological balance of payments' is not new. Atkinson and Hamilton (2003), for example, use international trade data in an IO-type framework to derive the demand for natural resource rents attributable to any given country's final consumption (see also Proops and Atkinson, 1998, Proops *et al*. 1999 and Bailey and Clark, 2000, in a computable general equilibrium, or CGE, setting).[3, 4] But arguably more important are the broader policy implications of this work. For Peters and Hertwich (2008), this is envisaged in terms of the carbon leakage problem and the construction of consumption-based carbon inventories as a building block in the response to this challenge (see, for example, Peters and Hertwich, 2008). Similarly, Helm *et al*. (2007) use their analysis to recast the story of the UK's carbon emissions record since 1990 (see, in addition, Wiedmann *et al*. 2008).

To date few studies appear to have linked the results of the type of IO analysis described above to specific types of carbon reduction policy such as carbon taxation (although see Delgado, 2008, which looks at the likely burden which might fall on the EU's traded goods sectors in this context). Nevertheless, a number of papers have examined such aspects in both theory and practice (e.g. Ismer and Neuhoff, 2007; Fischer and Fox, 2009) or used CGE models to simulate the impacts of policy changes (e.g. Babiker and Rutherford, 2005; Fischer and Fox, 2009; Mattoo *et al.* 2009a, 2009b). In what follows, therefore, we discuss our findings in relation to the specific question of taxing virtual carbon at the border. Before doing this we outline the model and methods that we use to generate our results.

3. The Input-Output Model

This section sketches the matrix algebra underlying the empirical results in this paper. This draws on a body of existing knowledge including Peters (2008) (but see Miller and Blair, 1985, for an earlier exposition of IO analysis in a multi-regional context). In what follows, the notation refers to the case of m regions (or countries) and k sectors. Superscripts indicate regions and subscripts indicate sectors. When either superscripts or subscripts have a pair of numbers, the pair should be interpreted as indicating 'from-to' flows. So, for example, p_{34}^{12} indicates exports of intermediate goods from sector 3 in region 1 to sector 4 in region 2.

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[3] In other contexts, Pedersen (1993) has used an IO framework to analyse net exports of transboundary ("acid rain") pollution in Denmark vis-à-vis the rest of the world. Young (1996) examines the relative pollution intensity of traded (export-oriented) sectors and non-traded sectors in the Brazilian economy.

[4] Another prominent way of thinking about the links between countries in this way is the 'ecological footprint'. This describes the extent to which a particular country (or region) is reliant on resources from elsewhere to support domestic economic activity (Rees and Wackernagel, 1994). In the carbon example, these needs can be expressed in a number of ways such as the land required to grow the equivalent biofuel. If this required area is larger than the area actually available to that country, then in this sense the country has an ecological deficit. Turner *et al*. (2007) provide an indication of how the ecological footprints standpoint relates to the IO approach.

Single Region or Country

Consider a region (or country) denoted by *r*. Input-output analysis begins with a simple balance of monetary flows (both within and 'to and from' this economy):

$$x^r = A^r x^r + y^r + e^r - m^r \qquad (1)$$

where: x^r is a *k*-dimensional vector of total output with each of the *k* element indicating a sector's output;

A^r is the matrix of inter-industry trade of intermediate products (including imported ones), where each element a_{ij}^r is such that $a_{ij}^r = \frac{b_{ij}^r}{x_j^r}$ and where b_{ij}^r are region *r*'s sales of intermediate goods from sector *i* to sector *j*;

y^r is a *k*-dimensional vector of final demand of goods and services (including imported ones);

$e^r = \sum_s e^{rs}$ is a *k*-dimensional vector representing the sum of exports from region *r* to all other regions *s*; and,

$m^r = \sum_s e^{sr}$ is the *s* the sum of exports from all regions (other than *r*) to region *r*: i.e. region *r*'s imports.

Removing imports from the system we obtain:

$$x^r = A^{rr} x^r + y^{rr} + e^r , \qquad (2)$$

where: $y^{rr} = y^r - \sum_s w^{sr}$ (where w^{sr} indicates region *r* imports of final consumption goods from region *s*); and,

$A^{rr} = A^r - \sum_s H^{sr}$ (where H^{sr} is the *k*x*k* matrix of region *r* imports of intermediate goods from region *s*).

Domestic carbon dioxide (CO_2) emissions can then be estimated as follows:

$$z^r = f^{r\,\prime} x^r = f^{r\,\prime} \left(I - A^{rr}\right)^{-1} \left(y^{rr} + e^r\right), \qquad (3)$$

where f^r is a k-dimensional vector with each element representing the emission intensity of each industry's output. Emissions z^r occur domestically to produce both the domestic component of final consumption and total exports.

Multiple Regions or Countries: The Bilateral Trade Input-Output (BTIO) Model

It is possible to use matrix algebra to represent the world's m regions in one compact expression. Given the definitions of x^r, A^{rr}, y^{rr}, e^{rs} and f^r provided in the single country case, define the following:

- The $(m\times k)\times m$ matrix of world's total output X: $X = \begin{pmatrix} x^1 & 0 & \cdots & 0 \\ 0 & x^2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & x^m \end{pmatrix}$;[5]

- The $(m\times k)\times(m\times k)$ matrix of domestically produced intermediate consumption, A:

- $$A = \begin{pmatrix} A^{11} & 0 & \cdots & 0 \\ 0 & A^{22} & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & A^{mm} \end{pmatrix};$$

- The $(m\times k)\times m$ matrix of domestically produced final consumption expenditure Y:

$$Y = \begin{pmatrix} y^{11} & 0 & \cdots & 0 \\ 0 & y^{22} & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & y^{mm} \end{pmatrix};$$

- The $(m\times k)\times m$ matrix of total (final and intermediate) exports E:

$$E = \begin{pmatrix} 0 & e^{12} & \dots & e^{1m} \\ e^{21} & 0 & \dots & e^{2m} \\ \vdots & \vdots & \ddots & \vdots \\ e^{m1} & e^{m2} & \dots & 0 \end{pmatrix};$$

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[5] Note that here, and in the following expressions, 0 indicates a k-dimensional vector of zeroes.

- The $(m\times k)\times m$ matrix of emission intensities F: $F=\begin{pmatrix} f^1 & 0 & \cdots & 0 \\ 0 & f^2 & \cdots & 0 \\ \vdots & \vdots & \ddots & 0 \\ 0 & 0 & 0 & f^m \end{pmatrix}$.

Broadly analogous to the single country case, the main national accounting identity in the BTIO model is:

$$X = AX + Y + E$$

It follows that:

$$X = (I - A)^{-1}(Y + E)$$

The matrix of world emissions necessary to support (global) final demand can then be estimated as:

$$Z_{BT} = F'(I - A)^{-1}(Y + E) \tag{4}$$

The ij^{th} element of the $m\times m$ Z_{BT} matrix represents region i's emissions necessary to support the production of goods sold to region j. The diagonal elements of Z_{BT} are simply domestic emissions necessary to produce domestic final demand, while the off diagonal elements are the emissions of region i necessary to produce exports from region i to region j. The sum of the elements of each row is total emissions produced in the corresponding region. The sum of the elements of each column is total emissions (domestic emissions plus foreign emissions to produce imports) commanded by the corresponding country's demand.

Multiple Regions or Countries: The Multi-Region Input-Output (MRIO) Model

The BTIO method to estimate emissions, and virtual carbon, does not take into account the fact that exports from region i to region j are made possible, among other things, by imports of region i from say region k. A more sophisticated method to estimate total emissions (including imports of virtual carbon) is through the use of multi regional input-output (MRIO) analysis.

To reiterate, a key feature of MRIO is that it differentiates between exports that go to final consumption and exports that go to intermediate consumption in the importing country. In the MRIO model intermediate imports are endogenized, whereas in the BTIO model they are exogenous (that is, they are treated as components of final demand). We define the following:

- The k-dimensional vector of region r's exports of final consumption goods to region s, denoted w^{rs}:

$$w^{rs} = \begin{pmatrix} w_1^{rs} \\ w_2^{rs} \\ \vdots \\ w_k^{rs} \end{pmatrix}$$

- The *(m*×*k)*×*k* matrix of exports of final consumption goods or *W*:

$$W = \begin{pmatrix} 0 & w^{12} & \dots & w^{1m} \\ w^{21} & 0 & \dots & w^{2m} \\ \vdots & \vdots & \ddots & \vdots \\ w^{m1} & w^{m2} & \dots & 0 \end{pmatrix}$$

- The *k*×*k* matrix of *intermediate goods and services traded* between region *r* and region *s* and which is denoted P^{rs}*:*

$$P^{rs} = \begin{pmatrix} p_{11}^{rs} & p_{12}^{rs} & \cdots & p_{1k}^{rs} \\ p_{21}^{rs} & p_{22}^{rs} & \cdots & p_{2k}^{rs} \\ \vdots & \vdots & \ddots & \vdots \\ p_{k1}^{rs} & p_{k2}^{rs} & \cdots & p_{kk}^{rs} \end{pmatrix}$$

  where $p_{ij}^{rs} = h_{ij}^{rs} \big/ x_j^s$ and h_{ij}^{rs} are region *r*'s sales of intermediate goods from sector *i* to region *s*'s sector *j*

- The *(m*×*k)*×*(m*×*k)* matrix of exports of *intermediate consumption goods P*:

$$P = \begin{pmatrix} 0 & P^{12} & \dots & P^{1m} \\ P^{21} & 0 & \dots & P^{2m} \\ \vdots & \vdots & \ddots & \vdots \\ P^{m1} & P^{m2} & \dots & 0 \end{pmatrix}.$$

Note that $E=PX+W$. The MRIO and the BTIO models differ in the way they identify exports therefore. This, in turn, has implications for the way emissions, and thereby virtual carbon, are then allocated across countries and sectors. It is worth noting that while the BTIO and MRIO approaches both yield the same total emissions from production in each country, the virtual carbon embodied in domestic final demand differs country by country in the two models – this follows from the different treatment of intermediate imports in the two approaches.

In the MRIO approach expression (4) can be rewritten as:

$$Z_{MR} = F'\left(I - A - P\right)^{-1}\left(Y + W\right) \tag{5}$$

Analogous to the case of the BTIO model, the ij^{th} element of the $m \times m$ Z_{MR} matrix represents emissions in country i necessary to support demand of final consumption goods in country j. Unlike the BTIO model, virtual carbon flows from i to j include emissions not directly associated with trade between i and j. In fact, these virtual flows include emissions that have been exported from i to regions other than j and from there where exported to j.

The key difference between MRIO and BTIO is that endogenizing intermediate trade results in full measurement of all indirect flows of carbon through trade of intermediate goods. So, for example, the diagonal entry in the Z_{MR} matrix includes domestic emissions linked to production of an intermediate good that is exported to another country, which in turn produces an intermediate good that is imported back into the original country. Off-diagonal row entries represent total emissions virtually exported to a given country (county j for example), including emissions to produce intermediate goods that are used in a third country, which are then exported as intermediate goods to country j. In contrast, the BTIO approach measures only the domestic emissions required to supply domestic final demand in the diagonal entry of the Z_{BT} matrix, while the off-diagonal entry for country j represents only the emissions in the producing country associated with exports, both intermediate and final, to country j.

In principle, therefore, the MRIO approach yields a more complete accounting of the flows of virtual carbon between countries than BTIO. The cost of this more complete accounting is that it is difficult to associate virtual carbon flows with bilateral trade flows, which is where the BTIO approach would be more appropriate. Accordingly, in what follows we use MRIO where complete accounting is needed, and BTIO where accounting linked to specific trade flows is needed.

4. Data

The data that we use in what follows are from version 7 of the Global Trade Analysis Project (GTAP) database for the year 2004 (Dimaramam, 2006). The GTAP data, widely used for computable general equilibrium (CGE) modeling, are available for 106 countries and regions and 57 sectors covering agriculture, industry and services. It includes IO, trade and CO_2 emissions data, among others. In the analysis that follows, however, these GTAP data are aggregated to 15 countries and regions and 19 sectors. Arguably this allows for enough detail without overcomplicating the analysis unnecessarily. Abbreviations for the countries and the regions discussed in tables, figures and results are outlined in an annex to this paper.

While the data in GTAP differentiates imports by use (i.e. final demand vs. intermediate consumption), these do not specify the country of origin. Because of this, in this paper, we use the GTAP trade data to estimate the proportion of intermediate (and final consumption) goods and services that come from a particular country assuming the share is the same as the share of imports from that country over total imports. Denoting, as above, H^{rs} as the matrix of intermediate goods and services traded between region r and regions s, we can express the imports of region s as:

$$m^s = \sum_r e^{rs} = H^{s,imp} i + w^{s,imp} = \left(\sum_r H^{rs} \right) i + \sum_r w^{rs}$$

We can then calculate the elements of H^{rs} and of w^{rs} as

$$H_{ij}^{rs} = H_{ij}^{s,imp} \frac{e_i^{rs}}{m_i^s}, \text{ and}$$

$$w_i^{rs} = w_i^{s,imp} \frac{e_i^{rs}}{m_i^s}$$

Note, however, that CO_2 emissions in GTAP are limited to those from fossil fuel consumption alone. Clearly, a fuller picture of virtual carbon would need to include emissions from other greenhouse gases and CO_2 emissions from agriculture, land-use change and other processes. It is important also to understand how trade in energy goods (such as coal or crude oil) is treated in this analysis. In the IO approach, carbon is accounted for when it is emitted in a production process. This means that exports of crude oil, for example, are measured in terms of how much carbon was emitted in its drilling, pumping, transporting and processing but not in terms of how much carbon the oil contains. The latter is only measured when (and where) the oil is actually burned and the carbon released.

Finally, because the GTAP data are measured in dollars at market exchange rates, it is worth considering whether the (relatively) low price of non-tradables in developing countries could distort the analytical results[6]. Since the sectors with the highest carbon intensity are typically the big traded sectors (metals, minerals, petroleum, chemicals, cement, and pulp and paper) this would not appear to be a concern. Moreover, for highly carbon-intensive non-tradables, the low price of these goods (resulting from the use of market exchange rates) is fully offset by a correspondingly high emission coefficient. When we wish to employ values for GNI as a numeraire below, we use both PPP and market exchange rate values.

5. Theoretical, Legal and Ethical Considerations for Border Taxation

As noted in the Introduction, our main interest in employing IO analysis to trace the flows of virtual carbon in international trade is to examine the potential size of border taxes on virtual carbon. It is important, therefore, to consider the theory of border taxation,

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[6] As noted in World Bank (2008), production in a developing economy will typically be underestimated if market exchange rates are used to compare its value with that in high-income economies. Because developing economies tend to have relatively lower wages leading to lower prices for non-traded goods and services, a unit of local currency has greater purchasing power within a developing economy than it does in the global market. It follows that conversion to an international currency (e.g. the US dollar) for the sake of comparison results in a distortion. PPPs adjust for differences in price levels between economies, which may not be reflected in market exchange rates, at least in the short run.

questions of carbon leakage linked to this taxation, the efficiency properties of border taxation, the WTO compatibility of border taxes on virtual carbon, and some of the ethical concerns that might arise from the use of these taxes.

Lockwood and Whalley (2008) point out that the discussion of trade taxes on carbon content should be rooted in a long-standing literature on border tax adjustments. One of the basic results in this literature is that, as long as tax rates (ad valorem) are uniform across sectors, then switching back and forth between taxing by origin and taxing by destination is not trade-distorting (see, for example, Whalley, 1979). Price levels and/or exchange rates between the trading countries will respond to the tax, but the volume of trade and relative prices of traded goods will not change.

Even if tax rates are not uniform across sectors, Lockwood and Whalley go on to note, as long as there are equilibrating factors at the sector level, such as flexible wage rates, then the same non-trade-distorting result will hold. This seems unlikely to hold in real-world settings. Grossman (1980) looks at the more complex issue of trade in intermediate as well as final goods, and concludes that a uniform product tax is trade-distorting under the origin principle, but trade neutral under the destination principle.

The incentive effects of taxing virtual carbon depend critically on the slope of the demand schedule for the good being taxed. If demand for the good is infinitely elastic then taxing virtual carbon is equivalent to taxing emissions at source – the loss of producer surplus (deadweight loss) under the virtual carbon tax is precisely equal to the cost of abatement which would be incurred by the producer under an equivalent pollution tax (that is, a tax which produces the same quantity of emissions reduction). If the demand for the good is perfectly inelastic then the tax has no effect on levels of production or emissions. Intermediate cases for demand elasticities would have the obvious effect – the steeper the demand schedule the less effective is the tax on virtual carbon.

Fischer and Fox (2009) provide a very useful partial-equilibrium analysis of various options for treating the potential competitiveness impacts of a carbon tax. These options include a tax on imports, a tax rebate on exports and the sum of these two treatments. The latter corresponds to a ‘full border adjustment’ and which, they note, is equivalent to taxing by destination: i.e. a consumption tax. The authors find that each of these border tax treatments increases domestic production (and therefore, implicitly, domestic emissions) relative to the no-border-tax case where production emissions are taxed (regardless of whether produced goods are for export or not). Importantly, from the perspective of dealing with the climate change problem, the effect on global emissions is ambiguous - this depends crucially upon the relative size of the elasticities of supply and demand, as well as the carbon intensities of domestic and imported goods.

There is also an important information dimension to the question of instrument effectiveness. In a world of perfect information, where the virtual carbon content of each good is known with precision, the efficiency of taxing virtual carbon for a good whose demand is perfectly elastic would be the same as the first best instrument: i.e. taxing emissions at source. In reality, the virtual carbon content of any good can only be known imperfectly and this information may not be freely available. Hence, there is reason to expect that taxing virtual carbon may not be as efficient as the first best instrument even if the demand for the good is perfectly elastic.

Another important consideration in taxing virtual carbon at the border is World Trade Organization (WTO) compatibility. As long as each unit of virtual carbon – whether domestic or imported – is taxed at the same rate, there is at least potential compatibility with the national treatment clauses of the GATT. Demaret and Stewardson (1994), Goh (2004) and Ismer and Neuhoff (2007) look at this question in more detail. The issues are complex – and depend at least as much on the minutiae of specific proposals as broader points of principle and practice – and perhaps not surprisingly contributors to this discussion have drawn divergent conclusions. De Cendra (2006) concludes that the WTO compatibility of a border tax on carbon, as proposed in the EU for example, will not be determined definitively until a case goes to the Appellate Body of the WTO.

The BTIO approach illustrated earlier provides information that, in principle, could be used to calculate a ‘carbon-added’ tax. In practice, inevitable inaccuracies in data, not to mention the inherent limitations of a Leontief production function, would limit the efficiency of the tax instrument for these traded goods, as noted above, and could provide the basis for a dispute at the WTO if virtual carbon taxes were applied to international trade. In other words, accurate measurement of virtual carbon is likely to be highly complex and subject to dispute, especially if conducted in a comprehensive way that taxes *all* virtual carbon.

Within this context, Barrett (2008) sounds a skeptical note about the credibility and acceptability of taxing virtual carbon, within a broader skepticism of prospects for success in negotiating international agreements which mandate economy-wide carbon reductions. In doing so, however, he speculates as to whether international deals to reduce carbon in particular (carbon intensive) economic sectors might incorporate trade restrictions as one means of increasing participation and ensuring compliance. Clearly, ‘leveling the playing field’ in several sectors represents a rather piece-meal approach, whereas taxing virtual carbon is a part of a comprehensive approach to this problem. For Barrett, however, a critical issue is what approach could command the necessary global consensus to make trade restrictions both credible (as a form of punishment) and acceptable (as it might be more likely to be if combined with positive measures such as financial assistance to developing countries).

Ambiguities about WTO compatibility aside, some commentators have identified concern about the possibly divisive influence of proposals to tax virtual carbon on future climate change negotiations (see, for example, Cosbey, 2008). Broader still, although relevant to framing such concerns, are equity considerations. Miller (2007), for example, argues for the principle that nations can be judged to be responsible for damages past and present. While taxing a bad is potentially welfare-improving at the global level, if poorer countries end up financing a global public good as a result then this raises severe ethical concerns, especially since the poorest countries have made minimal contributions to the source of the problem.

6. Empirical Results

Our IO analysis yields a rich array of results regarding the composition of trade in virtual carbon. We first use the MRIO approach to summarize total flows of carbon, in total and normalized to GDP, by country. We follow this with an examination of the composition of trade in virtual carbon using the BTIO approach. As noted above, the key advantage of the BTIO approach is that it allows the matching of bilateral trade flows to their carbon content.

Turning to the results for the MRIO approach to virtual carbon, Figures 1 and 2a and 2b decompose flows of carbon by country. The virtual carbon – from *domestic* sources – required to produce domestic final demand is represented by the dark bars. Gray bars represent the virtual carbon – from *foreign* sources – embodied in the country’s final demand. The outline bar measures how much carbon was actually emitted in all production processes inside the country. Note that these are emissions in the production sectors, meaning that household and government emissions are excluded. This is not to argue that these emissions are unimportant in the bigger picture of understanding the contribution to climate change of different economic sectors. However, since these emissions are not ‘virtually traded’ they fall outside the domain of analysis in this paper.

In Figure 1 we see – as expected – that the big emitters of carbon from production processes are the US, the EU, China and the aggregate of other middle income countries (excluding China, India, Brazil, Mexico, Russia and South Africa). Note that if the outline bar (emissions from total production) is higher than the sum of the dark and grey bars (domestic and foreign virtual carbon in domestic final demand), then the country is a net exporter of virtual carbon. The main net exporters of virtual carbon are China, Russia and other middle income countries, while the main net importers are the EU, USA and Japan.

Figures 2a and 2b look at carbon intensity of consumption (solid bar) and production (outline bar) by normalizing the numbers from Figure 1 to the GNI measured at market exchange rates and PPP. From a consumption perspective, the countries consuming the most (domestic and foreign virtual carbon) emissions per dollar of income are Russia, China, India and South Africa. Adjusting by PPP exchange rates increases the relative importance of the USA (now fourth) and diminishes that of India. To understand these numbers, consider India: one dollar of (PPP) income results in 0.4 tons of consumption driven emissions. This is much lower than China (almost 0.7) but higher than EU15 (0.26). So income growth in India will result in a higher 'demand' for emissions than income growth in the EU (assuming constant technology and PPP exchange rates). This reflects both India's production patterns but also the characteristics of India's demand for imported goods.

Turning now to bilateral trade flows (i.e. using the findings from the BTIO approach as discussed), Figures 3 and 4 break down the sources of flows of virtual carbon imported into the EU and the US. In terms of virtual carbon imports, the EU imports large amounts from China, the US, economies in transition and Russia, with smaller flows from India and Japan (Figure 3). The US imports significant flows of virtual carbon from China, the EU, and Canada, with smaller flows from Mexico, Russia and Japan (Figure 4). As seen in Figure 5, the major destinations for Chinese exports of virtual carbon are the EU, the US and Japan, with smaller flows to India, economies in transition, Mexico, Canada and Russia.

The bilateral trade IO analysis also lends itself to analysis of the net flows of virtual carbon between countries, as presented in Table 1. China has large net exports to the EU, the US and Japan, while the EU is a big net importer from other middle income countries, economies in transition and the US. The US is also a major net importer from other middle income countries. These bilateral flows of carbon provide the basis for estimating the effective tariff rate associated with any particular level of a border tax on virtual carbon.

Estimates of border taxes on virtual carbon

Table 2 contains our key results regarding the potential size of taxes on virtual carbon trade. It presents the effective tariff rate that exporting countries would face on their goods and services if all importing countries placed a \$50/ton CO_2 tax on the virtual carbon content of imports. This illustrative carbon price is in line with recent experience, given that emissions permits in the EU Emission Trading Scheme (ETS) traded as high as €35 in 2008.

Reading these results *by column* tells us about the (effective) tariff burden that the USA, for example, would place on the imports that it receives from its trading partners such as Russia and the European Union. This burden is, in turn, expressed in Table 2 as a percentage of the value of the total imports from that particular country (or region) to the USA. The effective tariff rate on trade in this example would vary from a high of 10.4% and 10.3% on imports from Russia and China respectively through to 8.9% for South Africa, 7.9% for India, to a low of 1.2% for the European Union. The final value in the column for the USA is the average tariff placed on the imports received from all of its trading partners (3.1%).

Reading these results *by row*, by contrast, tells us about the tariff that a given exporter would face in each of the countries where its goods are destined. In the case of China, for example, its exports are subject to an effective tariff rate (based on the virtual carbon in those exports) of 10.5% for those exports consumed in the European Union, 10.4% for Japan and 10.3% for the US. The final number in the row for China is the average tariff that its exports to its trading partners would face, 10.7%. As a comparison, US exports to other countries would face a trade-weighted average tariff rate of 3.1% and EU exports would face a rate of 1.2%.

As can be seen from Table 2, these effective tariff rates vary widely across countries. This, in turn, is the result of two factors: the sectoral composition of trade and the carbon intensity of different sectors in different countries. Clearly, a uniformly higher (lower) virtual carbon tax would uniformly boost (shrink) these percentages.

Table 3 shows the effective tariff rate that would be faced by country and sector if the virtual carbon content of traded goods were taxed at \$50 per ton of CO_2. Average tax rates, as reported in Table 2, give the big picture, but it is at the sector level that the economic impacts of virtual carbon taxes will be felt. The large developing countries highlighted in Table 2 have tradable sectors that would be particularly hard-hit by a tax on virtual carbon – chemicals, ferrous and non-ferrous metals, and other mineral products. 'Other mining' products are particularly carbon-intensive in Mexico and South Africa, as are paper products produced in China and India. Tradable sectors such as chemicals, ferrous metals and mineral products are highly carbon intensive in low income countries.

Modeling the wider economic impacts of taxing virtual carbon at the border is beyond the scope of this paper, since this would involve general equilibrium effects. But our analysis gives a strong sense of what would drive these general equilibrium effects (for which, see Mattoo *et al.* (2009a and 2009b).

7. Conclusions

The IO analysis of the flows of virtual carbon in international trade, as presented in the figures and Table 1, is of inherent interest. It shows that the combination of trade volumes, trade composition, and the carbon intensity of production across countries results in very large net flows of virtual carbon from the major developing countries to high income countries. This finding suggests that taxing virtual carbon at the border in high income countries could result in significant effective carbon tariff rates on developing country exports, a suggestion that is borne out in Tables 2 and 3.

Our main finding is that if virtual carbon is taxed at \$50 per ton of CO_2, a level of tax that has already been experienced in the European ETS, then the effective tariff rates faced by developing country exports is significant, up to 10% of the value of the average export bundle, and two to three times this level for specific tradable sectors. This, combined with our analysis of the border tax literature, suggests that border taxes on virtual carbon will be trade distorting in the sense that the volume and composition of international trade will change as a result, with associated losses in efficiency and welfare, particularly in developing countries.

At least four other perspectives on our findings are possible:

First, from the perspective of global climate change policy, the incentive to producers provided by taxing virtual carbon may be welfare-improving if global emissions decline.

Second, from a purely trade perspective, it is clear that *unilateral* moves to tax virtual carbon at the border would exacerbate trade tensions at a time when the international trading system is under severe stress – the potential for a trade war should not be discounted.

Third, the WTO compatibility of border taxes on virtual carbon is untested. Treating all tons of virtual carbon the same, whether from domestic or international sources, is potentially compatible with the national treatment clauses of the WTO, but until there is a case brought before the Appellate Body and a decision reached, the question of WTO compatibility is unclear.

Fourth, while taxing a bad is potentially welfare-improving at the global level, the fact that developing countries could end up financing a global public good as a result raises ethical concerns, particularly when low income countries have historically made minimal contributions to the source of the problem.

Finally, a cautionary note. All countries have a major stake in ensuring that the international trade regime continues to be open, fair and rules-based. Our analysis shows that unilateral border taxes on virtual carbon in high income countries would be harmful to developing country trade. Financial transfers from high income to developing countries could potentially offset some of all of the welfare losses. But opening the door to border taxes for climate could potentially lead to a proliferation of trade measures dealing with other areas where the competitive playing field is viewed as uneven – corroding the very basis of an open, fair and rules-based trading system.

References

Ahmad, N. and A. Wyckoff (2003) "Carbon Dioxide Emissions Embodied in International Trade of Goods", OECD Science, Technology and Industry Working Papers 2003/15, Organisation for Economic Co-operation and Development, Paris.

Andrew R., G. Peters, J. Lennox (2008) "New Zealand's Carbon Balance: MRIO Applied to a Small Developed Country", Paper presented at the International Input Output Meeting on Managing the Environment, Seville (Spain) July 9-11, 2008.

Atkinson G. and K. Hamilton (2003) "International Trade and the 'Ecological Balance of Payments'", *Resources Policy*, 28: 27-37.

Babiker, B. and T.F. Rutherford (2005) "The Economic Effects of Border Measures in Sub-Global Climate Agreements", *The Energy Journal*, 26(4): 99-126.

Bailey, R.W. and R. Clarke (2000) "Global Macroeconomic Sustainability: A Dynamic General Approach", *Environment and Development Economics*, 5: 177-194.

Barrett, S. (2008) "Climate Treaties and the Imperative of Enforcement", *Oxford Review of Economic Policy*, 24(2): 239-258.

Chapagain, A.K., A.Y. Hoekstra, H.H.G. Savenije, R. Gautam (2006) “The Water Footprint of Cotton Consumption: An Assessment of the Impact of Worldwide Consumption of Cotton Products on the Water Resources in the Cotton Producing Countries”, *Ecological Economics*, 60(1): 186-203

Cosbey, A. (2008) “Border Carbon Adjustment”, Paper presented to the ‘Trade and Climate Change Seminar’, June 18-20th 2008, Copenhagen.

De Cendra, J. (2006) “Can Emissions Trading Schemes be Coupled with Border Tax Adjustments? An Analysis Vis-à-vis WTO Law”, *Review of European Community and International Environmental Law*, 15 (2): 131-145.

Delgado J. (2007) “Why Europe is Not Carbon Competitive”, *Bruegel Policy Brief*, Issue 2007/05 (www.bruegel.org).

Demaret, P. and R. Stewardson (1994) “BTA Under GATT: Trade, Environment and the Future”, Washington, D.C.

Dimaramam, B.V. (ed.) (2006) *Global Trade, Assistance, and Production: The GTAP 6 Data Base. Center for Global Trade Analysis*, Purdue University.

Fischer, C. and A. Fox (2009) “Comparing Policies to Combat Emissions Leakage: Border Tax Adjustments Versus Rebates”, RFF Discussion Paper DP 09-02, Resources for the Future, Washington, D.C.

Goh, G. (2004) “The World Trade Organization, Kyoto and Energy Tax Adjustments at the Border”, *Journal of World Trade*, 38 (3): 395-423.

Grossman, G. (1980) “Border Tax Adjustments: Do They Distort Trade?” *Journal of International Economics*, 10: 117-128.

Guan, D. and K. Hubacek (2007) “Assessment of Regional Trade and Virtual Water Flows in China”, *Ecological Economics*, 61(1): 159-170.

Helm, D., R. Smale and J. Phillips (2007) “Too Good to be True? The UK’s Climate Change Record”,

Ismer, R. and K. Neuhoff (2007) “Border Tax Adjustment: A Feasible Way to Support Stringent Emission Trading”, *European Journal of Law and Economics*, 24: 137-164.

Lockwood, B. and J. Whalley (2008). “Carbon Motivated Border Tax Adjustments: Old Wine in Green Bottles?” NBER Working Paper 14025, National Bureau of Economic Research, Cambridge MA.

Mattoo, A., A. Subramanian, D. van der Mensbrugghe, and J. He, (2009a). "Can global de-carbonization inhibit developing country industrialization?" Policy Research Working Paper WPS5121, Washington: The World Bank.

Mattoo, A., A. Subramanian, D. van der Mensbrugghe, and J. He, (2009b). "Reconciling climate change and trade policy." Policy Research Working Paper WPS5123, Washington: The World Bank.

Miller, D. (2007) *National Responsibility and Global Justice*, Oxford University Press, Oxford.

Pan, J., J. Phillips and Y. Chen (2008) "China's Balance of Emissions Embodied in Trade: Approaches to Measurement and International Responsibility", *Oxford Review of Economic Policy*, 24(2): 354-376.

Pedersen, O.G. (1993) "Input-Output Analysis and Emissions of CO_2, SO_2 and NO_X: the Linkage of Physical and Monetary Data", Paper presented to the 10th International Conference on Input-Output Techniques, Seville.

Peters, G.P. (2008) "From Production-Based to Consumption-Based National Emissions Inventories", *Ecological Economics*, 65(1):13-23.

Peters, G. and E. Hertwich (2008) "CO_2 Embodied in International Trade with Implications for Global Climate Policy", *Environmental Science and Technology*, 42(5): 1401-1407.

Proops, J.L.R. and G. Atkinson (1998) "A Practical Sustainability Criterion When There Is International Trade", in S. Faucheux, M. O'Connor and J. Van den Straaten (eds.) *Sustainable Development: Analysis and Public Policy*, Kluwer Academic Press, Amsterdam.

Proops, J.L.R., G. Atkinson, S. Simon and B. von Schlottheim (1999) "A Practical Criterion for Sustainability in Europe When There Is International Trade", *Ecological Economics*, 28: 75-97.

Turner, K., M. Lenzen, T. Wiedmann and J. Barrett (2007) "Examining the Global Environmental Impact of Regional Consumption Activities – Part 1: A Technical Note on Combining Input-Output and Ecological Footprint Analysis", *Ecological Economics*, 62: 37-44.

Velázquez, E. (2006) "An Input-Output Model of Water Consumption: Analysing Intersectoral Water relationships in Andalusia", *Ecological Economics*, 56(2): 226-240.

Weber C.L., G. Peters, D. Guan, K, Hubacek (2008) "The Contribution of Chinese Exports to Climate Change", *Energy Policy*, 36: 3572-3577.

Whalley, J. (1979) "A Simple Neutrality Result for Movements between Income and Consumption Taxes", *American Economic Review*, 69(5): 974-976.

Wiedmann, T., R. Wood, M. Lenzen, J. Minx, D. Guan and J. Barrett (2008) *Development of an Embedded Carbon Emissions Indicator – Producing a Time Series of Input-Output Tables and Embedded Carbon Dioxide Emissions for the UK by Using a MRIO Optimisation System*, UK Department for Environment, Food and Rural Affairs, London.

World Bank (2008) *International Trade and Climate Change: Economic, Legal and Institutional Perspectives*, Washington DC: World Bank.

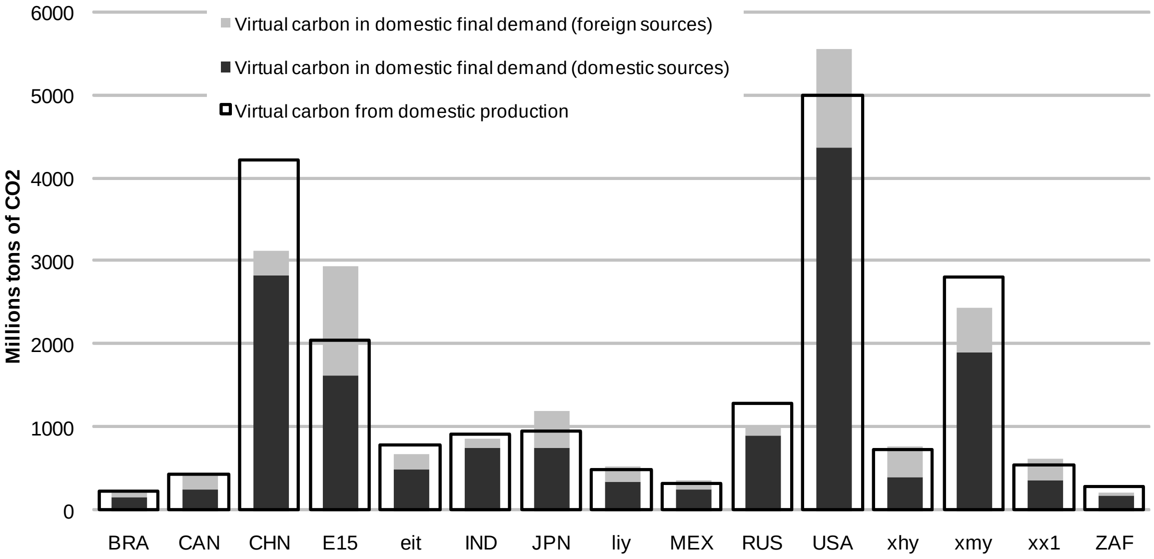
Young, C.E.F. (1996) *Economic Adjustment Policies and the Environment: A Case Study of Brazil*, Unpublished PhD thesis, University College London.

Annex: Abbreviations Used

BRA	Brazil
CAN	Canada
CHN	China
E15	European Union 15
eit	Economies in transition
IND	India
JPN	Japan
liy	Low income countries
MEX	Mexico
RUS	Russia
USA	USA
xhy	Other high income (mostly oil exporters)
xmy	Other middle income
xx1	Other Annex 1
ZAF	South Africa

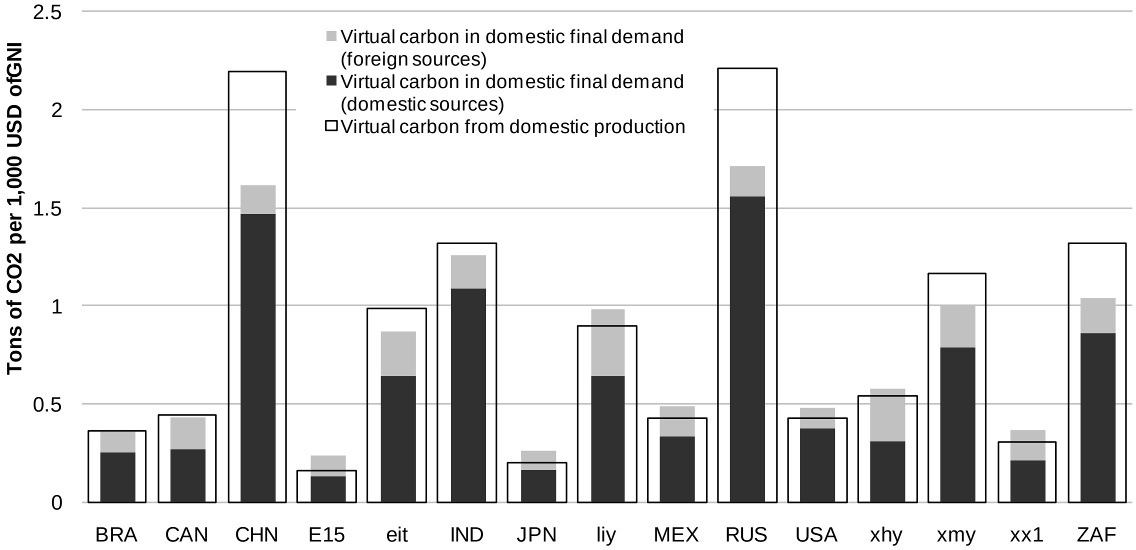
All data are for 2004.

Figure 1 – Virtual-C in production, domestic final demand, and imports (million tons)



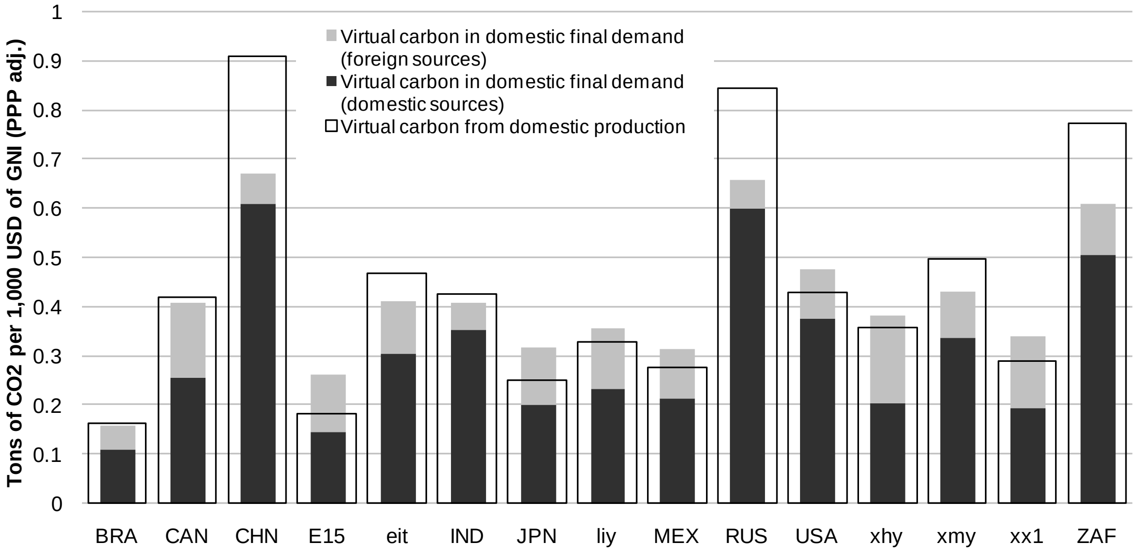
Source: authors

Figure 2a – Virtual-C intensity in production, domestic final demand, and imports (tons per 1,000 dollars of Gross National Income)



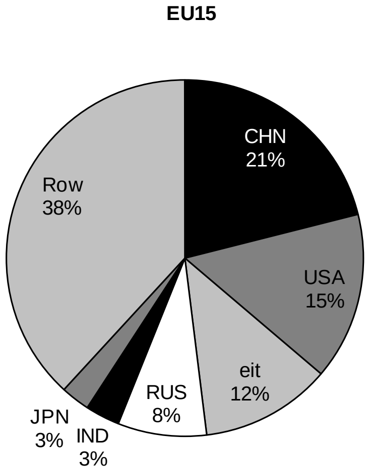
Note: virtual carbon flows have been estimated using the MRIO approach.
Source: authors

Figure 2b – Virtual-C intensity in production, domestic final demand, and imports (tons per 1,000 dollars of PPP adjusted Gross National Income)



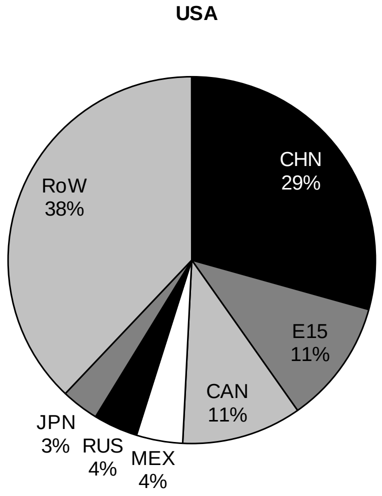
Note: virtual carbon flows have been estimated using the MRIO approach.
Source: authors

Figure 3 – Breakdown of virtual-C imports to EU15 (percent)



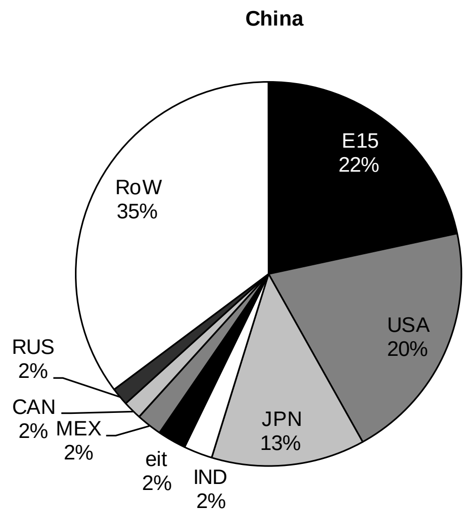
Note: virtual carbon imports have been estimated using the BTIO approach.
Source: authors

Figure 4 – Breakdown of virtual-C imports to USA (percent)



Note: virtual carbon imports have been estimated using the BTIO approach.
Source: authors

Figure 5 – Breakdown of virtual-C exports from China (percent)



Note: virtual carbon exports have been estimated using the BTIO approach.
Source: authors

Table 1. Net imports of virtual-C (1,000 tons of CO_2)

Exports from:	Imports into:														
	BRA	CAN	CHN	E15	eit	IND	JPN	liy	MEX	RUS	USA	xhy	Xmy	xx1	ZAF
BRA		40		10,318	11		1,707		1,873		5,840	331		822	
CAN				11,831			3,379				6,516	548		964	
CHN	10,630	17,841		294,101	28,580	27,377	157,990	38,143	29,189		261,587	162,077	96,499	37,115	5,651
E15															
eit		1,364		127,128			1,974		158		8,661	10,506		9,589	
IND	559	1,885		38,109	323		2,973	7,783	198		21,269	6,026	3,768	2,075	
JPN				9,452					74			9,148			
liy	91	741		35,219	514		2,651		412		13,609			3,041	
MEX		434		6,726										868	
RUS	1,890	2,768	6,464	109,970	39,493	4,903	12,861	8,221	3,342		33,866	18,991	38,181	23,300	
USA				120,230			15,684		12,834			11,081		14,688	
xhy				33,637				3,542	1,193					1,472	
xmy	4,560	11,400		212,120	1,565		55,141	22,796	6,637		109,281	59,734		28,189	
xx1				26,627			5,601								
ZAF	583	1,127		27,638	452	597	8,604	8,907	848	283	5,024	6,566	5,848	3,920	

Note: figures indicate that the column-country is a net importer of virtual-C from the row-country. Virtual carbon trade flows have been estimated using the BTIO approach.
Source: authors

Table 2. Average tariff on imports if virtual-C is taxed at \$50/ton CO_2

	Imports into:															
Exports from:	BRA	CAN	CHN	E15	eit	IND	JPN	liy	MEX	RUS	USA	xhy	xmy	xx1	ZAF	Average
BRA	0.0%	3.4%	3.2%	3.2%	3.1%	2.8%	4.0%	2.8%	2.7%	2.6%	3.0%	3.9%	3.0%	3.7%	2.9%	3.1%
CAN	4.5%	0.0%	3.4%	3.4%	3.2%	3.7%	3.2%	3.4%	2.8%	2.8%	2.6%	3.8%	2.9%	3.6%	3.0%	2.9%
CHN	12.1%	10.5%	0.0%	10.5%	11.7%	13.4%	10.4%	11.0%	9.9%	10.0%	10.3%	11.0%	10.9%	11.1%	11.1%	10.7%
E15	1.6%	1.1%	1.1%	0.0%	1.1%	1.3%	1.2%	1.2%	1.1%	1.1%	1.2%	1.3%	1.1%	1.2%	1.2%	1.2%
eit	6.6%	4.1%	4.3%	4.0%	0.0%	5.1%	3.9%	4.5%	4.2%	4.4%	4.2%	5.2%	4.5%	4.6%	4.6%	4.2%
IND	8.3%	7.8%	9.2%	7.7%	8.9%	0.0%	6.8%	8.5%	8.1%	8.7%	7.9%	7.0%	7.9%	8.5%	5.3%	7.8%
JPN	1.4%	1.3%	1.5%	1.4%	1.5%	1.6%	0.0%	1.5%	1.4%	1.4%	1.2%	1.5%	1.4%	1.4%	1.3%	1.4%
liy	8.2%	5.4%	5.7%	5.0%	5.6%	6.1%	4.7%	0.0%	5.1%	4.9%	5.0%	5.3%	5.7%	6.1%	7.0%	5.3%
MEX	3.5%	2.1%	4.2%	4.0%	3.6%	10.8%	4.0%	4.9%	0.0%	4.1%	1.7%	4.6%	3.4%	4.0%	3.5%	2.3%
RUS	18.0%	14.3%	12.4%	11.8%	13.9%	12.8%	11.3%	15.0%	14.7%	0.0%	10.4%	14.5%	13.6%	14.0%	15.9%	12.6%
USA	3.3%	3.0%	3.1%	3.1%	3.4%	3.3%	3.0%	3.3%	2.8%	2.8%	0.0%	3.2%	2.9%	3.5%	3.2%	3.1%
xhy	3.3%	2.3%	2.2%	2.3%	2.6%	2.2%	2.0%	2.3%	2.2%	2.5%	2.0%	0.0%	2.2%	2.4%	2.5%	2.2%
xmy	6.3%	5.6%	5.0%	5.4%	5.8%	4.1%	4.1%	6.1%	5.3%	6.1%	4.5%	4.5%	0.0%	6.2%	5.1%	5.0%
xx1	2.5%	2.1%	2.1%	2.1%	2.1%	3.2%	2.2%	2.3%	1.8%	1.8%	2.0%	2.3%	2.1%	0.0%	2.7%	2.1%
ZAF	15.9%	10.1%	10.6%	9.8%	10.1%	11.5%	11.4%	9.0%	16.6%	7.9%	8.9%	12.4%	8.8%	10.2%	0.0%	9.9%
Average	4.2%	3.0%	2.7%	4.3%	2.9%	4.2%	4.2%	4.2%	3.4%	3.2%	3.1%	4.1%	3.2%	3.1%	3.4%	

Note: Average figures represent the trade-weighted average tariff faced by the exporting country (row) or the average tariff imposed by the importing country (column). Virtual carbon trade flows have been estimated using the BTIO approach.

Source: authors

Table 3. Effective tariff rates by sector and country if virtual-C is taxed at \$50/ton CO_2

Sector	BRA	CAN	CHN	E15	eit	IND	JPN	liy	MEX	RUS	USA	xhy	xmy	xx1	ZAF
Agriculture	2%	3%	6%	1%	4%	5%	2%	2%	2%	7%	3%	3%	3%	2%	6%
Construction	1%	1%	11%	1%	2%	6%	1%	4%	1%	7%	1%	2%	4%	1%	6%
Coal	1%	4%	18%	2%	8%	4%	0%	5%	0%	14%	3%	3%	3%	2%	6%
Chemicals rubber and plastics	4%	5%	17%	2%	7%	12%	3%	14%	4%	27%	5%	5%	10%	2%	12%
Electricity	5%	23%	126%	18%	33%	68%	14%	34%	39%	86%	44%	39%	50%	30%	159%
Food processing	2%	2%	8%	1%	3%	5%	1%	2%	2%	8%	3%	2%	3%	2%	4%
Final services	0%	1%	5%	0%	2%	2%	1%	3%	0%	5%	1%	1%	2%	1%	2%
Natural gas	7%	8%	81%	1%	6%	7%	0%	4%	3%	10%	2%	0%	4%	3%	2%
Gas distribution	8%	1%	156%	3%	8%	0%	0%	1%	5%	10%	4%	0%	5%	9%	322%
Ferrous metals	9%	6%	23%	3%	12%	18%	4%	19%	7%	23%	6%	6%	15%	6%	29%
Non ferrous metals	7%	7%	24%	2%	6%	21%	2%	10%	2%	21%	6%	2%	8%	7%	15%
Mineral products etc	7%	4%	35%	3%	8%	28%	3%	17%	4%	23%	7%	8%	15%	6%	22%
Crude oil	3%	4%	13%	2%	6%	3%	0%	1%	2%	5%	3%	1%	2%	1%	1%
Other mining	5%	13%	12%	2%	6%	9%	3%	4%	33%	4%	4%	2%	5%	3%	20%
Refined oil	2%	8%	12%	2%	3%	2%	1%	3%	9%	10%	5%	0%	10%	4%	13%
Paper products etc	3%	4%	13%	1%	3%	20%	2%	7%	2%	5%	4%	3%	7%	2%	5%
Services	1%	1%	5%	0%	2%	4%	1%	3%	2%	5%	1%	1%	3%	1%	3%
Transport services	17%	12%	11%	4%	7%	8%	3%	11%	17%	22%	11%	5%	14%	4%	12%
Other manufacturing	2%	1%	8%	1%	2%	7%	1%	3%	1%	13%	2%	2%	3%	1%	5%

Note: Virtual carbon intensities have been estimated using the BTIO approach.
Source: authors.