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Analysis

Product level embodied carbon flows in bilateral trade

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ABSTRACT

As increasingly complex modelling approaches to quantifying embodied carbon in trade have become popular, the lack of disaggregation has been identified as a key weakness. This paper quantifies embodied carbon in bilateral trade at the product level. This is done using the material balance approach, by collecting product carbon intensity factors from multiple data sources and combining with bilateral trade data in physical quantities. The dataset covers trades between 195 countries for 1080 products in 2006. The detailed mapping of trade embodied carbon provides detailed insights into the nature of the flows that were previously masked or under-reported. For example, it finds that the lion's share of global trade embodied emissions are concentrated in a relatively small number of product categories of traded goods, suggesting that focusing mitigation efforts and trade-measures on these products would be an effective strategy to address potential carbon leakage, and to decarbonise international supply chains. The results also highlight that embodied carbon is focused in regional trade, thus regional harmonisation of climate mitigation policy will be effective in mitigating leakage.

1. Introduction

The industrial sectors currently account for around a third of global energy demand and CO_2 emissions (IEA, 2007). Decarbonising industrial production and consumption is therefore critical in achieving long term GHG stabilisation goals. However, in contrast to sectors such as transport, power generation and buildings, the geographic mobility of production facilities adds a layer of complexity to the issue of controlling industry sector emissions.

On one hand, the possibility to decouple production and consumption via international trade can facilitate carbon mitigation within production chains. Reducing emissions from the global aluminium sector, for example, could benefit from concentrating the electricity intensive primary aluminium smelting segment of the production chain in locations with ample zero-carbon power generation capacity such as hydro. On the other hand, trade also provides industries the opportunity to strategically choose production locations to avoid stringent environmental regulations. As countries introduce climate policy measures of varying stringency and global merchandise trade continues to grow,[1] there are increasing concerns about the impact on production, investments and carbon leakage.

A large number of studies have quantified embodied emissions in trade (EET), using several different methodologies, as reviewed by a number of papers (e.g. Kitzes et al., 2009; Liu and Wang, 2009; Peters, 2008; Sato, 2013; Wiedmann, 2009b; Wiedmann et al., 2011). Most studies use an input–output framework to capture indirect effects, either within a single region context (e.g. Druckman et al., 2008; Ferng, 2003), or a regional or multi-regional setting (e.g. Atkinson et al., 2011; Davis and Caldeira, 2010; Kanemoto et al., 2014; Peters and Hertwich, 2008). Alternative approaches include simplified methods using average carbon intensity of GDP multiplied by trade balance (e.g. Helm et al., 2007; Wang and Watson, 2008) and material balance methods using physical rather than monetary data (e.g. Muradian et al., 2002). Computable general equilibrium models have been used to estimate how EET will change in response to a policy shock (e.g. Kainuma et al., 2000).[2]

The literature overall provides some broad conclusions. Studies find large and growing volumes of emissions embodied in trade, ranging from 4–7 Gt CO_2 per year, equivalent to around a third of global annual CO_2 emissions during 2004-2006. (Peters et al., 2011; Wiedmann et al., 2010). In general, industrialised countries[3] are found to be net importers of EET, while the many emerging economies and resource rich

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[1] Merchandise trade grew 460% in value between 1991 and 2008, outstripping population and global GDP growth of 21% and 64% respectively (World Trade Organisation, 2012).

[2] Collectively, these approaches are grouped into the category of top-down methods, in contrast to the bottom-up methods used for the calculation of embodied emissions in products (e.g. Life cycle analysis (LCA)).

[3] Industrialised countries are defined here as the countries included in Annex I of the Kyoto Protocol.

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countries are net exporters: "high density OECD countries had higher emissions embodied in imports than exports, while for materials exporters like Russia, Canada, Australia, Finland, Norway and South Africa, the situation was the reverse. Emerging economies specialising in manufacturing, like China and India also had higher emissions in embodied exports and in imports" (Hertwich and Peters, 2010, p. 16).

However, thus far studies quantifying embodied carbon in trade have had limited impact on policy making, for a number of possible reasons. As recent reviews highlight, there is considerable uncertainty surrounding the measurement of EET (Wiedmann et al., 2011), and comparing across studies reveals a large variation in EET estimates (Sato, 2013). This is largely due to the fact that underlying data, methodology and choice of methods all suffer issues with accuracy and different methods are used for EET quantification with varying definitions and application of trade balances (Kanemoto et al., 2012). Moreover, so far the focus in this literature has been on country-level results while key policy issues such as carbon leakage is widely understood as a sectoral issue. While some studies use models with sector detail,[4] they are often not reported.

This study quantifies global embodied carbon in bilateral trade between 195 countries, disaggregated at the level of 1080 products for the year 2006. To the author's knowledge, the level of disaggregation in this study goes beyond previous work, and provides the most detailed mapping of EET flows yet. It does so by constructing and combining two large data sets: product level global bilateral trade in physical quantities and carbon intensities of products. The methodological principal of the material balance approach is applied to this data to estimate EET. This has been applied previously to analyses in ecological footprinting research (e.g. Moran et al., 2009) and has the advantage of offering a transparent way of quantifying EET, retaining the detailed information available in the source data. It also overcomes a number of key sources of uncertainty implicit in the more commonly applied input–output methods. At the same time, for data reasons, this analysis relies on the use of world average emission factors (WAEF), defined in physical terms (kg CO_2/kg product). The extent to which using WAEF affects the accuracy of results is explored using a case study of cement.

This study builds on recent studies, by further disaggregating estimations using high resolution bilateral trade information at the product level (Peters et al., 2011; Weber and Matthews, 2007). Doing so enables the identification of sectors, and products within sectors, where global EET flows are concentrated. It aims to provide insights into the nature of carbon flows that were previously masked under quantification exercises conducted using more aggregated models, or unreported by studies using detailed models but focusing on country level results. The complex picture emerging from the detailed analysis challenges the existing literature, which provides a more simplistic perspective which focuses on the exchange of embodied carbon between two large groups — Annex I vs non-Annex I.

This paper is structured as follows. Section 2 describes the methodology and the key assumptions, as well as the data collected and used to develop worldwide product level estimates of embodied emissions in trade. Section 3 presents results in terms of three key findings, with regard to the geographical and sectoral distributions of EET, the heterogeneity across countries (China, EU and US) as well as how countries can be characterised, in terms of their trade embodied carbon from a global supply chain perspective. Section 4 asks to what extent the results are sensitive to the WAEF assumption. The last section summarises the insights from the detailed quantification.

[4] Some exceptions include the study of Weber and Matthews (2007), which examines sectoral EET but only for the US and that ofWeber et al. (2008)which examines similarly for China. Peters et al. (2011) provides a detailed analysis using a disaggregated model with 113 regions and 57 sectors, but his sectoral results are aggregated for global trade, or the trade between Annex I and non-Annex I of the Kyoto Protocol, whereby bilateral trade by country information is lost.

2. Material and Methods

2.1. Quantification Approach

The material balance methodology was developed within the ecological footprinting literature as an alternative to input–output methods (Kitzes et al., 2009). 'Footprint' or 'intensity' multipliers usually derived from life cycle analysis (LCA)[5] are combined with isolated values of imports and exports by sectors (weight or value), in order to estimate ecological footprints embodied in traded goods (e.g. Bagliani et al., 2005; Bicknell et al., 1998; Muradian et al., 2002; Turner et al., 2007):

$$EEE_j^{r,s} = \sum_{r \neq s} X_j^{r,s} * EF_j^W. \tag{1}$$

Equation 1 states the CO_2 emissions embodied in exports from country r to country s ($s = 1, 2, 3,......, S$) is a product of country r's export matrix X of good j (where goods $j = 1,2,3,..., J$) expressed in physical quantities and a vector of world average emission factor, EF_j^W expressed also in physical terms (kg CO_2/kg). The CO_2 intensity factors are derived from engineering based techniques using large amounts of primary data. Specifically, intensity factors calculated using the *cradle-to-gate* system boundary are used, thus covering emissions from a partial product life cycle from manufacture (cradle) to the factory gate i.e., before it is transported to the consumer. $EEE_j^{r,s}$ thus reflects the *embodied* carbon emissions attributable to the production of the good throughout the production chain including the production of inputs. This is in contrast to carbon emission factors using alternative system boundaries such as *gate-to-gate*, *cradle-to-grave* (including the use phase and disposal phase of the product) and *cradle-to-cradle* (including recycling).

Mathematically, the material balance method represents a special case of a generalised physical input–output formulation. Yet in practice, data ability and necessary simplifying assumptions under both methods restrict their equivalence (Wiedmann and Lenzen, 2007). Importantly the *cradle-to-gate* carbon intensity coefficients under the material balance approach consider only domestic supply chains and exogenously include trade in intermediate and final products. In other words, it assumes that all production inputs are sourced domestically. The implied system boundary under this method is akin to that of the Bilateral Trade Input Output (BTIO) method which is also termed Embodied Emissions in Bilateral Trade (EEBT).

One of the major limitations of the method relates to the chosen system boundary, which raises the problem of double-counting of emissions when looking at aggregate global emissions. As discussed in Kanemoto et al.'s (2012) study, this approach is more suitable for comparing trade-adjusted emission inventories and indeed our aim here is to do so, at a detailed product-level. The alternative system boundary used under the MRIO framework which considers trade only into the final consumption is, instead, more suitable for consumption analysis. The problem of double-counting for the country-level results is bigger for countries with significant trade volumes relative to the country's economic size, and in particular those engaged in significant processing or intermediate goods trade such as Taiwan and South Korea. For large economies such as the US, the EU, Australia, Brazil and Japan, the import content of exports in the period mid-2000 was relatively low at around 10% to 15% (OECD, 2012). A second caveat relates to the use of world average emission factors (WAEF), and the results' sensitivity to this assumption will be examined in a sensitivity test using a case study

[5] LCA is designed to evaluate the environmental impacts of a given product or service and is similar in philosophy to input–output analysis as a method to calculate embodied emissions in products, but differs in several important respects. It is a process-based bottom-up technique used to examine the production process of a specific product in detail, unlike the top-down input–output approach which obstructs from analysis of specific materials or products. The latter captures all indirect effects (e.g. within the economy) whereas LCA imposes boundaries. LCA guidelines are given by the ISO standards.