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# Consumption-based carbon accounting: sense and sensibility

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## 1. Introduction

This Editorial serves as an introduction to this special supplement on consumption-based carbon accounting. Due to globalization, growth in trade has outpaced growth in global GDP. As a consequence, carbon emissions related to consumption of a country increasingly take place abroad. Consumption Based Carbon Accounting (CBCA) offers an alternative to the dominant production perspective on carbon emissions, where producers of carbon emissions are seen as fully responsible for these emissions. The production and consumption-based perspectives are two extremes along a continuum, and there are various approaches to allocate responsibilities for carbon emissions. As a first step, this introduction reviews various accounting approaches for allocating responsibility for carbon emissions. We then discuss briefly how this relates to the options and possibilities that different actors in the production-consumption system have to mitigate carbon emissions. From there, we define a number of research questions that are answered by the papers in this special supplement and summarize the findings of these papers.

Since the 1980s, with the advent of trade liberalization and globalization, global trade started to grow considerably more than the global GDP (Peters, Minx, Weber, & Edenhofer, 2011a). Only recently has this relative growth in trade levelled off (Wood et al., 2020a). It is not uncommon for imports and exports in small countries to constitute around 50% or more of their GDP. Even for medium sized economies, trade flows make up a significant part of their GDP.

Traditionally, monitoring of environmental pressures like carbon emissions and resource extraction by sector is done at a national level (e.g. PBL, 2018), or in the case of the EU by a joint agency (EEA, 2015). The simple rationale for this is that National Statistical Institutes (NSIs) or environment agencies only have a legal mandate to inventory data on economic transactions, emissions and resource use within the country in which they have been established. The indicators produced by these agencies are seen as policy-relevant by policy makers who similarly have a legal mandate only over their own sovereign territories. However, there is a feedback effect as well; the policies implemented tend to reflect the indicators that are produced, and hence there has so far been a policy focus on production within national boundaries.

Given the large amount of products that may enter and leave countries through trade compared to domestic production, this traditional territorial environmental accounting has become insufficient for various reasons. It fails to understand how production in a country drives impacts elsewhere via the use of exported goods or how consumption in a country drives impacts elsewhere via the use of imported goods (e.g. Lenzen, Kanemoto, Moran, & Geschke, 2012; Peters et al., 2011a). Or, otherwise stated – due to trade and globalization, one can have different perspectives on who is responsible for the emissions and resource extractions within a specific country.

Assessing such impacts that are driven by trade (being imports or exports) poses its own statistical problems. Since data on economic activity, emissions and resource extraction are usually compiled at a national level, there is (with one recent exception) no related coherent official data set at the global level. Since around 2005, scientists have started to compile databases that would allow for the assessment of pollution embodied in trade (Ahmad & Wyckoff, 2003; Hertwich & Peters, 2009; Lenzen et al., 2012; Tukker et al., 2009). Various methods for this were developed (for an overview, see Tukker, Wood & Giljum, 2018). These include methods that combine detailed trade data with coefficients for resource extraction and emissions (e.g. Hoekstra & Mekkonen, 2012; Schoer, Weinzettel, Kovanda, Giegrich, & Lauwigi, 2012), and the construction of Global Multi-Regional Input Output tables with environmental extensions (GMRIOs; see for a review Tukker & Dietzenbacher, 2013). Box 1 illustrates the basic approach to GMRIO calculations, which have now become the method of choice for allocating environmental responsibilities to actors in global value chains, for several reasons.

First, GMRIOs provide a consistent picture of the global economy and show how the inputs and outputs of economic sectors are linked within and between countries via (global) trade. Second, emissions and resource extraction by sector and country form the basis of any subsequent calculation that allocates responsibilities to actors. This implies that total global resource extraction and emissions are always allocated – hence, the allocated responsibilities by definition add up to the global total. Third, due to this consistency, GMRIOs are excellently suited to allocating environmental responsibilities with regard to different resource uses and emissions. Finally, GMRIOs are capable of truly following the full downstream and upstream value chain across different countries, whereas coefficient approaches assume that impacts related to imports or exports fully occur in the country of destination or origin. [1] However, consolidating and harmonizing individual country input-output tables (IOTs) and trade data into a GMRIO is time consuming, even with a high level of automatization or the use of virtual laboratories (e.g. Lenzen et al., 2014; Stadler et al., 2017; Tukker & Dietzenbacher, 2013). Due to asymmetries in trade data, the sum of country IOTs are not balanced at the global scale. Hence, GMRIOs need to adjust the official country IOTs a little. To date, just five GMRIOs have been constructed, mainly by researchers outside national statistical systems (see Table 1). The exception is the very aggregated Inter Country Input Output (ICIO) of the OECD.

**Table 1**. Characteristics of existing GMRIOs (Tukker & Dietzenbacher, 2013; Tukker et al., 2018). (Table view)

| No | Name | References and characteristics |
|---|---|---|
| 1 | Eora | Lenzen et al., (2012); sector detail varying from 25 to 500; about 180 countries |
| 2 | EXIOBASE | Tukker et al., (2013); Wood, Hawkins, Hertwich, & Tukker, (2014, 2015); Stadler et al., (2017); 200 products, 160 industries, 48 countries/regions |
| 3 | WIOD | Dietzenbacher, Los, Stehrer, Timmer, & de Vries, (2013); 35 sectors, 40 countries plus 1 Rest of World |
| 4 | GTAP-MRIO | Peters, Andrew, & Lennox, (2011b); 57 sectors, 140 countries/regions |
| 5 | ICIO (Inter-country Input Output table) | OECD, 2015; 34 sectors, 64 countries/regions. Previously, researchers used OECD IO data to build an early GMRIO called GRAM (Bruckner, Giljum, Lutz, & Wiebe, 2012; Wiebe, Bruckner, Giljum, & Lutz, 2012; Wiebe, Bruckner, Giljum, Lutz, & Polzin, 2012; 48 sectors, 53 countries/region) |


**Figure 1**. Example of a MR EE IOT for three regions.

Multi-regional Computable General Equilibrium (CGE) and structural macro-econometric models also incorporate GMRIOs, often using the same sources. The models link the accounting framework provided by the GMRIOs to a set of dynamic behavioural relationships that can provide both projections of future trade and industry interlinkages and also responses to policy stimuli through scenario-based analysis. The disadvantage is that the models tend to operate at a slightly lower level of sectoral detail because of the additional complexity added by the dynamic relationships.

This special supplement has used various forms of the aforementioned GMRIOs and dynamic models to assess climate mitigation policies from various perspectives, most notably the producer and consumer perspective. It reflects the work done by an international consortium that performed the Carbon CAP (Consumption based Carbon accounting and Policy) project funded by the EU's 7th Framework Programme. The title of the project indicates it set out to develop consumption-based carbon accounting methods, which are now widely seen in the literature as an essential alternative to the dominant production-based approach (Davis & Caldeira, 2010; Hertwich & Peters, 2009). Yet, since there are various other approaches to allocate responsibilities for carbon emissions, we feel it is relevant to investigate if the new emphasis on consumption-based approaches is not going too far. When does consumption-based accounting make sense? When are other approaches sensible? Hence, we will first review accounting approaches to allocate responsibilities for carbon emissions, that is, addressing the question: 'who is responsible for what?'. We then review how such accounting approaches relate to mitigation efforts and policies, that is, addressing the question 'who is in principle best placed for which mitigation effort?'. This leads to a number of research questions, to which the papers in this special supplement contribute. We summarize the contributions of these papers, followed by overall conclusions.

## 2. Consumption versus production: to whom can responsibility of carbon emissions be allocated?

Responsibility for emissions and resource use can be allocated in different ways across actors along (global) value chains. In the last 10–15 years, some four main allocation principles have been developed, along with mixes of these (e.g. Gallego & Lenzen, 2005; Kander, Jiborn, Moran, & Wiedmann, 2015; Lenzen, Murray, Sack, & Wiedmann, 2007; Lenzen & Murray, 2010; Marques, Rodrigues, Lenzen, & Domingos, 2012; Rodrigues, Domingos, Giljum, & Schneider, 2006; Steininger, Lininger, Meyer, Munoz, & Schinko, 2016).

Probably the most used one is the *production-based* approach. Here, in line with the *polluter pays* principle, emissions and resource extraction are seen as the responsibility of the actor who operates the economic (production) process that creates these emissions or extracts these resources. At country level, NSIs or Environment Agencies typically report the emissions and resource extraction from within their country's borders, which reflects a production-based approach at country level. The production-based approach is at the basis of international carbon accounting systems (UNFCCC, 2008) and efforts aiming at mitigation of carbon emissions such as the Paris Agreement (UNFCCC, 2015).

The focus on production-based mitigation led to an obvious critique: countries could lower their emissions by outsourcing carbon-intensive industries, importing the related products, and focus on value added creation by less polluting activities. For instance, the territorial emissions of the UK diminished from 1991 to 2004, while the impacts of satisfying UK consumption rose in the same period (Wiedmann et al., 2010), a pattern typical for developed countries (Davis & Caldeira, 2010; Hertwich & Peters, 2009). This led to the suggestion that a *consumption-based* approach that assesses the life cycle emissions and resources involved in satisfying final consumption should complement production-based assessments, in order to indicate if such burden shifting could be at work. This approach reflects by and large the *user pays principle,* which calls upon the (final) user of natural capital to compensate for loss of such natural capital (UN, 1997).

Another suggested accounting method is the *extraction-based* approach. This approach reasons that $CO_2$ emissions are ultimately generated by the use of fossil fuels, and hence that allocating these emissions to the producers that gain an income from the extraction and sale of fossil fuels provides useful insights. Related to this is the more general *income-based* approach that, in line with the principle of *producer responsibility*, allocates downstream emissions enabled by the sales of the product to the producer (or income receiver) of that product (e.g. Liang, Qu, Zhu, Guan, & Xu, 2017; Marques et al., 2012). In essence, downstream emissions are allocated according to earlier steps in the value chain according to the value they add in production (c.f. Steininger et al., 2016).

The last accounting method is the *value-added-based* approach. Consumption-based emissions of final consumption are allocated to earlier steps in the value chain according to value-added. The rationale for this approach is that it gives insight into who obtains most financial benefits from such life-cycle emissions. In line with the *beneficiary pays principle* (e.g. Steininger et al., 2016; closely related to the *ability to pay principle* (e.g. Caney, 2010)), such actors are seen as financially most able to support and contribute to emission mitigation (Lenzen et al., 2007; Pinero, Bruckner, Wieland, Pongracz, & Giljum, 2018).

As argued by Steininger et al. (2016), it is not possible to identify one actor that can be held causally responsible on its own. Carbon emissions are emitted by producers and/or product users, enabled by extractors and income earners, and driven by final consumers, while virtually all actors along the value chain benefit via the creation of value added. This insight has led to proposals for mixed approaches in which some form of responsibility sharing is suggested. Rodrigues et al. (2006) and Qian, Behrens, Tukker, Rodrigues, and Scherer (2019) use the average of consumption-based and income-based emissions. Kander et al. (2015) propose a 'technologically corrected' consumption-based approach. In their view, the consumption-based approach gives exporters no incentive to use clean technologies, since embodied impacts in their exports end up with final consumers abroad. They therefore propose to reward countries that export products with embodied emissions that are lower than the average embodiments in world trade for that product, by subtracting this difference.

GMRIOs with environmental extensions are fully capable of addressing these allocation perspectives, summarized in Table 2 with the same, consistent data set. Production-based emissions and extractions are directly given by sector and country as extensions. Consumption-based emissions can be calculated via the Leontief inverse. Value-added-based emissions are calculated by splitting up consumption-based emissions according to value added by sector/country, information that is also an integral part of a GMRIO. Income-based emissions and extractions can be calculated via the Ghosh inverse. For more complete technical descriptions of the calculation approaches, we refer to e.g. Rodrigues et al. (2006), Kander et al. (2015), Pinero et al. (2018) and others.

**Table 2**. Summary of approaches for allocating environmental impacts along value chains to actors operating in these value chains. (Table view)

| Type | Principle in short | Illustrative references |
|---|---|---|
| Production-based | Emissions generated during production. Responsibility is fully allocated to producers of goods and services where they occur in the value chain | UNFCCC, (2008) |
| Consumption-based | Emissions generated for satisfying consumption. Responsibility of life cycle emissions is fully allocated to final consumers of goods and services | Hertwich and Peters (2009); Peters et al. (2011b); Davis and Caldeira (2010) |
| Extraction based | Emissions related to the full life cycle of extracted resources. Responsibility is fully allocated to those who extract a resource. Usually focused on fossil fuels. | Davis, Peters, and Caldeira (2011); Steininger et al., (2016) |
| Income based | Emissions in the downstream value chains of products and services put on the market. Responsibility is allocated to the supplier of inputs to polluting production processes (according to the ratio of monetary value of intermediate and primary inputs flowing into that process). | Marques et al., (2012); Liang et al., (2017) |
| Value-added-based | Emissions related to the share of value added over the life cycle. Responsibility for consumption-based emissions is allocated according to value added created per step in the value chain | Lenzen et al., (2007); Pinero et al., (2018) |
| Mixes of the above | Average of consumption-based and income-based emissions | Rodrigues et al., (2006); Qian et al., (2019) |
| | Average of consumption- and production based footprint weighted on the basis of the Human Development Index (HDI, dubbed 'just footprint') | Oliveira (2020) |
| | Technology adjusted consumption-based: As consumption-based, but emissions embodied in exports of producing countries can be in part allocated positively or negatively to the producing country. If a sector in a country produces surplus emissions above the global average, such surplus emissions embodied in exports are allocated to the producer. If sector emissions are below the global average, these lesser emissions embodied in exports are subtracted from the producer. | Kander et al., (2015) |

All of the approaches above can be executed with various refinements, such as:

1. *The allocation of economic actors to countries.* This allocation can be done via the territorial principle and the residential principle (Usubiaga & Acosta-Fernández, 2015). In the first case, the impacts are allocated to the country where the actor produces, generates income or added value, or consumes, independent of nationality. In the second case, such impacts are allocated to the country where the actor resides, even if the action causing the impacts takes place outside this country.
2. *The allocation of emissions related to the use of (international) bunker fuels.* Bunker fuels related to international shipping or air transport are sometimes simply neglected, since in all approaches, some kind of allocation is necessary, for which data may be lacking (Davis & Caldeira, 2010). Bunker fuels present in a specific country are usually used by ships or airplanes registered or travelling to another country, so even in a production-based approach, emissions from bunker fuels should not be allocated to the country in which the bunker is physically located. In all of the other approaches, the (international) transport emissions are to some extent allocated to the goods or people transported (cf. Hu, Wood, Tukker, Boonman, & de Boer, 2019).
3. *The allocation of embodied emissions of capital formation.* In production-based accounts, the emissions related to capital formation are obviously allocated to the sector and country that produces the capital. However, in other approaches, one has the option to allocate emissions embodied in capital to the sector and country that uses this capital. There are two ways of doing this. First, the impacts embodied in capital formation in a specific year are directly allocated to the economic sector using them (e.g. Huppes et al., 2006; Södersten, Wood, & Hertwich, 2018). Second, a vintage approach can be used that allocates impacts embodied in capital produced in the past to current economic production according to depreciation of this capital stock (Chen et al., 2018). Note that, in this vintage approach, emissions (and resource use) embodied in capital production in year x will be allocated to another year. This implies that simple consistencies, such as that production-based emissions and resource use by definition equal consumption- or income-based emissions, cannot be maintained. Most consumption-based studies, however, neglect such allocation of impacts embodied in capital to industry sectors, and hence neglect that part of this capital is used to produce exported goods. This may lead to an over- or underestimation of consumption-based emissions of countries.
4. *Using a time frame that goes beyond the usual annual cycle in regular accounting systems.* Cumulative historical emissions (via any of the approaches) give insight into the extent to which an actor or country is responsible for using a total emission budget. Such information can be used to determine what remaining emission budget can be allocated to them (e.g. Frumhoff, Heede, & Oreskes, 2015).

## 3. Consumption versus production: what actionable mitigation strategies do actors have?

The different accounting approaches point to different actors and related actions to pursue climate mitigation (see Table 3 for a summary).

**Table 3**. Summary of typical reduction actions by accounting perspective. (Table view)

| Type | Target group | Typical reduction mechanism that is supported |
|---|---|---|
| Production-based | Producers | Reduction of the direct emissions and resource use in the sector or plant, e.g. supported by policies implemented via permits, Best Available Technology standards, etc. |

| Type | Target group | Typical reduction mechanism that is supported |
|---|---|---|
| Consumption-based | (Final) consumers | Shift of expenditure to low-impact products and services (between product categories; or selecting the cleanest supply chain within a product category), e.g. supported by sustainable procurement guidelines, environmental taxation, border tax adjustments, or sustainability labels. |
| Income-based; extraction-based | Sellers: Earners or extractors | Taking producer responsibility – designing products and services in such a way that downstream impacts are minimal, e.g. by eco-design criteria, producer responsibility schemes, etc. |
| Value-added-based | All actors in a value chain | Identifying who has most financial gains in the value chain, and as a consequence, who can finance best to reduction of emissions and resource use over the life cycle. In theory a carbon value added tax could be of support here, but in practice this will be difficult to implement due to the fact that value chains cross many borders. |

### 3.1. Actions related to production-based accounting

As indicated, the production-based approach identifies the most important direct emitters. Following the polluter pays principle, such emitters are expected to reduce emissions. Typically, this implies implementing technologies using renewable energy, enhancing energy efficiency, reduction of emission factors (e.g. by fuel switching, or carbon capture and storage) or implementing cleaner technologies. But if such actions cannot be done in a cost-neutral manner, policy has to provide a level playing field so that even if the actor cannot finance the costs from own profit or value added, that actor can pass costs on to other actors in the value chain, since competitors have to implement similar stringent mitigation measures at probably similar costs. An important limitation of the production-based approach is that it neglects the influence an actor could exercise over its supply chain and related emissions, or the emissions enabled by products produced out of sight in the downstream chain.

### 3.2. Actions related to consumption-based accounting

Consumption-based accounting helps final or intermediate consumers to identify the impacts in the supply chains of their purchases. Typical mitigation options highlighted by this approach include the following. First, actors could try to help suppliers to improve their environmental performance, or shift to low-impact suppliers of the same (final or intermediate) products (e.g. de Boer, Rodrigues, & Tukker, 2019). Second, actors could shift expenditure to alternative low impact products or services that provide a similar functionality. Third, actors could refrain from purchasing products with high impact supply chains and shift expenditure to low-impact products and related activities. Finally, actors could simply reduce purchases of products overall. Such approaches are greatly helped by transparency on the environmental impacts of products (e.g. via labelling) but may not always be realistically possible. Users of intermediate goods, in particular, have less freedom since they need such intermediate inputs for the production of other materials, products or services. Changing inputs can only work if the process or product design is changed, and inputs (apart from possible reduction by efficiency gains) are driven by the level of production. An important limitation of the consumption-based approach is that, particularly for intermediate users that produce other material or product output, it neglects the downstream life cycle impacts of this material and product output.

### 3.3. Actions related to extraction-based and income-based accounting

Extraction-, and in broader sense income-, based accounting gives producers of products and materials insight into the downstream environmental impacts of their sales/product output. In line with the concept of producer responsibility, this may help such producers to design their products and services in such a way that (particularly downstream) life cycle impacts are minimized. Examples are eco or circular design of products, or offering product-service systems (PSS) instead of products that leave the total cost of ownership with the actor offering the value proposition. With the costs in the use phase now the responsibility of the producer, the producer has an incentive to design products that have long life, can be easily repaired, and do not use a lot of energy or consumables in the use phase (Stahel, 2016; Tukker, 2015). This approach does not reflect the mitigation potential of production or consumption choices, however. It also may be difficult to implement for producers who have limited flexibility in changing their value proposition. To put it simply, a coal mine or oil firm generates income by selling fossil fuels, and usually does not have the flexibility to reduce such sales and embark on a totally different business.

### *3.4. Actions related to value-added-based accounting*

Value-added-based accounting to some extent gives interesting insights into who generates most benefits in the existing production system. However, unlike the accounting approaches discussed earlier, it does not point clearly to a way in which actors could reduce emissions or impacts in general. It does point to some extent to who currently owns the finances to pay for emission reductions, but that seems of limited value. Value added includes elements such as wages of employees and depreciation/replacement investments in capital, which are financial expenditures for the producer. One could question whether profit, rather than value added, should be used as a measure for the ability to contribute to emission mitigation.

Furthermore, in most cases, carbon mitigation (be it via the producer, consumer or income perspective) does not constitute an economic-environmental win-win. This implies that mitigation has to be driven by policy measures (e.g. regulations on performance characteristics, best available technology standards, emission caps; financial instruments such as emission trading schemes; or informative measures like labelling). Such measures, particularly in the case of regulatory and financial instruments, are intended to force actors to invest in carbon mitigation, leading to a different structure of the value chain and changes in the distribution of value added. Indeed, it is such dynamic analyses of the impact of measures on value added that is usually of interest, not how carbon emissions can be allocated to actors according to value added. The value-added-based approach hence at best identifies who currently has the most to lose from measures, and who may have least capacity to invest in mitigation (a factor relevant in the discussion on 'common but differentiated responsibilities and respective capabilities', typically indicating that developing countries have less historical responsibility for the current climate problem, and usually have less capabilities to reduce their emissions).

To conclude, different accounting perspectives support different mitigation strategies. This also implies, as concluded earlier by Steininger et al. (2016), that there is not one superior accounting approach. Particularly the production, consumption and income-based approaches are useful to be used side by side, since mitigation efforts via one perspective may create a (negative) trade-off that can only be detected via one of the other perspectives. Reducing production-based emissions by outsourcing production to others, and by this maybe enhancing emissions from a consumption-based perspective, is the classic example. But an equally relevant example would include producers that put low quality, cheap-to-make products on the market. They then probably have low impacts in their own production or supply chains. But such products may have inferior performance in the use and waste phase such as short life times, a high use of energy and consumables, low recyclability, etc. Figure 2 summarizes how different accounting approaches relate to different mitigation strategies, along with illustrative measures a firm or industry sector could take with regard to its purchases, production, and value proposition put on the market.

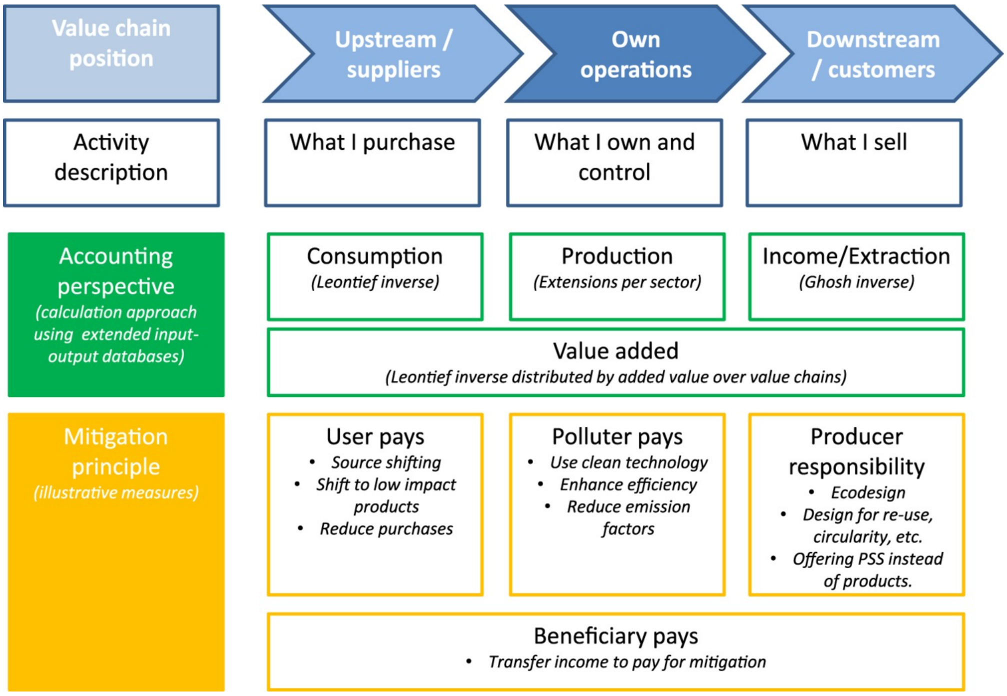


**Figure 2**. Perspectives on carbon accounting and related mitigation principles in relation to position in the value chain and sphere of influence of economic actors. In part inspired by work of a Greenhouse Gas Protocol Technical Working Group, as available as Figure 4.1 in WRI and WBCSD (2009, p. 15).

## 4. Key questions on CBCA and contributions of the papers in this special supplement

The Carbon CAP project focused on consumption-based carbon accounting. From the four main accounting approaches and mitigation strategies discussed above, it hence focused most on the consumption-based, and to a lesser extent the production-based approaches, while hardly looking at the other approaches such as the income-based or value-added-based approaches. The Carbon CAP project focused on a number of research questions, of which the following are highlighted in this special supplement.

First, while a large number of papers have analysed carbon emissions from a production- and consumption-based perspective (eg Davis & Caldeira, 2010; Hertwich & Peters, 2009), it is interesting to see how greenhouse gas (GHG) emissions of the EU28 have changed over time. Against this background, Wood, Neuhoff, Moran, Simas, and Stadler (2020b) analyse how production-based carbon emissions and carbon footprints of the EU changed between 1995 and 2016 and the implications of sectoral results for policy. Whilst the carbon footprint of the EU remains higher than the EU's production-based emissions, the carbon footprint has reduced faster than production-based emissions since peaking in 2008. A relative decoupling of both indicators from GDP took place, mainly driven by technology improvements both in the EU and abroad. The sectoral results point to areas where consumer focussed policy could be most effective (housing, including embodied impacts, services, transport, etc), and conversely where producer or supply chain policy could be most effective due to trade and questions of statutory responsibility (agriculture, mining, and to some extent manufacturing).

Second, while there is no doubt that the EU went through a strong period of growth of emissions embodied in imports as the engine of China took off after joining the World Trade Organisation, the question arises as to whether trade is going to be an increasingly important consideration for climate policy. To analyse this point, Wood et al. (2020a) looked at historical carbon emissions in trade and used the E3ME (Energy-Environment-Economy Macro-Econometric) model to model future global carbon emissions, including emissions embodied in trade, under a baseline and a nationally determined contribution (NDC) scenario. They find that emission transfers between OECD and non-OECD countries peaked in 2006, and declined afterwards. Large improvements in the overall carbon efficiency of trade in the mid-2000s overtook the growth in trade volume, resulting in the emissions embodied in imports for the EU plateauing, as seen in that paper. The forward-looking modelling results suggest that embodied emissions in absolute terms will plateau at current levels or even drop to the levels before the 2008 economic crisis. Given that, under the Paris Agreement, developed countries are expected to reduce territorial carbon emissions more aggressively than developing countries (which often aim for relative decoupling from GDP growth, rather than absolute reductions), emissions embodied in trade will, in relative terms, become a larger share of consumption-based emissions, posing further challenges to reducing the EU carbon footprint without significant international cooperation.

This last finding indicates, as a third point, that the consumption-based perspective remains relevant. Against this background, Moran et al. (2020) modelled a large portfolio of mutually exclusive actions that help to reduce emissions from a consumption-based perspective (e.g. 'use carpooling', 'turn room thermostat down 1 degree', and 'reduce food waste'). The paper employs a hybrid approach that uses bottom-up information on the life cycle of products and the GMRIO EXIOBASE (Wood et al., 2017). With a reasonable level of adoption of these options, a reduction of the EU's carbon footprint of 25% could be realized. Of these reductions, 75% are territorial emission reductions in Europe, while 25% relate to a reduction in emissions embodied in the EU's imports.

While this paper hence shows the considerable potential of climate mitigation via consumption-based actions, such measures usually are not taken automatically. Reduction options may be more expensive then business as usual, inconvenient, and so on. Grubb, Crawford–Brown, Neuhoff, and Shanes (2020) therefore analysed which policy portfolios would ideally be put in place to effectively support mitigation actions from a consumption-based perspective. They conclude that influencing consumption is politically sensitive and complex. Promising instruments include sustainable procurement (not only by government, but also retailers), a carbon-intensive materials consumption charge, and infrastructure improvements, next to novel instruments such as standards on embodied carbon, and positive environmental goods and services trade agreements favouring products with low embodied carbon. Pollitt, Lin, and Neuhoff (2019) further modelled the impact of one of these proposed policy instruments, namely a consumption charge on carbon-intensive materials. Basic materials account for around 25% of global carbon emissions. The E3ME model is used in the analysis. The modelling shows that a charge of about 80 Euro per ton of $CO_2$ could reduce the EU's (production-based) carbon emissions by about 10% by 2050. The charge creates incentives for resource-efficiency and substitution, and leads to a slight GDP increase and a minor reduction in employment.

All these results indicate that analysing climate mitigation from a much broader perspective than just the production-based approach is highly relevant. While this special supplement mainly focused on the consumption-based perspective, it is likely that an income-based perspective will also highlight less traditional routes to carbon mitigation. The consumption-, income- and value-added-based perspectives, however, require a more complicated carbon accounting system than the production-based approach. Not only would the direct emissions per economic sector have to be monitored, but also the relations between economic sectors in all countries globally in terms of purchases and sales of (intermediate) products and services along global value chains, as indicated in the first section of this editorial, typically in the form of a GMRIO table. There is genuine fear that this would lead to significant additional uncertainty that may hamper the use of consumption or income-based perspectives as a basis for future climate policies and/or negotiations. Tukker, Schmidt, and Wood (2020) hence set out to investigate such uncertainties and how these can be handled or minimized. An encouraging and important finding in this work is that, also in consumption-based accounting, the source used for (production-based) carbon emissions appears to create most uncertainty in carbon footprints at country level. Harmonizing production-based carbon emission databases therefore remains the top priority. This is followed by the structure of the national economy in a MRIO database – where uncertainty can be minimized by staying as close as possible to the Input-Output (IO) table provided by a country's NSI – and only then by trade. In the ideal case, NSIs of the largest economic blocks would harmonize their IO and trade statistics, a process already under way at EU level and supported at global scale by the OECD.

## 5. Conclusions

Climate policy has a long history in which production-based emissions and mitigation options have played a central role in analyses and policy approaches. Around 2000, however, the first studies appeared suggesting that such a production-based approach did not capture an important development: the outsourcing of high impact production processes from developed countries and related growth of international trade, leading to a situation whereby for many developed countries, the life cycle impacts of consumption in the country concerned now take place abroad, and are higher than the production-based impacts in the country. This insight led to the conclusion that other accounting approaches had to complement the production-based approach. At this point in time, several main accounting approaches can be distinguished in the literature, i.e. the production-based approach, the consumption-based approach, the income-based approach and the value-added-based approach, along with mixes thereof.

Particularly the production-, consumption and income-based approaches provide clear points of departure for different kinds of mitigation approaches. The production-based approach concerns options for direct emission reductions in economic sectors. The consumption-based approach identifies where in supply chains emissions take place and can be reduced, e.g. by source shifting. The income-based approach looks to the downstream uses of products and services produced, and can identify how measures such as producer responsibility, circular or low carbon design of products, can reduce impacts during use or waste management. Each of these accounting approaches therefore has its own merits and blind spots. This implies they are best used side by side instead of trying to determine which method would be superior. Environmentally extended IO tables are capable of calculating carbon emissions via each of these perspectives with the same, consistent data set.

This special supplement mainly focused on the consumption- and to a lesser extent the production- based approach for carbon accounting and policies. Work in this supplement confirmed the significant rise of carbon embodiments in trade, but also that this phenomenon peaked around 2006 and is currently levelling off. Modelling of a baseline and NDC scenario showed that embodiments in absolute terms will stay stable or slightly reduce, but will become more important as a share of national carbon footprint when direct emissions in developed countries are aggressively reduced. This implies that consumption-based mitigation will keep on having added value in the future. Findings in this supplement indicate that implementing consumption-based mitigation options can reduce Europe's carbon footprint by 25% by 2050. A consumption charge on carbon-intensive materials of 80 Euro per ton of $CO_2$ would incentivize resource efficiency and substitution of such materials, leading to a 10% reduction in Europe's carbon footprint. The last example already indicates that clear policies are needed to support such consumption-based mitigation options, including sustainable procurement, infrastructure improvements, standards on embodied carbon, and positive environmental goods and services trade agreements favouring products with low embodied carbon. In all cases, priorities and policies have to be supported by robust databases that can be used in the accounting approaches discussed above. GMRIOs with carbon extensions are the obvious accounting method to use. Interestingly, in both production- and consumption-based accounting, the factor contributing most to uncertainty is actually the emission data in the model. The uncertainty added by the GMRIO context is not as big. If NSIs and international organizations like the OECD or the UN Statistical Division were to expand ongoing harmonization efforts, it should be perfectly possible to use accounting methods other than the production-based approach as additional perspectives in international platforms where climate policies are discussed.

## Notes

1. Land use and water extraction tends to be mainly related to primary food production. For calculating land and water footprints, coefficient approaches are still often used (e.g. Hoekstra & Chapagain, 2007; Hoekstra & Mekkonen, 2012) since this takes the full advantage of the fact that trade statistics are much more detailed as GMRIOs, and the assumption that the agricultural product is fully produced in the country of origin usually holds (compare also Weinzettel, Steen-Olsen, Hertwich, Borucke, & Galli, 2014).

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