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A synthesis of carbon in international trade

G. P. Peters[1], **S. J. Davis**[2], **and R. M. Andrew**[1]

[1]Center for International and Environmental Research – Oslo (CICERO), PB 1129 Blindern, 0318 Oslo, Norway
[2]Department of Global Ecology, Carnegie Institution of Washington, Stanford, CA 94305, USA

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Correspondence to: G. P. Peters (glen.peters@cicero.uio.no)

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Abstract

In a globalised world, the transfer of carbon between regions, either physically or embodied in production, represents a substantial fraction of global carbon emissions. The resulting emission transfers are important for balancing regional carbon budgets and for understanding the drivers of regional emissions. In this paper we synthesise current understanding in two parts: (1) embodied CO_2 emissions from the production of goods and services produced in one country but consumed in others, (2) physical carbon flows in fossil fuels, petroleum-derived products, harvested wood products, crops, and livestock. We describe the key differences between studies and provide a consistent set of estimates using the same definitions, modelling framework, and consistent data. We find the largest trade flows of carbon in international trade in 2004 were fossil fuels (2673 MtC, 37 % of global emissions), CO_2 embodied in traded goods and services (1661 MtC, 22 % of global emissions), livestock (651 MtC, 20 % of total livestock carbon), crops (522 MtC, 31 % of total harvested crop carbon), petroleum-based products (183 MtC, 50 % of their total production), and harvested wood products (149 MtC, 40 % of total roundwood extraction). We find that for embodied CO_2 emissions estimates from independent studies are robust. We found that differences between individual studies is not representative of the uncertainty in consumption-based estimates as different studies use different production-based emission estimates as input and different definitions of allocating emissions to international trade. After adjusting for these issues, results across independent studies converge to give less uncertainty than previously assumed. For physical carbon flows there are relatively few studies to be synthesised, but differences between existing studies are due to the method of allocating to international trade with some studies using “apparent consumption” as opposed to “final consumption” in more comprehensive approaches. While results across studies are robust to be used in further applications, more research is needed to understand the differences between methods and to harmonise definitions for particular applications.

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1 Introduction

Sources and sinks of carbon dioxide (CO_2) are usually allocated to countries and industries according to the emissions and uptake that occur within their administered territory (IPCC, 2006). Territory-based emissions inventories are required for input into climate models, and in terms of climate policy, countries and industries have more power to accurately monitor and potentially regulate their territorial emissions. Allocation schemes are, however, a human construct and different allocation schemes may serve different purposes (Caldeira and Davis, 2011). When there is international trade between regions, for example, consumption-based inventories that add the emissions associated with imports and subtract the emissions associated with exports are often considered (Peters, 2008; Peters and Hertwich, 2008a; Peters et al., 2009; Munksgaard and Pedersen, 2001). While most research has focused on CO_2 emissions from fossil-fuel combustion (Davis et al., 2011; Davis and Caldeira, 2010; Hertwich and Peters, 2009; Peters and Hertwich, 2008b; Peters et al., 2011b), international trade is also important in accounting for emissions from land use and forestry (Cowie et al., 2006) and constructing regional carbon budgets (Ciais et al., 2007, 2008). Due to the continued growth in international trade relative to other macro-economic variables (e.g. GDP and population), it is becoming more important to have accurate quantification of the emissions embodied in traded products (Peters et al., 2009, 2011b).

In the case of CO_2 emissions from fossil-fuel combustion and industrial processes, several recent studies have highlighted the magnitude and importance of international trade in transferring emissions between regions (Peters et al., 2011b; Hertwich and Peters, 2009; Peters and Hertwich, 2008b; Davis and Caldeira, 2010; Davis et al., 2011; Nakano et al., 2009; Wiebe et al., 2012). For emissions from fossil-fuel combustion and industrial processes, CO_2 is not physically transported across borders, but is rather emitted during the production of goods and services that are consumed by other countries (thus, the emissions are said to be embodied in these goods and services). The embodied carbon is most relevant for understanding emission drivers (Peters et al., 2011b; Le Quéré et al., 2009) and responsibility issues (Davis and Caldeira, 2010; Davis et al., 2011; Peters et al., 2009). There are well-established methods and literature for estimating embodied carbon that consider complex supply chains and can be applied at both the country and global level (Wiedmann, 2009; Wiedmann et al., 2007). Current areas of research usually focus on improving data, harmonizing methods, and making analyses more policy relevant (Peters and Solli, 2010; Wiedmann et al., 2011). Several initiatives are underway to construct better and more consistent databases (see Table 1 in Peters et al., 2011a).

Of additional interest to the carbon cycle community are the physical flows of carbon among regions (i.e. lateral fluxes of reduced carbon that will be oxidised, consumed as food, or otherwise utilised), as these flows may affect regional carbon budgets. Several studies have modelled the trade of carbon present in harvested wood products, crops, and food with applications for regional carbon budgets (Ciais et al., 2007, 2008), more generally in terms of biomass flows among regions (Erb et al., 2009; Krausmann et al., 2008; Haberl et al., 2007; Kastner et al., 2011a, b), and recently for fossil-fuels (Davis et al., 2011). In addition to carbon budget studies, physical carbon flows are also important for emission inventories that include biomass carbon (Cowie et al., 2006). However, relative to the literature on embodied emissions, there are considerably fewer studies tracking trade of biomass, with the data and methods less developed. For instance, these studies often focus on "apparent consumption" which does not follow products along supply chains or consider processing (Kastner et al., 2011b). Except for the work of Davis et al. (2011) on fossil fuels, we are not aware of other analyses of physical flows of carbon that have used the more detailed and established models that have been developed and used to model embodied emissions.

The aim of this paper is to provide consistent estimates of carbon in international trade, including both emissions embodied in traded goods and services as well as physical flows of reduced carbon, using a single modelling framework and input dataset. We compare our results to existing studies. In the case of embodied carbon, we perform a larger synthesis of previous global studies to determine the range in independent estimates. We also highlight key results robust across all studies. In the case of physical flows of carbon, we expect to find large differences with previous studies that use "apparent consumption" as we apply more detailed modelling of processing and global supply chains. Since the lower apparent consumption estimates are used in most regional carbon budgets, our results might have implications for balancing carbon budgets.

The paper is structured as follows. First, we give an overview of the terminology used in the analysis. Second, we describe the method and data used. Third, we analyse embodied carbon with a synthesis of studies and additional calculations to understand the differences between estimates. Fourth, we provide detailed and consistent estimates of physical flows of carbon covering fossil-fuels, petroleum-derived products (plastic, fertiliser, etc.), harvested wood products, crops, and livestock. And finally, we discuss our findings and outline future work. Our results are presented for the RECCAP regions, and on occasion, for some specific countries where the detail is beneficial.

2 Description of methods and data

We use a well-established method to re-allocate emissions from a territorial perspective to international trade flows and ultimately a consumption-perspective. We consider carbon associated with both household activities and the industrial production of goods and services. The industrial emissions are allocated along the global supply chain from the point of production to the point of consumption which may be in a different region and sector. This section gives an overview of the methods and data.

2.1 Multi-regional input-output analysis (MRIOA)

Most studies of carbon embodied in international trade recommend accounting for the supply chain using multi-region input-output analysis (MRIOA) (Peters, 2010a; Minx et al., 2009; Wiedmann, 2009). Input-Output Analysis (IOA) is a top-down method

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specifically designed to enumerate and study supply chains (Leontief, 1936) and has been applied to environmental problems since about 1970 (Leontief, 1970; Ayres and Kneese, 1969). IOA is grounded in economic statistics describing the relationship between all regions and sectors in the database. Since the method is top-down, full coverage is obtained and the method acts to distribute emissions along supply chains and ultimately allows a linkage between producers and consumers, or exporters and importers. IOA allocates emissions to the *final consumption* of households, government, and capital investment. Methods to study multiple regions and global supply chains were developed early (Isard, 1951; Oosterhaven, 1984) and are now one of the primary methods to study environmental repercussions arising globally (Wiedmann, 2009; Wiedmann et al., 2007). Input-output data are a key component of many economic models and the data is widely available, including for some key developing countries (Narayanan and Walmsley, 2008). Even though MRIOA is generally applied at the country and sector level rather than product or company level, as in Life Cycle Assessment (LCA), MRIOA has the important advantage of representing the entire global economic structure, including all trade linkages, and can analyse large bundles of goods simultaneously (Peters, 2010a).

An MRIO Table (MRIOT) contains information on the relationships between sectors in each country (intermediate consumption), the relationships between sectors in different countries (international trade), and the final consumption of households, government, and capital investments. The source data is the core of the System of National Accounts in many countries (European Communities, 2008). Within an MRIOT goods and services can be consumed by industry and final consumers (households, government, and capital investments), and consequently, international trade can be consumed either by industry or directly by consumers. Final consumers are the end point of all consumption in MRIOA and intermediate consumption between industries exists to facilitate the production of goods and services entering into final consumption. Thus, the results are driven by final consumption, with the supply chain represented by

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intermediate consumption which ultimately dictates the emissions due to a given final consumption.

2.1.1 Definitions of consumption

There are two main definitions of "consumption" (and hence trade) in environmental applications, *apparent* and *final* consumption, and these can produce significantly different results. The difference between the two definitions is subtle but important.

Many physical accounting approaches are based on the concept of *apparent consumption* (Erb et al., 2009; Krausmann et al., 2008; Haberl et al., 2007; Kastner et al., 2011a, b; Ciais et al., 2008; Ciais et al., 2007). Apparent consumption is the amount of product produced within a country plus imports minus exports, and it is typically assumed that there is no processing or transformation of products (Kastner et al., 2011b). For example, imported products are assumed to be consumed in the state in which they were imported without any further processing.

In contrast, methods based on standard environmental-economic accounts (United Nations Statistics Division, 2005; European Commission et al., 2009), usually adhere to the concept of *final consumption*. Final consumption refers to consumption activities by individual households or government to satisfy individual or collective requirements (European Commission et al., 2009). If using final consumption, it is necessary also to consider *intermediate consumption*, which comprises all goods and services consumed by industries in the production of final goods and services, and this is ultimately allocated to final consumers via the supply chain. Thus, studies that include a supply chain necessarily require a differentiation between intermediate and final consumption.

There is a variant of the *final consumption* approach that limits the level of processing at national borders (Peters, 2008; Peters and Hertwich, 2008b). The Emissions Embodied in Bilateral Trade (EEBT) approach only distinguishes between intermediate and final consumption domestically, and not globally. The advantage of this approach is that at national borders the distinction between intermediate and final consumption is

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not made, and hence the exports correlate directly with bilateral trade statistics (Peters, 2008).

Depending on the application, apparent and final consumption can give quite different results with quite different interpretations. In the case of paper products, apparent consumption would be the paper produced in the country plus imports of paper products minus exports. However, some of that paper product is processed into other goods (e.g. books) before being finally consumed, and some is used by industry in the activity of producing another good (e.g. stationery used in the offices of a steel mill); both of these latter cases are called intermediate consumption. Paper products are also used directly in final consumption (e.g. households purchasing notepads). An emissions inventory based on apparent consumption would allocate emissions to imported paper, no matter how that paper is used. The final consumption approach, in contrast, allocates the emissions associated with the paper's production to the finally consumed product, here possibly a car made from the steel with the office in the steel factory using paper. However, the methods used to calculate emissions associated with final consumption allow the choice of the stage in the supply chain to which the emissions are allocated: the finally consumed good or service, the traded good with embodied emissions, or the industry that actually produced the emissions.

The different definitions of consumption and allocation of emissions to international trade will be discussed below in the relevant model comparisons, and, through these comparisons, we will discuss in more detail the differences between the methods.

2.1.2 Exports and imports

While we have focused on production and consumption, exports and imports are an integral part of these concepts. Conceptually, the relationship can be expressed as: Consumption = Production – Exports + Imports, though important differences can exist (Peters, 2008; Kanemoto et al., 2012). In this paper, we use the following definitions for country X:

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– Production: emissions occurring on administered territories over which X has jurisdiction (territorial emissions).

– Exports: the production-based emissions occurring within X to produce exports and including the domestic supply chain only.

– Imports: the emissions in each country (other than X) required to produce final consumption in X and including the global supply chain.

– Consumption: the global emissions required to produce the final consumption in X and including the global supply chain.

2.1.3 System boundaries

Spatial: all our analysis is at the country or regional level, but we consider a global system boundary to capture the imports into a country.

Temporal: all our analysis is valid for one calendar year. For the case of harvested wood products, crops, fossil fuels, and similar, we assume that products move along the international supply chain within one year (that is, there is no change in storage). As an example, if a forest is harvested in one country, and several countries process the product along the global supply chain before it is consumed as paper, then we assume this all occurs within one year. While this will not be strictly true, our assumption implicitly assumes the imbalance at the start of the calendar year balances with the imbalance at the end of the calendar year.

2.1.4 Embodied versus physical carbon

We differentiate carbon transferred along supply chains as either "embodied carbon" or chemically reduced carbon that is physically present in traded goods.

It is now common to study carbon emissions embodied in trade, which is the CO_2 emissions that occur during the manufacture of traded products or provision of traded

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services at some stage in the supply chain. These carbon emissions can be "reallocated" from the point of production (oxidisation) to the point of consumption. As an example, the CO_2 emitted in China to produce exported products can be reallocated to the importer and ultimate consumer of those products (Weber et al., 2008). In recent times, studies of embodied emissions have become common due to their importance in understanding the environmental repercussions of globalisation (Wiedmann, 2009; Wiedmann et al., 2007; Peters et al., 2011b; Hertwich and Peters, 2009; Peters and Hertwich, 2008b; Davis et al., 2011; Davis and Caldeira, 2010; Wiebe et al., 2012; Nakano et al., 2009).

The carbon cycle community is usually interested in physical flows of carbon, which are often called lateral carbon flows or horizontal displacement (Ciais et al., 2007, 2008). Here, the carbon physically follows the product along the supply chain without being oxidised, such as from industrial roundwood and through processing to a newspaper. However, some of that carbon may be oxidised through transformation and this can be allocated in a variety of different ways. Examples of physical flows of carbon include harvested wood products, fossil-fuel trade, petroleum-derived products such as plastics and fertiliser, and agricultural products such as crops and livestock.

2.1.5 Data for the MRIOT

The MRIOT used in this paper is based on the Global Trade Analysis Project (GTAP) database (Narayanan and Walmsley, 2008) version 7.1 representing the world economy in 2004. The GTAP database "combines detailed bilateral trade, transport and protection data characterizing economic linkages among regions, together with individual country input-output data bases which account for inter-sectoral linkages within regions" (Narayanan and Walmsley, 2008). In each region and each year the economy is divided into 57 economic sectors and three final consumers (households, government, capital investments). The world is divided into 112 countries and regions. The method to convert the GTAP database into an MRIOT is described elsewhere (Peters et al., 2011a). The dataset and method has been applied in several peer-reviewed

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publications (Peters et al., 2011b; Hertwich and Peters, 2009; Andrew et al., 2009; Peters and Hertwich, 2008b).

2.2 Input data for externalities in production

MRIOA reallocates the "externalities" (here, carbon and carbon emissions) that occur in production along the global supply chain to consumption. Thus, the MRIOT remains the same, but different externalities are allocated along the supply chain differently depending on the sector where the emissions occur. For example, emissions in the agricultural sector may mostly end at food consumption, while emissions in the steel sector may mostly end in manufactured products. The following sub-sections describe the externality data used in our analysis.

2.2.1 Energy and feedstock data

We use the energy and feedstock data from GTAP (Lee, 2008; Narayanan and Walmsley, 2008), but updated for GTAP version 7.1. The GTAP energy and feedstock data is built around International Energy Agency data, but modified to be consistent with the economic data used in the GTAP database (Narayanan and Walmsley, 2008).

2.2.2 Carbon dioxide data

We use several different CO_2 emission datasets in the analysis below to show the importance of variations in this input dataset. The CO_2 data sets are from CDIAC (Boden et al., 2011), the UNFCCC (2012), EDGAR (European Commission, 2011), GTAP (Lee, 2008), and an updated version of the GTAP data (Peters et al., 2011a). These datasets, and their differences, are described in more detail in the model comparisons.

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2.2.3 Forestry data

The Food and Agriculture Organisation (FAO) provides data on the extraction of different forestry products (FAO, 2012a, c). We only consider the extraction of roundwood (FAO code 1861) and use the GTAP-MRIO to estimate the products that are produced from roundwood and potentially entering international trade. Since we consider all products containing roundwood, directly and indirectly, we have covered a broader spectrum of processed wood products than appears in the FAO database. Roundwood can be broadly split into fuelwood (FAO code 1629) and charcoal (FAO code 1630), and industrial roundwood (FAO code 1865). Since fuelwood and charcoal are primarily for domestic uses, and often in the informal economy (FAO, 2012c; Kastner et al., 2011a), we only include industrial roundwood in our analysis.

To convert the industrial roundwood from cubic metres in the FAO data to carbon we take several steps. First, we divide the industrial roundwood into coniferous (FAO code 1866) and non-coniferous (FAO code 1867) and convert from cubic metres to dry-weight in tonnes using a conversion factor of $0.45\,\mathrm{t\,m^{-3}}$ for coniferous raw wood and $0.59\,\mathrm{t\,m^{-3}}$ for non-coniferous raw wood (Pingoud et al., 2006). We convert the tonnes of biomass to tonnes of carbon using a factor of $0.45\,\mathrm{t\,tC^{-1}}$ (Ciais et al., 2008). Since all the data is scaled by the carbon content, it is possible to scale the results up or down to represent different carbon contents.

2.2.4 Crop data

The FAO provides data on the harvest of different crops (FAO, 2012b). This data needs to be converted from tonnes harvested to tonnes of dry matter and then from tonnes of dry matter to tonnes of carbon. We based our conversions on Ciais et al. (2008) supplemented with additional data where necessary (USDA, 2010).

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2.2.5 Livestock data

The FAO provides data on live animals (FAO, 2012b). Based on the number of live animals, we estimated the feed requirements using the models from Krausmann et al. (2008). This gives the total carbon consumed by livestock. These data do not differentiate between intake from grazing and that from feed and this requires additional calculations.

3 Embodied CO_2 emissions

Embodied carbon refers to the CO_2 emissions that occur in the production of goods and services, which may then be traded internationally and consumed in another country. For simplicity, we include direct household emissions in the term "embodied emissions" even though they are not actually embodied in purchased goods or services. The literature on embodied carbon is a growing rapidly and well-established methods exist (Wiedmann, 2009; Wiedmann et al., 2007). However, there is yet to be a broad synthesis of existing studies. One study on the Nordic countries found large variations between independent estimates, but after adjusting for inconsistent definitions and data it was found that the results were similar and quite robust (Peters and Solli, 2010). Our goal in this section is to perform a synthesis of existing global studies, explore the reasons for any differences between studies, and give a summary of results that are robust across studies.

3.1 Synthesis of previous global studies

A number of independent studies have now estimated the emissions embodied in international trade of goods and services (Ahmad and Wyckoff, 2003; Davis and Caldeira, 2010; Nakano et al., 2009; Peters et al., 2011a, b; Peters and Hertwich, 2008b; Hertwich and Peters, 2009; Atkinson et al., 2011; Wiebe et al., 2012). We restricted ourselves to global studies, despite the existence of many country-specific studies (see

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the review articles; Wiedmann, 2009; Wiedmann et al., 2007). Figure 1 shows the results of the selected global studies for the EU-27, the USA, Japan, China, the Russian Federation, and India; though these studies cover up to 112 countries and regions. Table 1 shows the growth rates between the two time series studies (Wiebe et al., 2012; Peters et al., 2012). The figure shows that the results of the studies are broadly consistent, despite some differences. Here we focus on three differences: (1) different emissions data and (2) different definitions of consumption-based emissions, and (3) different allocation models; and we explore these differences in more detail in the following section.

Generally the studies show a correlation between the production-based estimates (left side of Fig. 1) and the consumption-based estimates (right side): if the production-based estimates are relatively high in comparison to other studies, then the consumption-based estimates are usually also relatively high. There is also a large spread in the production-based estimates. The EEBT and MRIO methods of Peters et al. (2011b) in 1997, 2001, and 2004 and the MRIO of Davis and Caldeira (2010) in 2004 all use the CDIAC emissions data as input (Boden et al., 2011). While Peters et al. (2012) also uses the CDIAC data, annual updates of the CDIAC data often have different estimated emissions leading to the difference with Peters et al. (2011b). Peters and Hertwich (2008b), Hertwich and Peters (2009), and Peters et al. (2011a) use a modified version of the GTAP emissions data (Lee, 2008) which is different to the CDIAC estimates. Atkinson et al. (2011) use an unmodified version of the GTAP emissions data. Ahmad and Wyckoff (2003), Nakano et al. (2009), and Wiebe et al. (2012) are all based on the IEA energy or emissions data (IEA, 2011) – each study estimates different emissions – and these estimates generally differ to the CDIAC estimates (see Andres et al., 2012 for more details). These differences in the production estimates, lead to differences in the consumption estimates. Since the consumption estimates are essentially the production estimates adjusted for trade, the difference in production propagate through to consumption. Thus, if the production estimates are high in one study, then it follows the consumption estimates are also likely to be high.

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There are also different ways of defining the consumption-based emissions (Peters, 2008; Kanemoto et al., 2012), and hence the same production-based emissions can lead to different consumption estimates. Figure 1 also shows that the use of two main different definitions (labelled MRIO and EEBT) is also an important cause of differences between studies. Peters et al. (2011b) in 1997, 2001, and 2004, Peters and Hertwich (2008b) in 2001, Hertwich and Peters (2009) in 2001, and Atkinson et al. (2011) in 2004 all show results for the EEBT and MRIO methods; thus, even though each study starts with the same production-based estimates, the estimates for consumption are different due to different definitions of consumption. The studies of Peters et al. (2011b) and Davis and Caldeira (2010) both for 2004 lead to the same consumption estimates as they use the same data and methods. Peters et al. (2011a) in 2004 uses an MRIO method extended to include international transportation in more detail, and thus leads to different estimates. All remaining methods are based on variants of the MRIO method. Thus, even after controlling for different production-based emissions as input, different definitions can lead to different estimates.

In some cases, the emissions data for a given country is similar between studies and the definitions used are similar. Thus, the differences are due to the economic allocation method used. Primarily, this involves the method of compiling the data into an allocation model as the raw data often comes from the same ultimate source. In the case of the Russian Federation, where the production estimates are all similar, there is a spread in the consumption estimates. In most cases, the spread in consumption for the displayed countries is larger than the spread in the production based emissions used as input. To further detail the underlying reasons for the different results from different allocation models requires detailed model comparisons, which is beyond the scope of this paper.

Overall, the results shown in Fig. 1 and Table 1 show a spread between consumption based estimates. However, much of this spread can be explained by different production-based estimates used in different studies and different definitions. These factors should be controlled for to give a realistic model intercomparison. To compare

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the differences between attribution models requires a more concerted community effort of model runs. At this stage, it would appear that the current spread between estimates of consumption-based emissions from different studies does not represent the uncertainty in the individual studies. Thus, the uncertainty in estimates may be smaller than generally assumed. We explore the role of these three factors in causing differences between studies in more detail below.

Based on the studies in Fig. 1, Table 1, and the cited literature, a robust result is that a significant fraction of emissions produced in emerging markets like China and India are embodied in exported goods to consumers in developed regions like the US, Japan and the EU-27. Similarly, those studies which have modelled the trend of embodied emissions over time (e.g. Peters et al., 2011b; Wiebe et al., 2012) have shown that, although growth of emissions occurring within these developed countries has slowed in some cases, the emissions related to goods and services consumed in these regions has continued to grow with increased imports of embodied emissions (Fig. 1). In particular, Table 1 shows the growth rates between key regions and countries showing that in developed countries consumption-based emissions are growing faster than consumption, with the opposite holding in developing countries. These issues are explored further in the literature (Ahmad and Wyckoff, 2003; Andrew et al., 2009; Davis and Caldeira, 2010; Nakano et al., 2009; Peters et al., 2011b; Peters and Hertwich, 2008b; Hertwich and Peters, 2009; Atkinson et al., 2011; Wiebe et al., 2012) and below.

3.2 Explanations of variations in results

As demonstrated in the previous section, different studies often produce different estimates. These differences, however, do not necessarily translate into uncertainty as the different studies use different carbon emissions as input, definitions, in addition to different attribution models. An earlier study of the Nordic countries found that differences between studies were reduced when using consistent definitions of consumption-based emissions and production-based emissions data (Peters and Solli,

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2010). For example, in the previous section we found that production-based emissions may vary substantially between datasets, and these differences propagate through to the consumption-based emissions. In this section, we use modifications of the GTAP-MRIO to investigate what may cause the variation in results between different studies. We focus on (1) differences in production-based emissions, (2) differences in definitions, and (3) variations in the economic data.

3.2.1 Production-based emissions

As shown earlier in the model comparisons, and in more detail elsewhere (Andres et al., 2012), production-based emissions can vary substantially between data sets. While the spread on global estimates may be small, there may be much larger variations at the region and sector level. The differences in production-based emission estimates will propagate through and affect the resulting consumption-based emission estimates. In this sub-section we explore the differences in more detail focusing on (a) variation in total emissions, (b) allocation of bunker fuels, (c) allocation to sectors, and, (d) the propagation effects on estimates of consumption-based emissions.

Variation in total emissions

Table 3 shows estimates of carbon emissions from five different emission data sets (Table 2). We briefly summarise the five data sets here, but more specific details can be found elsewhere (Andres et al., 2012).

1. The Carbon Dioxide Information Analysis Center (CDIAC) data includes emissions from the combustion of fossil fuels, emissions from cement production, and emissions from gas flaring (Boden et al., 2009). The CDIAC data is based on energy statistics reported by countries to the United Nations. Bunker fuels used for international transportation are not allocated to countries, but are included in the global totals.

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2. The UNFCCC data includes emissions from the combustion of fossil fuels and process emissions such as from cement production, flaring, and other activities (IPCC, 2006). Bunker fuels are not allocated to countries, but each country shows a memo of the bunker fuels sold from that country.

3. The Emissions Database for Global Atmospheric Research (EDGAR, version 4.1) includes emissions from the combustion of fossil fuels and process emissions such as from cement production, flaring, and other activities (European Commission, 2009). The EDGAR data allocates the emissions to sectors, and in the standard EDGAR database bunker fuels are not allocated to countries. However, for the analysis that follows, we reallocated bunkers fuels to using countries based on the economic activity in the GTAP database. The EDGAR database includes forest fires, though for consistency with the other datasets, we do not include them in our analysis.

4. The GTAP data only covers emissions from the combustion of fossil fuels (Lee, 2008). The data is originally based on data from the International Energy Agency (IEA), but undergoes manipulation in construction of the GTAP database (Narayanan and Walmsley, 2008) and uses different assumptions than IEA to convert energy into CO_2. Thus, the GTAP CO_2 emissions will differ from the IEA CO_2 dataset (IEA, 2011). In principle, bunker fuels are allocated to countries based on the use of bunker fuels by resident institutions within a country; however, in version 7.1 of the GTAP database we use, the methodology for doing this is inadequate for an accurate attribution (McDougall and Leeuwen, 2010).

5. The GTAP+NAMEA data is a modification of the GTAP data (Peters and Hertwich, 2008b), to include the National Accounting Matrices with Environmental Accounts (NAMEAs) in the countries where they are easily available (mainly EU countries, Australia, Canada, China, Japan, and the USA), in addition to including the cement and flaring emissions from CDIAC. In the countries that use NAMEAs, bunker fuels are allocated according to resident institutions using bunker fuels.

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Table 3 shows the global total from each database, in addition to the top 10 emitters and top 10 countries with the largest absolute difference in emissions. Even though the global totals are reasonably close, there is considerable variation between the country totals. These differences relate to different system boundaries, energy data, emission factors, definitions, and similar, and are discussed in more detail elsewhere (Andres et al., 2012). At the country level, even the biggest emitters have variations of up to 10–15 %. The largest absolute difference is for the Netherlands (up to 100 %), but this results from incorrectly assuming fossil fuels used as feedstock are combusted (this problem has been fixed in updated versions). The other large absolute difference occurs for both developed and developing countries, which highlights it is not only data quality that is at fault, but inconsistent system boundaries, assumptions, etc. The average range of the top 10 emitters is 13 %, and the average range of all the 112 regions in the database is 30 %. In the context of consumption-based emissions estimates, it is important to note these large variations, as these differences will propagate through to give differences of similar magnitude in consumption-based estimates.

Allocation of emissions from bunker fuels (international transport)

For some countries, the method of allocating the emissions from bunker fuels to countries can have a significant effect on the emission estimates (Peters et al., 2009; Peters, 2008). The use of bunker fuels occurs in international territory, and, for the purpose of energy statistics, this energy use occurred outside of the system boundary of a nation (IEA, 2005). This definition seems to also have been applied to emissions statistics, where national emissions inventories "include all greenhouse gas emissions and removals taking place within national (including administered) territories and offshore areas over which the country has jurisdiction" (IPCC, 1996). A consequence of this is that countries are not allocated emissions from the use of bunker fuels (international transport); however, countries do report the sales of bunker fuels as a memo in UNFCCC statistics. For economic analysis, the international transport should be allocated to the country where the operator of the vessel is resident (Peters and Hertwich, 2008a;

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Peters, 2008; Peters et al., 2009), corresponding to the user of the bunker fuel (and independent of the ship's flag and owner). Emissions statistics that allocate emissions consistent with the system of national accounts (as required for economic analysis) are often called National Accounting Matrices with Environmental Extensions (NAMEAs) (European Commission, 2001; Pedersen and de Haan, 2006).

While estimates of bunker-fuel emissions allocated to selling country are available, the necessary data on bunker fuel use allocated to the operator of the vessel are often not reported (Peters et al., 2009). Many European countries, however, report the necessary data to Eurostat to make the "bridge" table between emissions allocated to the national accounts and the emissions submitted to the UNFCCC. Table 4 demonstrates the potential differences between bunker-fuel sales (memo in the UNFCCC reporting) and usage (as required for NAMEAs) for European countries reporting the data. For the 17 countries reporting data in Europe, the bunker fuels sold represent 8.1 % of the UNFCCC inventory, while bunker fuel use is slightly lower at 7.7 %, suggesting that across Europe, bunker fuel sales roughly balance with bunker fuel usage. However, there are large variations between countries. The Netherlands, for example, has very high bunker fuel sales (34 % of UNFCCC inventory) and relatively small use (11 %). Denmark, in contrast, has very large bunker fuel use (almost equal to the total emissions reported to the UNFCCC), but relatively small bunker fuel sales (11 %).

The NAMEA adjustment to include resident institutions requires adding emissions from residents abroad and deducting emissions from visiting foreigners. For land transport, technical issues arise as a vehicle may purchase petrol in one country but drive in another. This is problematic for small countries such as Luxemburg where the NAMEA is lower than the UNFCCC due to non-residents purchasing petrol in Luxemburg. However, the distinction is usually clearer for aviation and shipping as outlined in the earlier examples.

As demonstrated in Table 4, these examples highlight the extremes in how bunker fuels are allocated and demonstrate the potential differences in consumption-based

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emissions inventories if bunker fuels are treated differently in each study (Peters and Solli, 2010).

Allocation of emissions to sectors

For economic analysis, or attribution studies as in this article, it is necessary to distribute the emissions to the sectors where they occur. For our analysis it is necessary to have detail for 57 sectors in each region, but it is not uncommon to differentiate around 500 sectors in some individual countries (such as the USA and Japan). Uncertainty increases as emissions are disaggregated to sectors, and consequently the differences between data sets increase. In this section we compare the sector differences between three datasets to indicate the possible implications that they may have on consumption-based emissions inventories.

Figure 2 shows the absolute difference between the standard GTAP sector emissions and the updated version, GTAP+NAMEA. The relative differences are larger, but often occur in outliner sectors with small emissions and hence do not have a large impact on results. Most of the differences occur in the countries that are updated (Australia, New Zealand, Canada, China, Japan, the USA, and the EU27). However, differences are also apparent in mineral products (cement), oil and gas (flaring), and refineries (downward adjustment of incorrectly combusted feedstocks). The differences can be quite large, in excess of 100 MtC in either direction. The largest errors occur due to the treatment of bunkers (air and sea transport), land transport, and electricity. Relative errors are largest in sectors with low levels of emissions.

Figure 3 shows the analogous results comparing the standard GTAP emissions with the EDGAR dataset. The EDGAR dataset is initially allocated to different sectors then GTAP, and thus we remapped the EDGAR sector emissions to the GTAP classification. This step may introduce additional errors as the mapping is not one-to-one. Since the EDGAR and GTAP database are independent, the differences are more widespread. The largest differences occur in the transport sectors (including bunker fuels), electricity, and the energy intensive sectors such as metal manufacturing and cement.

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Thus, while emissions may vary at the country level, there may be more significant and important differences at the sector level. The differences in these datasets will propagate through to the estimates of the consumption-based emissions.

3.2.2 Consumption-based emission estimates

The previous section demonstrated that there can be significant differences between emission datasets and these occur at three levels: (1) aggregated emissions, (2) treatment of bunker fuels, and (3) allocation of emissions to sectors. The production of goods and services for international trade is around 25 % of global emissions (Peters et al., 2011b). Consequently, for most countries, the production-based emissions account for about 75 % (on average) of the consumption-based emission inventories. The differences in the production-based estimates explain much of the differences in consumption-based emission estimates. Thus, if studies use different production-based emission estimates, then it will potentially give the perception that the methodology to construct consumption-based emission estimates is highly uncertain. This section quantifies these differences for five emission datasets.

Table 5 shows the consumption-based emission estimates using five different production-based emission inventories. The variation in consumption-based emission estimates is comparable with the variation in production-based estimates. The average range of the estimates for the top 10 is 11 %, slightly less than for production estimates (13 %). The average range of all 112 regions in the database is 16 %, less than the average for production (30 %). Interestingly, the spread in production-based emission inventories is generally higher than the spread in the consumption-based inventories (Fig. 4); 90 of the 112 have a more accurate consumption-based inventory. This counter-intuitive result is probably since (1) the range of the consumption-based estimates only includes a part of the production-based with the remainder due to imports, and (2) most exports come from countries where there is a smaller spread in production-based estimates. The countries with the largest spread in production-based estimates are importing from countries with a lower range in production-based

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estimates, and this thereby reduces the overall consumption-based estimates. As an extreme example, if a country had a 10 % spread in the production-based estimates and imported from countries with a 5 % spread, then it would be expected that the spread in the consumption-based estimates would be less than 10 % but greater than 5 %. Likewise, if the import partners had a spread of 15 %, then it would be expected that the consumption-based estimate would have a spread of between 10–15 %. These examples are based purely on the variation in the production-based estimates, and does not consider additional uncertainties at the sector level which would need a more detailed analysis (e.g. Lenzen et al., 2010). Despite this, the spreads in production- and consumption-based estimates are of comparable magnitude. Thus, if two studies use an emission dataset where a country has a 10 % spread in production-based emissions, then it would be expected that the spread in the consumption-based emissions would be around 10 % too.

Figure 5 shows the spread in the difference in consumption-based and production-based estimates for the 20 countries with the largest differences; this is similar to a "trade balance" in embodied emissions (Kanemoto et al., 2012; Peters, 2008). The uncertainty of both the production and consumption results is included here, though they may tend to cancel leading to a relatively robust trade balance. The figure shows that the trade imbalance of the selected countries is robust across different data sets. The largest spread is on the "Rest of Western Asia" which represents a region without specific data (derived from other countries' data), hence uncertainty is expected. The largest trade imbalances are for China and the USA. Even though the figure represents the 20 largest trade imbalances, some small countries that are highly dependent on trade appear in the results, for example, Taiwan, Switzerland, Belgium, and Hong Kong. The normalised trade balance (relative to the production-based emissions) is relatively stable for the top 20 countries, excluding the small countries. For smaller countries, in general, the spread in estimates is much larger, and can change sign (results not shown). Overall, the trade balances are robust for the largest emitters, independent of the dataset used.

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3.2.3 Differences due to the definition of consumption-based emissions

There are different ways to define the "carbon footprint" or "consumption-based emissions" (Peters, 2008, 2010a; Wiedmann and Minx, 2008; Kanemoto et al., 2012). Table 6 shows the top 10 emitters, and top 10 relative differences, in terms of consumption using two different definitions (Peters et al., 2011a). In the top 10, the differences can be as large as 25 % (China). The mean relative difference for the top 10 countries is 17 %. The largest relative differences are around 50 %, and occur for either small countries or countries with poor data. It is not possible to know the magnitude or direction of the difference without performing a calculation (Kanemoto et al., 2012). Differences are generally larger for small and trade-exposed countries such as Singapore, Taiwan, Malaysia, Belgium, and so on (Peters et al., 2011a). The average difference for the 112 regions in the database is 21 %, signifying that definitions could be a key reason for differences in results. While we have only compared two main definitions, other studies can use other different and less standard definitions (cf. Peters and Solli, 2010). These results clearly show, that to ensure robust comparisons between studies, it is important to control for different definitions.

3.2.4 Variations in economic data

We are not aware of a detailed comparison of the differences between MRIOTs, but we can get an indication using a comparison GTAP7.0 and GTAP7.1. The main differences between these two versions are an update of all EU27 countries and updates of the macroeconomic data.

Table 7 shows the top 10 emitters and relative differences between the two versions of the GTAP7 database. The average difference over all countries was 1 %, the average for the largest 10 emitters was 2 %, but the maximum difference was 11 % (Bulgaria). The average difference for the top-10 relative differences was 5 %. Of the 20 countries listed, 14 are from the EU27 which is also where most of the differences are between the GTAP7.0 and GTAP7.1 databases (around 5 % on average). This suggests that the

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changes in the EU27 data primarily affected the carbon footprint of the EU27 countries, and of the order of 5 %. However, there were some surprises, such as the large absolute differences in the "Rest of Western Asia", China, Japan, and the USA. These are presumably due to changes in trade with the EU27 and updated macro data. At least for the MRIOTs we compare here, the differences between MRIOTs are less than for different emissions data and the consumption-based emission definition. Even if comparing the EU27 countries only, the differences due to the emissions data and the consumption-based emission definition is still larger.

3.2.5 Summary of the differences in consumption-based estimates

Table 5, Table 6, and Table 7 showed the differences in consumption-based estimates when only one factor was varied at a time: Table 5, the production-based emissions data used as input; Table 6, the definition of the consumption-based emissions; and Table 7, modest variations in the economic input data. The differences were largest due to different production-based estimates, then different definitions, and finally different economic and trade data. However, it should be emphasised that the differences in the economic and trade data are modest compared with the differences between the five independent emission data sets we considered.

Figure 1 shows the variation between different emission estimates, but based on results in this section it is expected that if these studies used the same production-based emission data and the same definitions, then the results would become more similar. This suggests that the model spread for consumption-based estimates may be less than presently presumed. In particular, variations in the economic and trade data may be much less than variations due to definitions and production-based emission data used as input. This is supported by Monte-Carlo analysis of the UK consumption-based inventory (Lenzen et al., 2010) and data variations in annual data (Yamakawa and Peters, 2009). A typical MRIOA involves an infinite number of additions and subtractions (achieved via a matrix inverse), and differences based on uncorrelated errors tend to cancel (Peters, 2007). It is also found that the most uncertain data are usually

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small and have only little impact on the results (Lenzen et al., 2010; Jensen, 1980; Jensen and West, 1980). These points indicate that the variation in economic data may not be that important for consumption-based estimates, with the CO_2 data and definitions more important. In addition, the model spread of consumption-based estimates is strongly influenced by the spread in production-based emission estimates used as input.

3.3 Overview of key results

The previous two sections have given an overview of the differences between studies, but not much has been said about the results. It is clear from comparing the results of independent studies that the main conclusions are consistent and robust (Ahmad and Wyckoff, 2003; Andrew et al., 2009; Davis and Caldeira, 2010; Nakano et al., 2009; Peters et al., 2011b; Peters and Hertwich, 2008b; Hertwich and Peters, 2009; Atkinson et al., 2011; Wiebe et al., 2012). In this section, we summarise some of the main conclusions using the GTAP-MRIO version 7.1 with 2004 data.

Figure 6 shows the difference between production and consumption emissions for the RECCAP regions with Japan, USA, Canada, and China additionally disaggregated. Most developed countries are importers of embodied CO_2 emissions, with the exception of some exporters such as Canada and Oceania (mainly Australia). We have separated Japan and China from East Asia as the exports and imports tend to cancel each other losing some policy relevant information; we do the same for the USA, Canada, and North America. While Europe imports 23 % of its production-based emissions, there is a lot of variation within European countries; for example, Latvia has a net import of 92 % and the Czech Republic has a net export of 19 %, but 21 of the 27 EU countries are net importers of emissions.

Figure 7 shows the consumption-based emission estimates in each region and where the emissions occur. At the regional level, most of the emissions occur within the region, though for some individual countries most of the consumption-based emissions can occur outside of the country (e.g. Singapore 67 %, Switzerland 60 %, and Sweden

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55 %). For imports, China is a particularly important region with a sizeable share of emissions in most countries. Figure 8 shows the 12 largest trade flows between the regions, highlighting the role of China and Russia as important exporters to both Europe and the US. There are also large flows between Europe and the USA, and these tend to cancel each other.

Recent studies have found that the sizes of these flows are growing rapidly over time, much faster than many other macro-variables ...(Peters et al., 2011b; Wiebe et al., 2012; Nakano et al., 2009). Steinberger et al. (2012) explore these differences in terms of indicators of human development. Despite the rapid growth in embodied emissions, it is important to recall that territorial emissions to meet domestic consumption are still the largest contributor to consumption-based emissions in most countries. However, the trade flows are significant enough to have a large impact on regional emissions. The emission transfers between regions, while not directly effecting the carbon cycle, are relevant to understanding emission drivers and potentially policy applications (Caldeira and Davis, 2011; Davis and Caldeira, 2010; Peters et al., 2011b; Hertwich and Peters, 2009; Peters and Hertwich, 2008b). More details on the results can be found in the cited literature.

4 Physical flows of carbon

4.1 Fossil fuels

Global trade in fossil fuels is substantial and growing (BP, 2011). A recent study that analysed CO_2 emissions from the burning of fossil fuels according to where the fuels were extracted found that, in 2004, 2.8 GtC emissions (37 % of global emissions that year) were from burning of fuels that had been traded internationally (Davis et al., 2011). Davis et al. (2011) remains the only analysis of the physical flow of carbon in traded fossil fuels, derived from fuel-specific emissions factors for 112 countries and regions and 57 industry sectors using trade and energy data from the GTAP dataset

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(Narayanan and Walmsley, 2008). Using these factors, they reallocated CO_2 emissions back to the point where fuels were extracted. The model considered complex cases where raw (primary) fuels were imported for conversion to secondary fuels (e.g. refining of crude oil into gasoline) and then re-exported, but assumed that primary fuels that were imported and burned in a region were shipped directly from the country of extraction (Davis et al., 2011). The results of Davis et al. show the geographical concentration of fossil-fuel resources: fuels extracted in China, the US, the Middle East (a region of 13 countries), Russia, Canada, Australia, India and Norway account for 67 % of global CO_2 emissions. Oil and its refined products dominate international trade in fossil carbon (7.0 $GtCO_2$ in 2004), but international markets for coal (1.8 $GtCO_2$) and natural gas (1.5 $GtCO_2$) are substantial and growing (BP, 2011).

For this paper we updated the results of Davis et al. (2011) to include the most recent data updates and present the results by fossil fuel. The updated results are very similar to the original results, but provide slightly more detail. In 2004, 2.7 GtC (37 % of global emissions that year) were from burning of fuels that had been traded internationally. We focus on the results from the extraction of fossil fuels to the point of energy consumption (or emission production). Davis et al. (2011) additionally link the results from energy consumption to emissions consumption (embodied CO_2 emissions).

Table 8 shows the results for the extended RECCAP regions. The largest extraction occurs in North America (1.6 GtC), followed by similar values in West Asia (1.2 GtC) and East Asia (1.2 GtC). Most of the extraction in North America is used domestically (4 % exported), and similarly in East Asia only 2 % is exported. While in West Asia most of the carbon is exported (61 %). Other regions exporting a large share of their extraction are the Russian region (350 MtC, 42 % of extraction), Africa (362 MtC, 64 %), Oceania (153 MtC, 62 %) and South America (171 MtC, 42 %). Key importers of fossil fuels are Europe (626 MtC), which imports as much as it extracts; East Asia (610 MtC), which imports 50 % of its extraction; and North America (415 MtC), whose imports are relatively much smaller at 25 % of its domestic extraction. Even though North America imports large amounts of fossil fuels, it is less dependent on foreign sources of

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fossil fuels than many other regions. Europe, East Asia, and North America are the largest net importers and West Asia, Africa, and the Russian region are the largest net exporters of carbon. These results change when Production is further linked to Consumption to provide the full link from the Extraction of fossil fuels to the point of Consumption of goods and services (Davis et al., 2011).

Figure 9 shows the top 12 inter-regional flows between the extended RECCAP regions (USA, Canada, Japan, China disaggregated) disaggregated by fuel type (coal, oil, gas). The total trade between all 112 regions in the database is 2.7 GtC (27 % total emissions), and 2.1 GtC (29 %) between the RECCAP regions. The largest flow is from the Russian region to Europe (245 MtC) dominated by oil and some gas. There are many large flows from West Asia, mainly oil, with the largest to Japan (165 MtC) and Europe (132 MtC). Africa has a large export to Europe (163 MtC) with a mix of coal, oil, and gas, and a large export of oil to North America (85 MtC). There are large imports into Europe dominated by the Russian region, Africa, and Middle East. North America has more varied imports from Canada, Mexico, South America, and Africa. Australia has a large export of coal to Japan (62 MtC). These flows reflect the location of fossil resources together with the demand for fossil fuel above domestic resources. The flow of carbon in fossil fuels represents the largest fluxes considered in this article.

4.2 Petroleum-derived products

Carbon is traded in petroleum-derived products such as plastics, fertilisers (e.g. ammonia and urea), and fuels (e.g. methanol), though we are unaware of studies that attempt to estimate the amount of carbon in these products that enters international trade. Using the GTAP-MRIO emission dataset (Peters et al., 2011a) we have estimates of the carbon used as feedstock into chemical industries based on the GTAP methodology (Lee, 2008). The feedstocks are consistent with the feedstocks removed from the analysis in the study on trade in fossil-fuel carbon (Davis et al., 2011) and presented in the previous section.

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We found that 183 MtC (50 % of the carbon in that year, 367 MtC) were in petroleum-derived products traded internationally, with this amount reducing to 122 MtC (33 %) for the RECCAP regions. Table 9 shows the results for the RECCAP regions. North America has the largest production of feedstocks for products (103 MtC), followed by East Asia (88 MtC) and Europe (66 MtC). North America uses most of its feedstocks domestically and supplements them with a net import, similarly for Europe. Other regions have larger relatively trade flows than these regions. The largest export is from East Asia to North America (12 MtC) and East Asia to Europe (9 MtC). North America exports to Europe (9 MtC) and Europe back to North America (6 MtC) giving a much smaller net export from North America to Europe (3 MtC). Likewise, North America exports back to East Asia (5 MtC) giving a net flow of carbon from East Asia to North America (7 MtC). The Russian region exports are large amount to Europe (4 MtC) which accounts for almost half of the regions exports. Despite large trade flows relative to production, considerably less carbon is traded international in petroleum-based products compared to fossil fuel carbon (petroleum-products are only about 5 % of fossil fuel carbon extracted).

4.3 Biomass flows

In this section we consider biomass flows: Harvested Wood Products (HWPs), crops, and feed used for livestock. We first perform a set of consistent global estimates of all biomass flows using the GTAP-MRIO and then we compare with existing studies.

Since we use the GTAP-MRIO to allocate carbon from biomass flows, we expect to get different results from previous studies as we include a high level of processing. Previous studies on biomass flows have not considered processing directly. In the GTAP-MRIO the biomass carbon is allocated to the sector that harvests it, and then the GTAP-MRIO reallocates it to the sectors that consume the carbon. Other studies in the literature do not consider this processing endogenously, but consider the trade in processed products exogenously. As an example for forest products, Kastner et al. (2011a) consider the trade in roundwood and processed products directly, whilst we allocate the

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forest harvest to the forestry sector and allow the GTAP-MRIO to allocate the carbon to processed and traded products. As a consequence, the GTAP-MRIO is expected to allocate a larger share to international trade due to the high level of processing that can potentially be included.

4.3.1 Harvested wood products

Estimates of carbon flows in harvested wood products

We linked the GTAP-MRIO to harvested wood products (industrial roundwood) to estimate the carbon traded via Harvest Wood Products (HWPs). In this analysis we only consider the transport of carbon between regions, and we do not estimate when that carbon maybe emitted to the atmosphere. The release of carbon to the atmosphere will depend on the decay times of the different product pools (Pingoud et al., 2006).

Table 10 shows the industrial roundwood in terms of carbon that is extracted (produced), consumed, exported, and imported into each region. Globally, we find that 373 MtC are extracted globally with the largest extraction occurring in North America (138 MtC) followed by Europe (72 MtC), South America (38 MtC), and then the Russian region (31 MtC). The ranking is only slightly changed when using a consumption basis with North America having slight net import to increase its contribution (to 143 MtC), Europe also has a net import increasing its share (86 MtC), East Asia has a large increase in its contribution (42 Mt) representing a net import of 65 % of its harvest, and South America has a slight decrease (30 MtC) representing a net export. The largest importer is North America (143 MtC), followed by Europe (86 MtC), and East Asia (42 MtC). The regions with the largest differences between production and consumption in absolute terms are the Russian Region (exporter), East Asia (importer), Europe (exporter), and South East Asia (importer). Countries with a small domestic forestry sector, such as West Asia and Central America, have large relative imports.

We estimate the global trade in HWPs to be 148 MtC (40 % of global production), though when aggregating to RECCAP region many of the intra-region flows cancel

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leaving 88 MtC (24 % of the global total; Table 10). The intra-regional flow can be considerable: for example, including intra-regional flows increases North America's exports from 14 MtC to 40 MtC mainly due to a large flow from Canada to the USA (22 MtC). Figure 12 shows the largest inter-regional trade-flows. The Russian Region is the largest exporter of HWPs (18 MtC, 58 % of total) with large flows to East Asia (6.2 MtC), Europe (5.9 MtC), and a smaller flow to North America (1.8 MtC). South East Asia is the next biggest exporter (14 MtC, 66 % of total), with large flows to East Asia (4.6 MtC), North America (3.1 MtC), and Europe (2.5 MtC). The third and fourth largest exports (North America and Europe) do not occur in many of the top flows, signifying that they export to a wide range of regions. The fifth largest exporter is South America (9 MtC, 25 % of total), with the largest flows to North America (3.4 MtC) and Europe (2.5 MtC). The large flow from Oceania represents exports from Australia and New Zealand. To put the inter-regional flows into perspective, the largest intra-regional flow at the disaggregate level is from Canada to the USA (22 MtC), much larger than any single inter-regional flow. In addition, the inter-regional flows can differ substantially depending on how the results are allocated. For example, the second larger inter-regional flow is from China to the USA (3.6 MtC) which is not seen in the RECCAP results as it is offset by trade in the aggregated regions, for example, from USA to Japan (3.1 MtC, third largest flow). Thus, care needs to be taken if interpreting the inter-regional flows in country specific applications.

Comparisons with other studies

We are not aware of many studies that consider international trade in Harvested Wood Products (HWPs) at the international level. We compare three variations of our methodology with the results of Kastner et al. (2011a) and Ciais et al. (2008).

Our standard approach, as presented in Table 10, is based on a full GTAP-MRIO model which considers full processing along the global supply chain. Our method captures trade in a wide range of sectors even if they are not clearly identified as containing forest products; for example, miscellaneous toys and books would be included.

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This level of detail may overestimate the carbon flows, as a share of paper products used in an office that produces metal products, for example, would get allocated to exports even if the paper product itself is not exported. We have also used a method called Emissions Embodied in Bilateral Trade (EEBT) which considers the domestic (not global) supply chain and thus contains a lower level of processing (Peters, 2008; Peters and Hertwich, 2008b). It is not possible to determine in advance if the MRIO or EEBT method gives a higher estimate, as it depends on how much trade a country has in intermediate (semi-processed) products (Kanemoto et al., 2012; Peters, 2008). To determine the effects of using apparent consumption (that is, without further processing), we have also estimated the trade flows using trade data only (VXMD). For this, we distribute the carbon allocated directly to a sector according to the share of exports from that sector and we distribute the exports according to the bilateral export data. In the case of HWPs we distributed the forest harvest over both the forestry and wood and paper products sectors (not just the default to the forestry sector). We compare these three sets of results with Kastner et al. (2011a) and Ciais et al. (2008), Figure 10. Both these authors use an apparent consumption approach, though Kastner et al. (2011a) consider multiple levels of trade (but not processing).

Figure 10 shows a relatively large spread between the estimates. Our MRIO and EEBT approaches generally give larger net flows and they are of similar magnitude and sign, except for China. We find a total global trade flow of 148 MtC for the MRIO method and 153 MtC for the EEBT method. The VXMD approach gives a trade flow of 105 MtC, less than the MRIO and EEBT methods, but this is expected as it does not include processing. In most cases, VXMD also gives smaller estimates at the country level. All three methods give a similar trend for the countries shown. Ciais et al. (2008) only consider European countries with a base year of 1997. They use an apparent consumption approach and their estimates are generally in line with the other results for the countries considered. There is no clear trend on whether their approach is better approximated by any of our three methods.

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Kastner et al. (2011a) estimates a total global trade of 129 MtC yr^{-1} averaged over 1997–2007, representing 33 % of the total extraction (our MRIO found 149 MtC or 40 % in 2004). It is expected that the method of Kastner et al. (2011a) is lower than our MRIO method as they do not include processing between industry sectors. At the country level, we find much larger variations between Kastner et al. (2011a) and our estimates (Fig. 10). China, for example, differs in size and considerably in magnitude (net importer of −21 MtC in Kastner et al. (2011a), net exporter of 3 MtC in the GTAP-MRIO). There are other significant outliers for the Russian Federation, Indonesia, Chile, Korea, Japan, and the USA. In the particular case of China, there is considerable processing of raw materials before export as manufactured products and different levels of processing may be the underlying cause of the differences we report. However, it is not possible to conclusively determine without further analysis what the cause of the difference is. For many other countries, the results of Kastner et al. (2011a) differ to our three methods and there is not a clear trend on whether any of our methods better approximate the results of Kastner et al. (2011a).

Overall, Fig. 10 shows that the carbon fluxes between regions follow similar trends for all the methods used, though, there are more outliers for the Kastner et al. (2011a). Further investigation is required to understand these differences.

4.3.2 Crops

Estimates of carbon flows in crops

We linked the GTAP-MRIO to the crop production data to estimate the carbon traded through crops. Table 11 shows crops in terms of carbon that is extracted (produced), consumed, exported, and imported into each region. Globally, we find that 1704 MtC are extracted with the largest extraction occurring in East Asia (329 MtC) followed by North America (265 MtC), South East Asia (221 MtC), South Asia (208 MtC), South America (168 MtC), and then Africa (158 MtC). The ranking is only slightly changed from a consumption basis with East Asia having net imports to increase its share

(375 MtC), Europe increases its contribution (246 MtC) through a large net import (83 MtC),North America decreases its contribution (226 Mt) with a net export, South Asia has a similar contribution (213 MtC), Africa has a net import to increase its contribution to (182 MtC), South East Asia has a net export decreasing its contribution (152 MtC), and South America has a large net export decreasing its contribution (96 MtC). The regions with the largest differences between production and consumption in absolute terms are Europe (importer), South America (exporter), South East Asia (exporter), East Asia (importer), and North America (export). Countries with a small domestic crop sector compared to population have large relative imports, such as West Asia and Europe. Oceania and South America both have a net export of around 50 % of their production.

We estimate the global trade in crops to be 522 MtC (31 % of global total), though when aggregating to RECCAP regions many of the intra-regional flows cancel leaving 396 MtC traded (23 % of the global total; Table 11). Figure 12 shows the largest inter-regional trade flows. North America is the largest exporter of crop carbon (92 MtC, 35 % of total) with large flows to East Asia (26 MtC), Africa (10 MtC), and Europe (10 MtC). South East Asia is the next biggest exporter (83 MtC, 38 % of total), with large flows to East Asia (21 MtC), Europe (17 MtC), and North America (11 MtC). The third largest exporter is South America (79 MtC, 47 %) with large flows to Europe (26 MtC), East Asia (11 MtC), and Africa (10 MtC). East Asia is the fourth largest exporter (49 MtC, 15 %) with a large flow to Europe (14 MtC). The largest importer is Europe (99 MtC), followed closely by East Asia (95 MtC), and then North America (53 MtC), Africa (39 MtC), and West Asia (38 MtC). These intra-regional flows hide the most significant inter-regional flows. The largest regional flows are from the US to Japan (22 MtC) and China to Japan (15 MtC). These individual flows can be as large as the intra-regional flows as they tend to cancel; for example, the US to Japan flow is partially compensated by flow from China to the US (8 MtC). Thus, the RECCAP inter-regional flows can mask significant and more policy-relevant flows between individual countries in and between the RECCAP regions.

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Comparisons with previous studies

Figure 11 shows a comparison of different methods and estimates of carbon trade in crops. We show three methods based on the GTAP database, MRIO, EEBT, and VXMD as explained earlier, and we show independent results from Krausmann et al. (2008) and Ciais et al. (2007). We convert the results of Krausmann et al. (2008) into carbon using a dry matter to carbon conversion of 0.45 tC/tDM. Krausmann et al. (2008) estimate crop harvest as 1544 MtC and crop trade as 393 MtC, comparable to our estimates of 1704 and 396 MtC. We could expect similarity in the crop harvest, but the similarity in the total trade may simply be down to chance, given large differences in methodology; this is clearly seen at the country level. Ciais et al. (2007) estimates crop harvest of 1290 MtC for 1998 and trade of 174 MtC. This is lower than our estimate and Krausmann et al. as Ciais et al. does not consider all crops.

Figure 11 shows a high degree of scatter in the results at the country level, although these can largely be explained by the background methodologies. The GTAP-MRIO and GTAP-EEBT approaches both consider a high level of processing (for example, carbon from crops that are embodied in clothing). When using the GTAP-VXMD method to approximate apparent consumption it is found that it is quite close to the estimates of Krausmann et al. (2008) and Ciais et al. (2007). This confirms that the variation in the results is due to a different definition of consumption: apparent versus final consumption. While a similar result was found for HWPs (Fig. 10), the results were more similar there as the apparent consumption approach of Kastner et al. (2011a) included multi-linked trade flows but no processing. Thus, based on this comparison, it would appear that processing is particularly important in estimating the carbon flows between regions.

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4.3.3 Livestock

Estimates of carbon flows in livestock

We linked the GTAP-MRIO to a model on the consumption of livestock to estimate the carbon traded via the trade in livestock and meat. A small part of the crop carbon from Table 11 represents crops that are fed to livestock; 244 MtC out of 1704 MtC of crops (14 %) or 3236 MtC of livestock carbon consumption (7.5 %), comparable with FAO data (FAO, 2012b). We did not reallocate this to livestock and thus it remains in the crop data (this is discussed in a separate section below). Thus, the carbon flows in livestock follow carbon from the point of consumption by the livestock until the point of final consumption.

Table 12 shows livestock consumption in terms of carbon that is produced, consumed, exported, and imported into each region. Globally, we find that 3236 MtC are consumed by livestock with the largest consumption occurring in South America (641 MtC) followed by South Asia (493 MtC), Africa (440 MtC), and equal values in East Asia and North America (429 MtC). The ranking is changed from a human consumption basis with North America having a large increase in its share (514 MtC) due to a large net import, South America decreases its contribution (493 MtC) through a large net export (148 MtC),South Asia decreases its contribution (467 MtC) with a net export, Europe increases its contribution (426 MtC) through a large net import (115 MtC), and Africa has a small decrease in its contribution (417 MtC). The regions with the largest differences between production and consumption in absolute terms are South America (exporter), Europe (importer), North America (importer), and West Asia (importer). Countries with a small domestic livestock sector compared to consumption have large relative imports, such as West Asia and Europe. Oceania has a net export of around 50 % of their production.

We estimate the global trade in livestock carbon to be 651 MtC (20 % of global total), though when aggregating to RECCAP regions some of the intra-regional flows cancel leaving 465 MtC traded (14 % of the global total; Table 12). Figure 12 shows the largest

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inter-regional trade flows. South America is the largest exporter of livestock carbon (152 MtC, 24 % of total) with large flows to Europe (57 MtC), North America (22 MtC), West Asia (19 MtC), Russia (16 MtC), and East Asia (13 MtC). East Asia is the next biggest exporter (101 MtC, 23 % of total), with large flows to North America (38 MtC), and Europe (28 MtC). The third largest exporter is Oceania (54 MtC, 48 %) with large flows to East Asia (18 MtC) and North America (13 MtC). The largest net importer is Europe (141 MtC), followed by North America (105 MtC), West Asia (70 MtC) and East Asia (59 MtC). These intra-regional flows hide the most significant inter-regional flows. The largest regional flows are from the China to the USA (39 MtC), East Africa to West Asia (28 MtC), and China to Japan (16 MtC). These individual flows can be as large as the intra-regional flows as they tend to cancel. Thus, the RECCAP inter-regional flows can mask significant and more policy relevant flows between individual countries in and between the RECCAP regions.

Comparisons with previous studies

We are not aware of other global studies that track carbon in livestock.

4.3.4 Crops used as livestock feed

A share of the harvested crops are used for livestock feed. Foley et al. (2011) report, for example, that 35 % of global crop production is used for animal feed and Ciais et al. (2007) reports 29 %. Early, we estimated that 244 MtC out of 1704 MtC of crops (14 %) or 3236 MtC of livestock carbon consumption (7.5 %), was used as livestock feed. Our estimate is consistent with the FAO data we used (FAO, 2012b). This is considerably lower than the estimates of Foley et al. and Ciais et al., but they are not directly comparable. Our input data for crops considers crops primary used for human consumption[1]. Thus, we assume livestock feed is primarily estimated using the feed model presented earlier.

[1] http://faostat.fao.org/site/362/DesktopDefault.aspx?PageID=362

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4.3.5 Combined carbon in biomass flows

Table 13 shows the aggregated flows of forests, crops, and livestock carbon (Table 10, Table 11, and Table 12). We estimate the total carbon in biomass flows is 5.3 GtC for 2004, comparable with the used extraction of 5.5 GtC for 2000 in Krausmann et al. (2008). We estimate total exports as 1.3 GtC (25 %) for total trade, or 948 MtC (18 %) for trade between RECCAP regions. Krausmann et al. (2008) estimate trade in plant biomass as 393 MtC (crops and forests), less than our estimate for crops and forests (484 MtC, Table 10 and Table 11). Since Krausmann et al. use apparent consumption, we expect their estimate to be lower. We find that the largest net exporters of carbon are South America (228 MtC), South East Asia (81 MtC), and Oceania (63 MtC). The largest net importers of carbon are Europe (213 MtC), West Asia (101 MtC), and North America (51 MtC). These fluxes between regions are particularly important for balancing regional carbon balances.

Figure 12 shows the top-10 trade flows for HWPs, crops, and livestock. The flows for crops and livestock are similar in magnitude, but the flows of HWPs are much smaller. The figure clearly shows there is a large net flux out of South America with the largest flows to Europe (87 MtC), North America (37 MtC), East Asia (28 MtC), Africa (23 MtC), and West Asia (27 MtC). This flow is dominated by the carbon consumed by livestock. There is a large flow from East Asia to North America (68 MtC) dominated by livestock carbon, and a large flow from North America to East Asia (59 MtC) dominated by crops. East Asia also exports a large share to Europe (50 MtC). Despite the large exports from East Asia, it also imports large amounts from North (59 MtC, dominated by crops) and South (28 MtC, livestock) America, South East Asia (35 MtC, crops), and Australia (28 MtC, livestock). The flows are considerable in magnitude, almost as large as fossil emissions, and could have a large effect on balancing regional carbon budgets.

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5 Discussion

Table 14 summarises the total carbon and flows of carbon between all 112 regions analysed and the 12 RECCAP regions considered. We split the table into fossil fuel carbon and biomass carbon. Fossil fuel carbon is split into physically traded carbon, embodied carbon additionally includes cement and gas flaring (hence the total carbon is different to the total fossil fuel carbon), and carbon in petroleum-based products. Physically traded fossil fuels are the largest source of internationally traded emissions, at 2.7 GtC from total emissions of 7.3 GtC from combustion of fossil fuels (37 %). Emissions embodied in internationally traded goods and services from fossil-fuel combustion, cement, and gas flaring, represents 1.7 GtC (22 % of all embodied emissions). Also associated with fossil fuels is the carbon in petroleum-derived products (plastics, fertilisers, and so on). The total carbon for petroleum-derived products is much smaller (0.4 GtC), as are the trade flows 0.2 GtC (50 %). For biomass carbon, we consider the carbon consumed by livestock, crop harvest, and industrial roundwood harvests leading to HWPs. At the aggregated level, the total flows in biomass are comparable, but smaller, than fossil-fuel emissions. The largest contribution is from livestock 0.7 GtC (20 % of 3.2 GtC total carbon), with crop flows similar in magnitude due to higher trade flows 0.5 GtC (31 % of 1.7GtC), and harvested wood products much smaller with 0.1 GtC (40 % of 0.4 GtC). All of the flows are of sufficient magnitude to warrant deeper investigation. The carbon associated with fossil fuels is of most relevance to climate policy, while the carbon associated with biomass is relevant to both climate policy and to balancing regional carbon budgets. International trade is growing rapidly at the global level (Peters et al., 2009) indicating these flows will become more important in time.

There is a growing literature on the importance of embodied emissions in climate policy (Wiedmann, 2009; Wiedmann et al., 2007; Davis and Caldeira, 2010; Hertwich and Peters, 2009; Peters and Hertwich, 2008b; Nakano et al., 2009; Wiebe et al., 2012). Due to the rapid growth of international trade relative to economic activity, embodied emissions are growing over time (Wiebe et al., 2012; Peters et al., 2011b; Caldeira

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and Davis, 2011; Nakano et al., 2009). Much of the literature has focused on the issue of weak "carbon leakage" (Peters, 2010b). The studies robustly indicate that there are large, and increasing, flows of carbon between regions with a net flow of embodied carbon from emerging to developed countries. Understanding these flows helps to understand regional emission drivers (Le Quéré et al., 2009; Raupach et al., 2007) and may assist in the design of climate policies (Peters and Hertwich, 2008a; Peters, 2008). Understanding embodied flows is also useful for the assessment of border taxes (Atkinson et al., 2011) and competitiveness concerns more broadly (Peters, 2010b). More recently, the importance of carbon flows in fossil-fuels have been identified and compared with embodied carbon (Davis et al., 2011) and linked to human development indicators (Steinberger et al., 2012). The methods to estimate embodied emissions are well-established (Wiedmann, 2009; Wiedmann et al., 2007; Peters, 2010a), but independent studies often do not provide a clear comparison with other studies and explanations for differences. Thus, it appears estimates vary considerably between studies, when differences may be caused by controllable difference in data and definitions (Peters and Solli, 2010; Wiedmann et al., 2011). While data and methods will improve over time with further research, the greatest need to for further research is to identify how consumption-based emission estimates can be best utilised in policy settings.

Relative to embodied emissions, the literature on carbon and biomass flows in international trade is small. There are only a few global studies, all of which have different objectives (Erb et al., 2009; Krausmann et al., 2008; Ciais et al., 2007; Kastner et al., 2011a). All of these studies have used the concept of "apparent consumption" and thus they do not include processing nor, with the exception of Kastner et al. (2011a), multiple levels of international trade. We believe our estimates are the first across the most significant biomass flows using a standard and well-established method for embodied emissions. Since our analysis considers multiple levels of processing, our estimates of carbon flows are much higher than those reported in the cited literature. The relevant level of processing depends on the research question. For example, our analysis would include the carbon in paper used in an office of a company exporting cars and thus it would appear as though the carbon in office paper is exported when it is actually the car. A similar issue might arise with the carbon associate with livestock: we assume all the carbon consumed by livestock enters the economic system and can be traded. This is likely an overestimate, particularly for balancing carbon budgets, and more detailed modelling would be required. While our analysis on biomass flows was primarily in the context of regional carbon budgets, there are also policy applications. As for embodied carbon, understanding the regional drivers of biomass production and consumption is important (Erb et al., 2009; Krausmann et al., 2008). Tracking carbon in HWPs is already important in policy (Cowie et al., 2006), and has many parallels with concepts used in embodied carbon analysis. We believe carbon and biomass flows in international trade have currently received too little attention, and there is a need for more research on methodology, scientific applications, and understanding the implications for policy.

In this paper we have covered most of the important flows of carbon associated with the economic system, however, we have not included carbon associated with deforestation. The carbon associated with deforestation is around 1.1 $\mathrm{GtC\,yr^{-1}}$ (Houghton et al., 2012) and international trade associated with deforestation is likely to be important (Zaks et al., 2009; Meyfroidt et al., 2010; DeFries et al., 2010). This is an important area for further research.

6 Conclusions

We have quantified the carbon associated with international trade in physical flows (fossil fuels, petroleum-derived products, livestock, crops, and HWPs) and embodied flows (fossil-fuel and industrial emissions from the production of goods and services). We used the same economic and trade data to make consistent estimates.

Comparisons between some of the key literature on embodied carbon shows that results are robust across studies. Differences between studies do not necessarily reflect the uncertainty in an individual estimate, but rather, reflect controllable differences due

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to input data and definitions. A general finding supported by all studies is that there is a large and growing flow of embodied carbon from poor and emerging to developed countries. This is important to understand regional emission drivers and may have a variety of applications in policy. There are far fewer studies on the physical flows of carbon and methodological differences are much larger leading to a larger spread between estimated carbon flows. We generally find higher estimates of carbon flows than in the literature since we consider a higher level of processing. Further research is needed by independent groups to resolve the differences between studies. We have not included carbon flows associated with deforestation and this is an important area for further research.

Overall, the carbon flows between regions are significant and important for both scientific issues, such as balancing regional carbon budgets and understanding regional carbon drivers, and policy issues, such as designing more efficient policies given the political constraints that current exist. While further research is needed on methodological issues and comparability of studies, the largest gap in the literature is how to utilise the results to better support decision making in policy.

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Table 1. A summary of the trends in two time-series studies for key countries and regions (Peters et al., 2012; Wiebe et al., 2012). The Peters et al study runs from 1990–2010, but growth rates are also shown for 1995–2005 for direct comparison with Wiebe et al. Differences in the production growth rates are evident in the consumption growth rates.

	Production Growth rate (% yr^{-1})			Consumption Growth rate (% yr^{-1})		
	Peters et al. (1990–2010)	Peters et al. (1995–2005)	Wiebe et al. (1995–2005)	Peters et al. (1990–2010)	Peters et al. (1995–2005)	Wiebe et al. (1995–2005)
EU-27	−0.3	0.0	0.4	0.2	0.3	1.4
United States of America	0.4	0.4	1.0	1.1	1.5	1.9
Japan	0.3	0.5	0.7	0.4	−0.2	0.3
Russian Federation	−1.6	−0.3	0.1	−1.0	0.1	−0.5
China	6.1	5.5	4.9	4.9	4.6	4.0
India	4.9	3.8	3.7	4.6	3.4	3.5

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Table 2. The key features included in the different carbon emission data sets used in this study.

	CDIAC	UNFCCC	EDGAR	GTAP7.1	GTAP7.1+NAMEA
Fossil fuels	Yes	Yes	Yes	Yes	Yes
Cement production	Yes	Yes	Yes	No	Yes
Gas flaring	Yes	Yes	Yes	No	Yes
Other process emissions	No	Yes	Yes	No	Mixed
International transport (bunker fuels)	No (in global total)	No (reported as a memo by the fuel supplier)	No (we allocated to countries based on the fuel user)	Yes (in principle, though uncertain)	Yes (in principle, though varies by country)

Table 3. Estimates of carbon emissions (2004) from fossil-fuel combustion and, in some cases, process emissions from different data sources. The first column shows the total emissions from CDIAC, and the other columns are percentage comparisons with CDIAC. The characteristics of each dataset are shown in Table 2. The CDIAC global total does not include bunker fuels.

		Region	CDIAC (GtC)	UNFCCC (%)	EDGAR (%)	GTAP7.1 (%)	GTAP7.1+NAMEA (%)
		Global	7.397	–	3.7	2.2	0.4
1	Top 10 emitters globally	United States of America	1.517	9.2	7.3	13.5	6.7
2		China	1.442	–	−1.3	−12.0	−8.5
3		Russian Federation	0.437	−4.8	2.3	0.5	−1.1
4		Japan	0.344	1.8	9.9	−0.4	1.9
5		India	0.367	–	−8.7	−17.3	−15.7
6		Germany	0.226	6.7	15.3	9.8	6.3
7		Rest of Western Asia	0.248	–	−7.4	15.5	3.6
8		United Kingdom	0.149	2.7	16.0	17.2	15.7
9		Canada	0.152	4.1	4.7	11.1	8.0
10		Italy	0.128	4.4	5.9	5.1	4.9
1	Top 10 differences globally	Netherlands	0.048	2.4	23.5	105.3	19.5
2		Korea	0.132	–	12.6	−1.4	−6.7
3		Ukraine	0.094	−8.4	3.7	−10.9	−16.5
4		France	0.106	7.5	16.5	6.0	5.7
5		Caribbean	0.029	–	−2.9	51.2	45.8
6		Belgium	0.030	14.0	29.2	50.0	14.0
7		South Africa	0.113	–	−13.0	−11.1	−11.7
8		Nigeria	0.026	–	−11.1	−46.3	1.6
9		Thailand	0.073	–	−13.7	−14.9	−14.1
10		Taiwan	0.071	–	3.0	14.7	3.2

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Table 4. The "bridge" table connecting the UNFCCC and NAMEA inventories for reporting European countries in 2007. By convention, the UNFCCC memo on bunker fuels (2) is recorded but not included in national totals. According to the NAMEA (economic accounting), allocation should be based on resident institutes, and thus adjustments must be made primarily for bunker fuel use when converting from a UNFCCC inventory to a NAMEA. The last set of rows show the percentages relative to the UNFCCC totals. In most cases the NAMEAs are higher as they include international transport while the UNFCCC inventories do not.

Values for 2007 (MtC, %)	Austria	Belgium	Czech Republic	Denmark	Finland	France	Germany	Hungary	Latvia	Lithuania	Luxembourg	Netherlands	Norway	Poland	Portugal	Sweden	United Kingdom	Total of countries
Emissions reported to the UNFCCC (1)	20	31	34	15	18	106	228	16	2	4	3	50	12	89	17	14	149	810
UNFCCC Memo: Bunker Fuels (2, not in any totals)	1	9	0	2	1	7	10	0	0	0	0	17	1	1	1	3	12	65
Activities by national residents abroad (3)	0	3	0	14	2	3	15	1	0	1	0	7	4	2	1	3	16	72
Activities by non-residents in the territory (4)	2	0	1	0	0	0	2	0	0	0	1	2	0	0	1	0	0	9
Other adjustments and statistical discrepancy (5)	−1	0	1	0	0	−1	0	0	0	0	0	0	0	0	−1	0	1	−1
Emissions for the NAMEA (5)=(1)+(3)−(4)−(5)	19	34	33	29	20	109	241	16	3	5	2	56	16	91	18	17	165	874
UNFCCC Memo: Bunker Fuels (2)/(1) %	3.0	30.2	0.8	11.2	4.8	7.0	4.2	1.2	9.3	3.7	11.5	33.9	7.2	0.6	6.8	18.3	8.3	8.1
Net activities by residents (3–4)/(1) %	−8.5	8.1	−0.9	96.8	9.2	2.6	5.8	3.5	14.4	14.1	−28	10.5	31.1	2.2	−2.0	18.4	10.9	7.7
Emissions for the NAMEA (5)/(1) %	94	109	97	197	109	104	106	102	114	114	72	111	131	102	104	119	110	108

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Table 5. Estimates of consumption-based inventories (2004) using the emissions data from Table 2 (see caption and text). The first column shows the total emissions from CDIAC, and the other columns are percentage comparisons with CDIAC. The percentage differences are around the same order as for production, suggesting that the dataset used for the production-based emissions is important in determining the variation in consumption-based emissions between studies.

		Region	CDIAC (GtC)	UNFCCC (%)	EDGAR (%)	GTAP71 (%)	GTAP71+NAMEA (%)
		Global	7.397		3.7	2.2	0.4
1	Top 10 emitters globally	United States of America	1.730	7.6	5.4	9.5	5.1
2		China	1.134		−1.0	−10.9	−7.9
3		Japan	0.409	1.7	9.0	2.5	0.6
4		Russian Federation	0.353	−4.4	0.3	−0.4	−1.1
5		Germany	0.277	4.9	13.6	11.5	4.2
6		India	0.338		−7.8	−15.9	−14.4
7		United Kingdom	0.208	2.5	13.7	14.6	9.0
8		Rest of Western Asia	0.225		−4.6	6.9	2.1
9		Italy	0.164	3.5	7.0	4.1	3.3
10		France	0.151	5.3	11.6	6.1	4.1
1	Top 10 differences globally	Canada	0.139	4.2	9.8	12.8	6.0
2		Netherlands	0.059	2.3	13.8	28.9	9.8
3		Korea	0.134		6.7	−2.3	−5.2
4		Caribbean	0.032		−0.3	35.7	31.2
5		Australia	0.091	6.8	12.4	7.0	4.7
6		Brazil	0.084		8.7	2.0	−3.7
7		South Africa	0.075		−12.7	−9.9	−10.4
8		Norway	0.016	2.6	59.5	19.5	15.1
9		Belgium	0.045	6.7	20.2	20.9	6.2
10		Ukraine	0.064	−7.4	−8.4	−11.0	−14.1

Table 6. The differences resulting from using different definitions for consumption-based inventories (2004) showing the top 10 emitters in terms of consumption. The differences are measured relative to the MRIO definition.

		Region	EEBT (MtC)	MRIO (MtC)	Difference (MtC)	Difference (%)
1	Top 10 emitters globally	United States of America	1619	1818	−198.8	−10.9
2		China	1319	1044	275.3	26.4
3		Russian Federation	432	349	83.0	23.8
4		Japan	350	411	−61.1	−14.8
5		India	310	290	20.0	6.9
6		Germany	240	288	−48.3	−16.8
7		Rest of Western Asia	257	229	27.2	11.9
8		United Kingdom	172	227	−54.3	−24.0
9		Canada	164	148	16.0	10.9
10		Italy	135	170	−35.2	−20.7
1	Top 10 differences globally	Nigeria	27	17	10.0	59.5
2		Malawi	0.2	0.5	−0.2	−53.3
3		Malaysia	40	26	13.4	51.6
4		Switzerland	14	27	−12.9	−48.3
5		South Africa	100	67	32.3	47.9
6		Latvia	2.1	4.0	−1.9	−47.9
7		Hong Kong	16	29	−13.5	−46.0
8		Singapore	12	21	−8.8	−42.6
9		Ukraine	78	55	22.9	41.5
10		Mauritius	0.7	1.1	−0.5	−41.4

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Table 7. The top-10 emitters and relative differences using the GTAP7.0 and GTAP7.1 databases with the same (GTAP7.0) emission data set (2004). The main differences are for the EU27 countries, which is where the economic data is most different.

		Region	GTAP7.0 (MtC)	GTAP7.1 (MtC)	Difference (MtC)	Difference (%)
1	Top 10 emitters globally	United States of America	1828	1818	9.5	0.5
2		China	1019	1044	−24.9	−2.4
3		Japan	416	411	4.5	1.1
4		Russian Federation	349	349	−0.1	0.0
5		India	291	290	1.3	0.4
6		Germany	293	288	4.9	1.7
7		Rest of Western Asia	218	229	−11.4	−5.0
8		United Kingdom	231	227	4.3	1.9
9		Italy	163	170	−6.3	−3.7
10		France	160	157	3.7	2.3
1	Top 10 differences globally	Bulgaria	13	11	1.3	11.2
2		Finland	20.2	21.6	−1.4	−6.4
3		Sweden	27	26	1.6	6.2
4		Netherlands	68	64	3.7	5.8
5		Slovenia	5	5	0.3	5.4
6		Belgium	45.4	47.3	−1.9	−3.9
7		Austria	30	29	0.9	3.1
8		Slovakia	10	10	0.3	2.9
9		Romania	27	28	−0.8	−2.8
10		Ireland	17.1	17.4	−0.4	−2.1

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Table 8. The 2004 fossil fuel carbon extracted in each region (extraction), the amount and share exported, the consumption of fossil fuel carbon (hence the production of emissions) amount and share imported, and the difference between extraction and production (and exports and imports). Exports and imports only represent the trade between the RECCAP regions, and do not include the trade between countries within a region (e.g. Finland and Sweden). The shares are always in terms of extraction.

Region	Extraction			Production			Balance	
	Extraction (MtC)	Exports (MtC)	Share (%)	Production (MtC)	Imports (MtC)	Share (%)	Balance (MtC)	Share (%)
Africa	566	362	64	240	36	6	325	58
Oceania	245	153	62	115	23	9	130	53
East Asia	1230	24	2	1817	610	50	−587	−48
South East Asia	298	138	46	252	92	31	46	15
South Asia	249	4	2	344	99	40	−95	−38
Europe	620	55	9	1191	626	101	−571	−92
North America	1567	60	4	1922	415	26	−355	−23
Russia	840	350	42	520	30	4	320	38
South America	357	171	48	223	37	10	134	38
Central America	35	14	41	52	31	90	−17	−49
Eastern Europe	39	1	4	69	31	78	−29	−74
West Asia	1247	759	61	547	60	5	699	56
Global	7293	2090	29	7293	2090	29	0	0

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Table 9. The 2004 fossil fuel carbon used as feedstock in each region (production), the amount and share exported, the consumption of feedstock for products (consumption) amount and share imported, and the difference between production and consumption (and exports and imports). Exports and imports only represent the trade between the RECCAP regions, and do not include the trade between countries within a region (e.g. Finland and Sweden). The shares are always in terms of production.

	Production			Consumption			Balance	
Region	Production (MtC)	Exports (MtC)	Share (%)	Consumption (MtC)	Imports (MtC)	Share (%)	Balance (MtC)	Share (%)
Africa	6	2	30	10	6	93	−4	−64
Oceania	2	1	32	5	3	138	−3	−106
East Asia	88	31	35	75	18	20	13	15
South East Asia	20	13	65	13	6	28	7	36
South Asia	16	4	27	16	5	31	−1	−3
Europe	66	17	26	85	36	55	−19	−29
North America	103	20	19	113	30	29	−10	−10
Russia	17	10	59	10	2	14	8	45
South America	11	3	29	13	5	41	−1	−13
Central America	5	2	36	5	2	32	0	4
Eastern Europe	2	1	55	3	2	72	0	−17
West Asia	30	18	60	20	8	27	10	33
Global	367	122	33	367	122	33	0	0

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Table 10. The 2004 industrial roundwood extracted in each region (production) in terms of carbon, the amount and share exported, the consumption amount and share imported, and the difference between production and consumption (and exports and imports). Exports and imports only represent the trade between the RECCAP regions, and do not include the trade between countries within a region (e.g. Finland and Sweden). The shares are always in terms of production.

	Production			Consumption			Balance	
Region	Production (MtC)	Exports (MtC)	Share (%)	Consumption (MtC)	Imports (MtC)	Share (%)	Balance (MtC)	Share (%)
Africa	19	4	22	17	3	14	1	8
Oceania	11	4	35	9	2	16	2	20
East Asia	25	9	34	42	25	99	−17	−65
South East Asia	22	14	66	9	2	8	13	58
South Asia	8	1	10	10	3	36	−2	−26
Europe	72	11	15	86	25	34	−14	−19
North America	138	14	10	143	19	14	−5	−4
Russian Region	31	18	58	15	2	5	17	53
South America	38	9	25	30	1	3	8	22
Central America	1	0	29	2	1	105	−1	−76
Eastern Europe	5	3	56	3	1	15	2	42
West Asia	3	1	21	8	6	190	−5	−170
Global	373	88	24	373	88	24	0	0

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Table 11. The 2004 crops extracted in each region (production) in terms of carbon, the amount and share exported, the consumption amount and share imported, and the difference between production and consumption (and exports and imports). Exports and imports only represent the trade between the RECCAP regions, and do not include the trade between countries within a region (e.g. Finland and Sweden). The shares are always in terms of production.

Region	Production			Consumption			Balance	
	Production (MtC)	Exports (MtC)	Share (%)	Consumption (MtC)	Imports (MtC)	Share (%)	Balance (MtC)	Share (%)
Africa	158.4	15.6	10	182.1	39.3	25	−23.7	−15
Oceania	22.5	16.9	75	11.2	5.5	24	11.4	50
East Asia	329.2	49.1	15	375.0	94.8	29	−45.7	−14
South East Asia	221.2	83.1	38	152.8	14.7	7	68.3	31
South Asia	207.9	10.9	5	213.1	16.0	8	−5.1	−2
Europe	163.2	16.1	10	246.3	99.3	61	−83.1	−51
North America	264.6	91.6	35	226.3	53.2	20	38.4	15
Russia	69.9	15.9	23	65.7	11.7	17	4.2	6
South America	167.6	79.3	47	96.2	7.9	5	71.4	43
Central America	15.1	4.6	30	20.1	9.5	63	−4.9	−33
Eastern Europe	25.7	5.2	20	25.7	5.2	20	−0.1	0
West Asia	58.4	7.5	13	89.3	38.4	66	−30.9	−53
Global	1703.7	395.6	23	1703.7	395.6	23	0.0	0

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Table 12. The 2004 carbon feed to livestock in each region (production), the amount and share exported, the consumption amount and share imported, and the difference between production and consumption (and exports and imports). Exports and imports only represent the trade between the RECCAP regions, and do not include the trade between countries within a region (e.g. Finland and Sweden). The shares are always in terms of production.

Region	Production			Consumption			Balance	
	Production (MtC)	Exports (MtC)	Share (%)	Consumption (MtC)	Imports (MtC)	Share (%)	Balance (MtC)	Share (%)
Africa	440.1	45.9	10	416.8	22.6	5	23.3	5
Oceania	113.9	54.3	48	64.9	5.4	5	48.9	43
East Asia	428.9	100.7	23	387.6	59.4	14	41.2	10
South East Asia	121.4	16.7	14	121.5	16.7	14	0.0	0
South Asia	493.2	31.1	6	466.5	4.4	1	26.7	5
Europe	310.7	24.8	8	426.3	140.5	45	−115.6	−37
North America	429.1	20.3	5	513.6	104.7	24	−84.5	−20
Russia	81.0	4.1	5	101.6	24.7	31	−20.6	−25
South America	640.9	152.3	24	492.7	4.1	1	148.2	23
Central America	37.3	4.7	13	38.4	5.8	16	−1.1	−3
Eastern Europe	22.7	4.7	21	24.7	6.7	29	−1.9	−8
West Asia	116.3	5.0	4	180.9	69.6	60	−64.6	−56
Global	3235.6	464.6	14	3235.6	464.6	14	0.0	0

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Table 13. The total biomass in carbon (HWPs, crops, livestock) for production, consumption, exports, imports, and the balance (2004). All percentages are relative to the regional production.

	Production			Consumption			Balance	
Region	Production (MtC)	Exports (MtC)	Share (%)	Consumption (MtC)	Imports (MtC)	Share (%)	Balance (MtC)	Share (%)
Africa	617.0	65.5	11	616.0	64.5	10	1.0	0
Oceania	147.5	75.1	51	85.0	12.6	9	62.5	42
East Asia	783.6	158.3	20	804.7	179.4	23	−21.1	−3
South East Asia	364.7	114.2	31	283.7	33.2	9	81.0	22
South Asia	708.8	42.7	6	689.2	23.1	3	19.6	3
Europe	545.8	51.8	9	758.4	264.5	48	−212.7	−39
North America	831.5	125.8	15	882.8	177.0	21	−51.3	−6
Russia	182.3	38.1	21	182.2	37.9	21	0.1	0
South America	846.5	240.9	28	618.5	13.0	2	227.9	27
Central America	53.6	9.6	18	60.5	16.6	31	−6.9	−13
Eastern Europe	53.9	13.0	24	53.6	12.7	24	0.3	1
West Asia	177.6	13.0	7	278.0	113.5	64	−100.5	−57
Global	5312.6	948.1	18	5312.6	948.1	18	0.0	0

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Table 14. A summary of the total and traded carbon associated with different activities (2004). Embodied carbon is emitted in the production of goods and services which are consumed in other countries, while all the other categories are physical flows of carbon. The total biomass includes HWPs, crops, and livestock. The total trade considers international trade between all 112 regions in our analysis, while RECCAP trade considers only the trade between the RECCAP regions.

		Total trade		RECCAP trade	
	Global carbon (MtC)	Traded carbon (MtC)	Share traded (%)	Traded carbon (MtC)	Share traded (%)
Fossil fuels					
Physical carbon	7293	2673	37	2090	29
Embodied carbon*	7427	1661	22	1199	16
Petroleum products	367	183	50	122	33
Biomass total	5313	1322	25	948	18
Livestock	3236	651	20	465	14
Crops	1704	522	31	396	23
HWPs	373	149	40	88	24

* Embodied carbon includes emissions from fossil fuel combustion, cement, and gas flaring and uses the GTAP7.1+NAMEA emission dataset. Thus, the total carbon differs to the total for physical carbon which necessarily uses the GTAP7.1 emission dataset and does not include cement production and gas flaring.

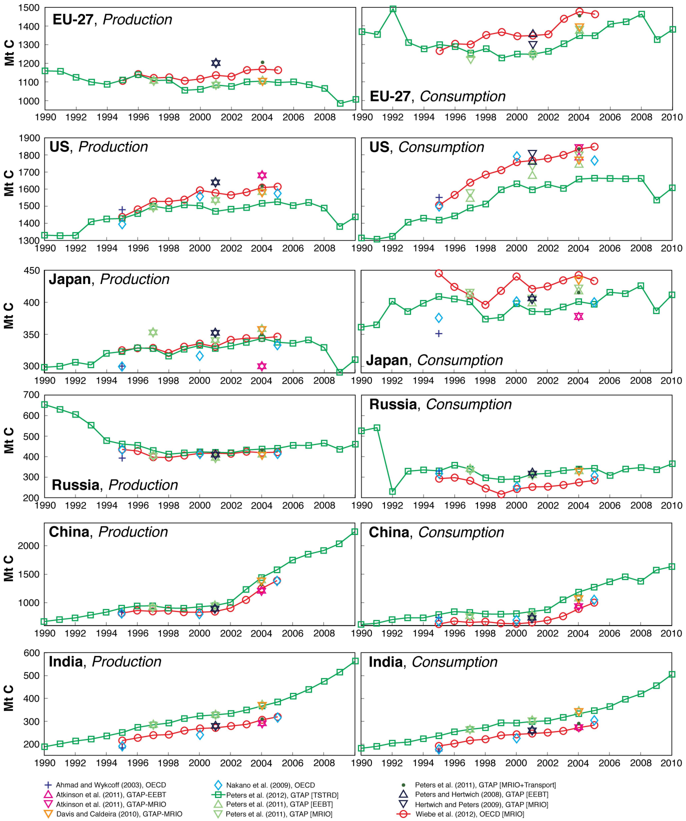

Fig. 1. Comparisons of global models of CO_2 emissions embodied in traded goods and services. Although there is some variation among studies due to differences in the underlying data and modelling methods, the patterns and trends are broadly consistent among all the studies shown.

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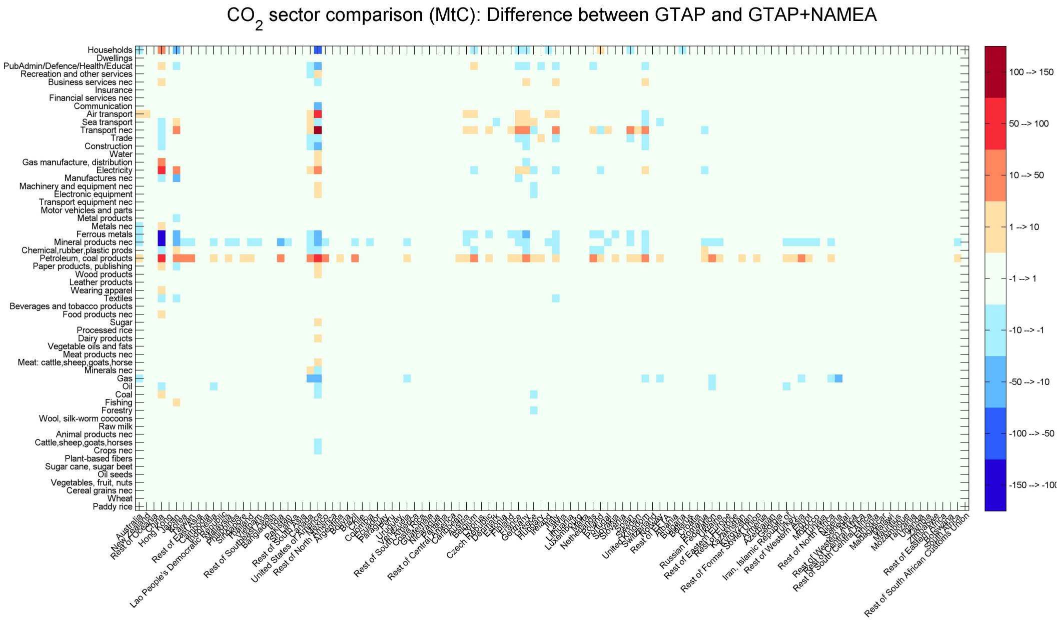

Fig. 2. The difference between the default GTAP CO_2 emission data set and a version which includes (1) national statistics when available (Australia, NZ, China, Japan, USA, Canada, EU27), (2) cement and flaring emissions, (3) adjustments to feedstocks used in the refinery sector. The differences are shown by sector and region and are in MtC for 2004.

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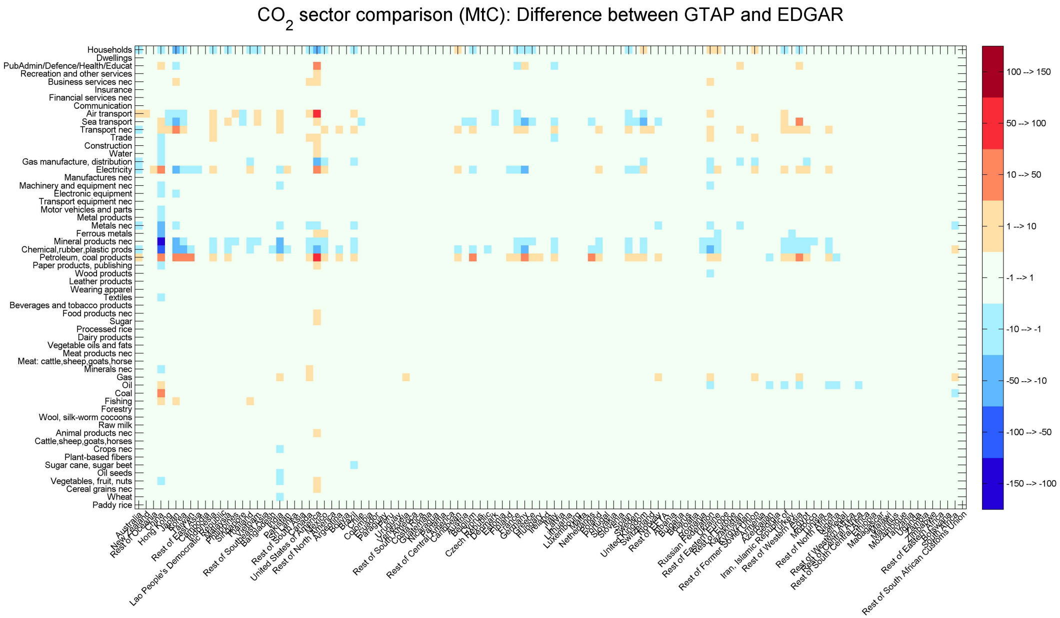

Fig. 3. The difference between the default GTAP CO_2 emission data set and the EDGAR dataset with the sectors reallocated to the GTAP sectors. The differences are shown by sector and region and are in MtC for 2004.

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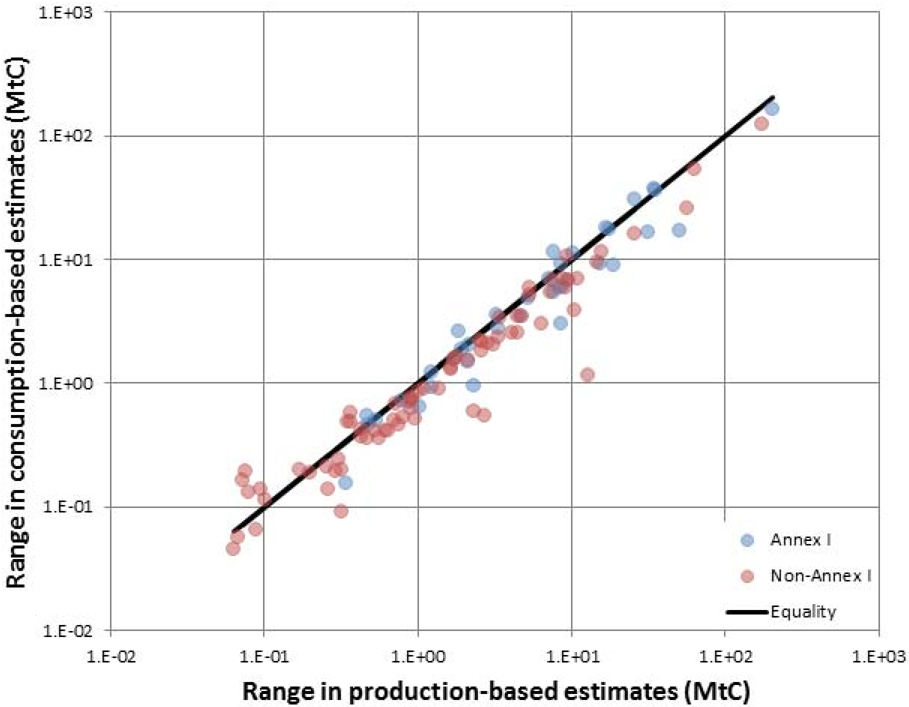

Fig. 4. The range in the production- and consumption-based estimates (2004). The straight line is equal ranges ($y = x$). The consumption-based estimates are, counter-intuitively, more accurate than the production based estimates.

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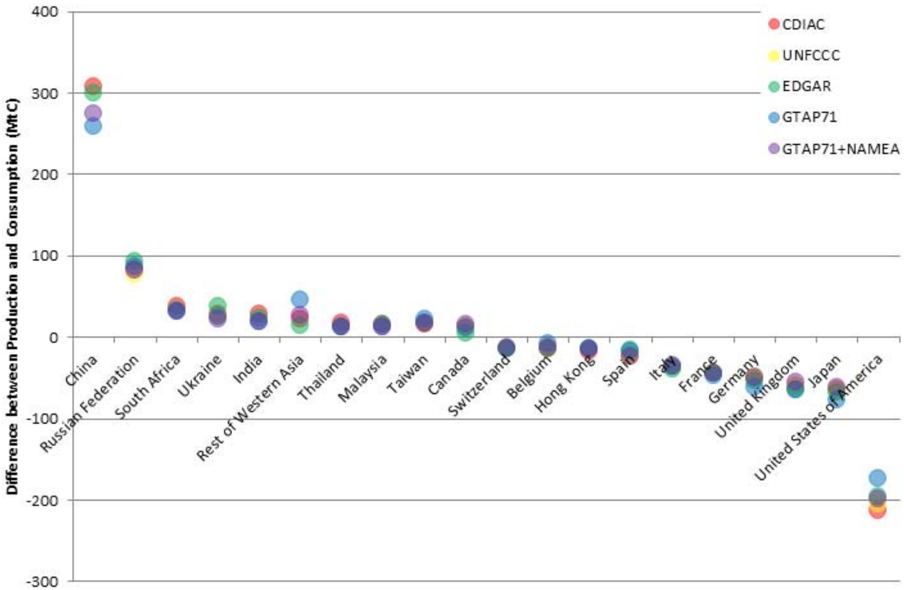

Fig. 5. The difference between Production and Consumption for the 20 countries with the largest differences for the CDIAC database (2004). The results are shown for all the databases. Note that UNFCCC only has values in Annex I countries.

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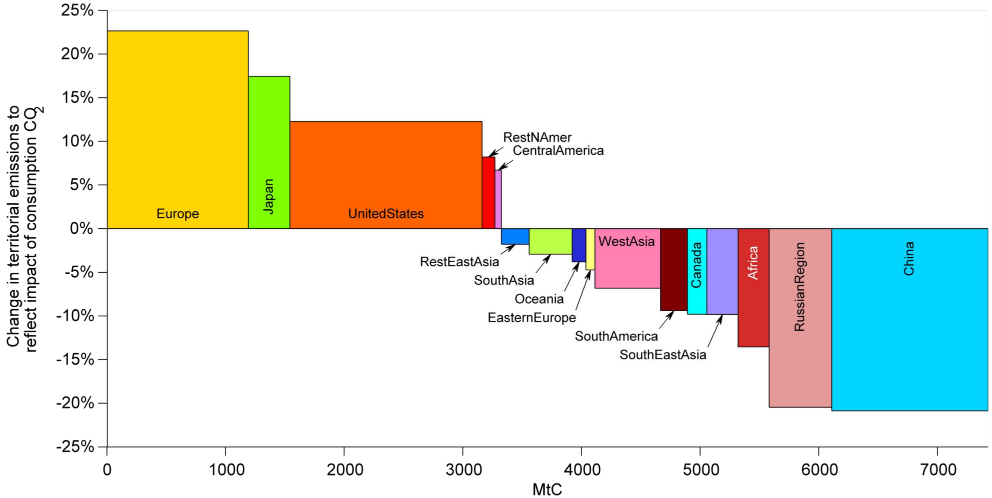

Fig. 6. The change in production-based CO_2 emissions when adjusted to a consumption basis (2004). The horizontal axis shows production emissions, while the vertical axis shows the relative change. This figure disaggregates key regions from the RECCAP region set. In particular, this highlights the significant difference between Japan and China, both in the East Asia region.

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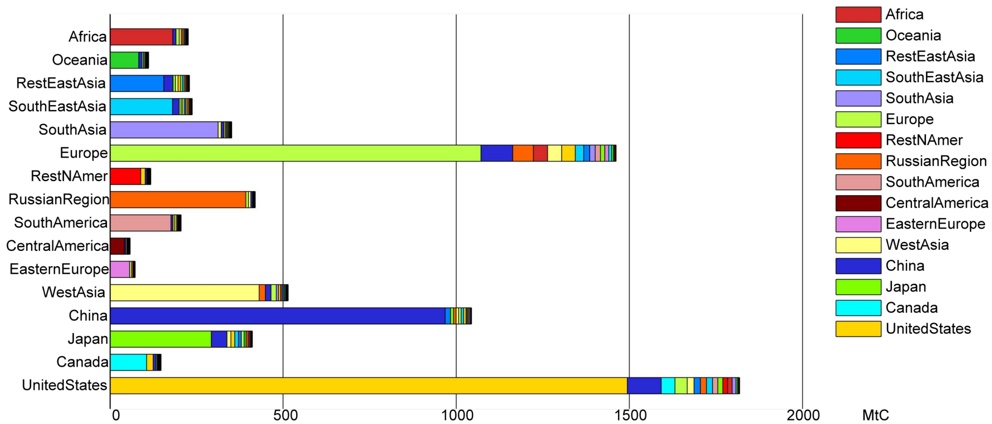

Fig. 7. Consumption-based emissions by region, disaggregating the regions where the emissions occur after adjusting for international trade (2004). Developed regions have a higher proportion of consumption emissions from other regions, and the largest single contributor to imported emissions in developed regions is China.

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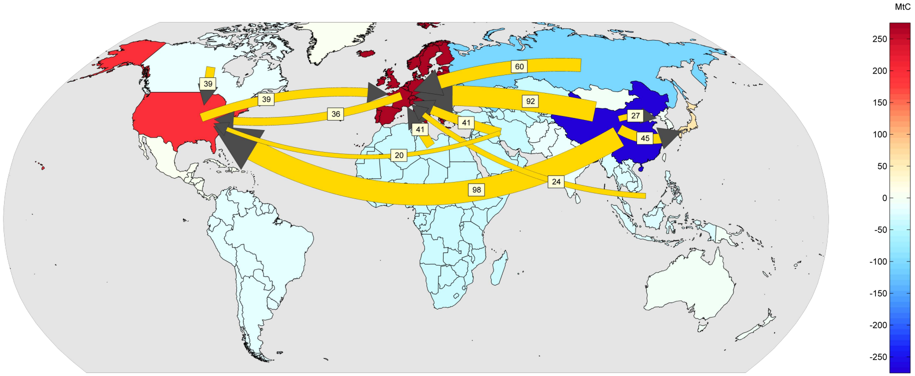

Fig. 8. The 12 largest inter-regional flows of carbon embodied in trade, from origin of emissions to the region of final consumption, with key regions disaggregated (2004). The largest single inter-regional flow is from China to USA (98 MtC). These 12 flows account for 40 % of all inter-regional flows using this grouping.

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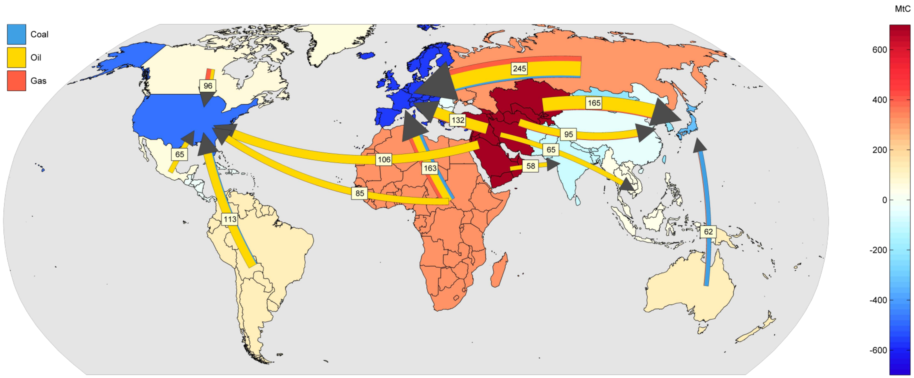

Fig. 9. The top 12 inter-regional flows of fossil-fuel carbon embodied in trade from extracting region to producing region, broken down by primary fuel type, and disaggregated further to highlight key countries (2004). With Japan and China separated, the largest single inter-regional flow is from Russia to Europe (245 MtC), primarily oil and gas. This grouping also highlights that most of the emissions imports to North America are in fact to USA.

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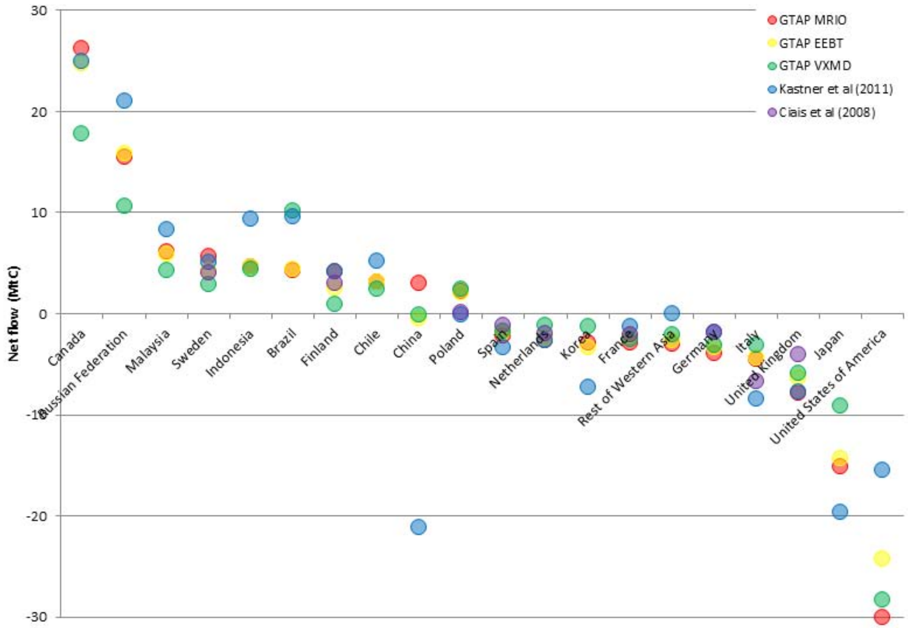

Fig. 10. A comparison of different methods of estimating the trade in harvested wood products (HWPs) for the 20 largest net (exports minus imports) flows (see text). The Ciais et al. results are for 1997, while all other studies are for 2004.

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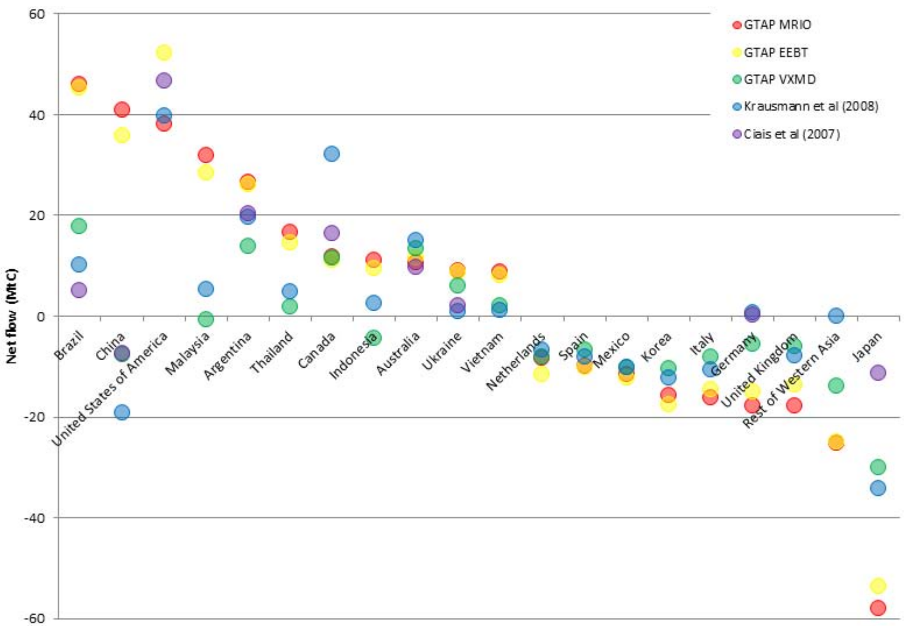

Fig. 11. A comparison of different methods of estimating the carbon trade in crops for the 20 largest net (exports minus imports) flows (see text). The Ciais et al. results are for 1997, Krausmann et al. for 200, and the MRIO, EEBT, and VXMD results are for 2004.

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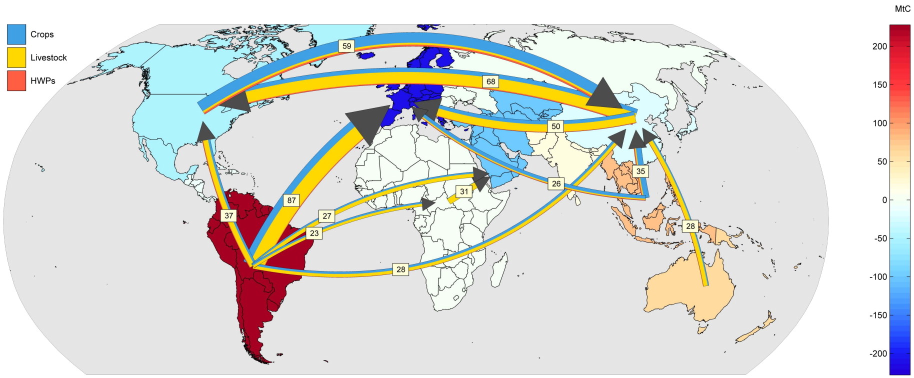

Fig. 12. The top 10 flows for carbon flows in HWPs, crops, and livestock (2004). The region colours represent the net flows out of each RECCAP region (Table 13). The colours of the arrows refer to the different types of carbon flows; for example, the flow from Brazil to the EU27 is dominated by livestock, while the flow from North America to East Asia is dominated by crops.

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