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Sharing carbon responsibility in the global value chains: a value-capturer responsibility principle

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Abstract

The rise of global value chains indicates ever growing international fragmentation of production. A lot of products now have been produced in global supply chains involving many countries. The present article argued that all producers engaging in production sharing should also share their environmental responsibility for environmental impacts of the global value chains. Combining the basic idea of ‘beneficiary pays’ and the ‘ability to pay’ principles, we propose a value-capturer responsibility (VCRP) principle for responsibility allocation among producers in the supply chains, according to which the environmental responsibility of a producer participating in producing a specific product (group) is proportional to its share of captured value from that product (group). Based on dataset from the World Input-Output Database, we calculated emissions inventories for major economies under VCRP in the period of 1995-2009 and compared them to inventories under producer responsibility principle, consumer (upstream) responsibility principle, and downstream responsibility principle. The results show that, compared to traditional inventories under producer responsibility principle, emissions inventories for major advanced economies, like the US, the EU, and Japan, increased under VCRP, while inventories for major developing economies, like China, Russia, and India, decreased. We had discussed some major advantages and disadvantages of VCRP.

Keywords

Value-capturer responsibility principle; Producer responsibility principle; Consumer responsibility principle; Downstream responsibility principle; Global value chains

1. Introduction

The global value chain of a finished product may cross many countries. Based on its specific resources, each country participates in one or several production stages of the production, which is referred to production sharing (Yeats,1998; Johnson and Noguera, 2012). Every country captures some portion of value, that is, income, from the participation in the global value chains, while at the same time bears some environmental impact due to the production. However, depending on the production technology and production stage that one country engages in, the share of income captured by this country may be significantly different compared to the share of environmental impact, such as pollutant emissions, borne by this country. Such difference may give rise to efficiency problem in the mitigation of environmental impact. And there is also some sort of unfairness in the difference in the sense that one country benefits so little according to its captured value whereas it bears so much environmental damage induced by related production. For example, a South American country who supplies wood for the production of furniture sold to the world may obtain only very small portion of value from furniture sales in the market, whereas it may bear most of the environmental impacts from deforestation activities.

The United Nations Framework Convention on Climate Change (UNFCCC) defines the responsibility of greenhouse gases in one country based on producer responsibility principle (PRP). One country bears only the responsibility of emissions directly generated within this country under PRP. Many scholars have pointed out various weaknesses of the PRP (e.g., Munksgaard and Pedersen, 2001; Peters and Hertwich, 2008; Peters, 2008). One major drawback of carbon accounting based on PRP is that carbon leakage may occur severely compromising the effectiveness of climate policy. Another important drawback of PRP is the weak incentive for the consumers to change their behavior. Therefore, consumer responsibility principle (CRP) is proposed to supplement PRP (e.g., Eder and Narodoslawsky, 1999; Munksgaard and Pedersen, 2001; Peters and Hertwich, 2008; Peters, 2008; Wiedmann, 2009). CRP defines the environmental responsibility for a country as the global environmental impact induced by the final consumption of this country.

An accounting approach based on CRP adds up all upstream emissions from the production of final demand. Final consumers at the end of supply chains bear the upstream responsibility because their consumption activities induce those upstream emissions according to CRP. Symmetrically, we can say that workers and investors at the beginning of supply chains enable the downstream production and related emissions. Therefore, they may bear the responsibility. Emissions responsibility according to such principle is called worker-investor responsibility or downstream responsibility (Gallego and Lenzen, 2005; Lenzen and Murray, 2010; Rodrigues et al., 2006; Rodrigues and Domingos, 2008). It is also called income-based responsibility since the responsibility of emissions is allocated to the workers and investors who obtain income from the production (Marques et al., 2012). For convenience, we refer this principle as downstream responsibility principle (DRP). A major advantage of DRP is that it gives a strong incentive to basic resource suppliers (workers and investors) to reduce labor and financial resource inputs to the downstream production that generates large quantities of emissions.

While PRP, CRP, and DRP allocate environmental responsibility respectively to direct producers, consumers, and workers and investors in the supply chain, without considering the responsibility sharing between these groups, some scholars have also proposed approaches for the responsibility sharing between producers (including workers and investors) and consumers (e.g., Ferng, 2003; Gallego and Lenzen, 2005; Kondo et al., 1998; Lenzen et al., 2007; Peters, 2008; Rodrigues et al., 2006; Rodrigues and Domingos,2008). [1] Responsibility-sharing approaches combine to some extent advantages of PRP/DRP and those of CRP since incentives to lower emissions exists for both producers and consumers. Some of these approaches have been used to assess sectoral or regional environmental responsibility within a country (e.g., Andrew and Forgie, 2008; Zhang, 2013, 2015).

The PRP has another major shortcoming, that is, it does not account for the possible large gap between economic benefit distribution and environmental impact distribution. Generally, participator in the supply chain who obtains more income has greater ability to bear the cost of mitigation of environmental impacts. In contrast, participator who gains little economically may lack the ability and therefore the incentive to deal with the environmental

[1] Note that DRP also allocate to environmental responsibility to producers instead of final consumers because worker and investors are necessary parts of the producer (in a broad sense). Therefore, both PRP and DRP only consider the environmental responsibility of production rather than consumption.

problem. Unfortunately, raw material inputs and emissions usually occur in the production stages that participators engage in who capture relative small portion of value of the finished product. Therefore, while the PRP makes the *direct* polluters pay, generally it does not make the polluters pay who benefit most from the pollution and have greater financial ability to mitigate it. This problem is not resolved under the DRP (and CRP) since a producer enable a large quantity of emissions downstream is not necessary the one who captures a huge amount of value from the production.

In the present article, we propose a simple responsibility allocation principle which is based on the value distribution among participators in the supply chain. Specifically, the responsibility share of a producer is set to its proportion of value captured by this producer. We call this principle as value-capturer responsibility principle (VCRP). Take a fictitious example. Suppose that e units of emissions is generated in the supply chain of a phone with two producers, country A and country B. Note that e is the total emissions in the production of the phone indicating that it's calculated under CRP. Denote the market price of the phone as p. Further assuming that values captured by firms in country A and country B are v_1 and v_2, respectively. Then the emissions responsibility of country A and country B is $e\times(v_1/p)$ and $e\times(v_2/p)$, respectively. Therefore, the bigger share of economic benefit one produce captures the greater emissions responsibility it bears under VCRP proposed in the present article.

We can see that the VCRP combines the 'beneficiary pays' principle and the 'ability to pay' principle when allocating emissions responsibility for each supply-chain participator. Both 'beneficiary pays' and 'ability to pay' principles for environmental burden sharing have been proposed and discussed widely mainly from ethical perspectives (e.g., Barry and Kirby, 2015; Butt, 2007, 2014; Page, 2012, for 'beneficiary pays' principle and Caney, 2005; Page, 2008; Shue, 1999, for 'ability to pay' principle). And both principles are embodied in the 'common but different responsibility' principle established in the UNFCCC which has guided international climate change agreements, such as Kyoto Protocol and Paris Agreement.

The economic benefit and environmental burden distribution among participators is rebalanced under VCRP. Even though a participator engages in activities without direct emissions (e.g., design and innovation), it would bear some emissions responsibility depending on its share of captured value under VCRP. Under VCRP, the 'polluters' are not those producers who directly generate emissions but all producers who benefit from emissions. Hence, all producers for a finished product share the responsibility of emissions generated in the whole supply chain of that product.

The remainder of this article proceeds as follows. Section 2 describes methodology and data. We compare accounting approaches under PRP, CRP, DRP, and VCRP in the framework of a multi-regional input-output (MRIO) model in this section. Section 3 presents main results of emissions accounting under different allocation principles. Section 4 discusses advantages and disadvantages of VCRP compared to the other principles. Section 5 concludes.

2. Methodology and data

2.1 Production and consumption and their linkage in a MRIO model

A MRIO model is a major technique to assessing the environmental impact of supply chains which may involve producers in many countries. A MRIO model has become a standard method to calculate emissions responsibility under CRP.

A MRIO model with m countries (regions) has following basic identity

$$\begin{pmatrix} \mathbf{x}_1 \\ \mathbf{x}_2 \\ \vdots \\ \mathbf{x}_m \end{pmatrix} = \begin{pmatrix} \mathbf{A}_{11} & \mathbf{A}_{12} & \cdots & \mathbf{A}_{1m} \\ \mathbf{A}_{21} & \mathbf{A}_{22} & \cdots & \mathbf{A}_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ \mathbf{A}_{m1} & \mathbf{A}_{m2} & \cdots & \mathbf{A}_{mm} \end{pmatrix} \begin{pmatrix} \mathbf{x}_1 \\ \mathbf{x}_2 \\ \vdots \\ \mathbf{x}_m \end{pmatrix} + \begin{pmatrix} \sum_i \mathbf{y}_{1i} \\ \sum_i \mathbf{y}_{2i} \\ \vdots \\ \sum_i \mathbf{y}_{mi} \end{pmatrix} \tag{1}$$

where $\mathbf{x}_i$ is gross output vector of country i. Matrix $\mathbf{A}_{ij} \equiv \mathbf{Z}_{ij}(\hat{\mathbf{x}}_j)^{-1}$, is a normalized matrix of intermediate requirement of production sectors. $\mathbf{Z}_{ij}$ is delivery of intermediate input from sectors in country i to sectors in country j. $\hat{\mathbf{x}}_j$ is the diagonalization of output vector $\mathbf{x}_j$. Thus, elements of a column in $\mathbf{A}_{ij}$ reflect the input from sectors in country i required to produce one unit of output from a specific sector in country j. When $i \neq j$, $\mathbf{A}_{ij}$ reflects international trade in intermediates between countries i and j. $\mathbf{y}_{ij}$ is a vector of final demand (consumption and investment) in country j for products supplied by country i. When $i \neq j$, $\mathbf{y}_{ij}$ reflects international trade in final products between countries i and j.

By simple operation, equation (1) can be re-written as

$$\begin{pmatrix} \mathbf{x}_1 \\ \mathbf{x}_2 \\ \vdots \\ \mathbf{x}_m \end{pmatrix} = \begin{pmatrix} \mathbf{I}-\mathbf{A}_{11} & -\mathbf{A}_{12} & \cdots & -\mathbf{A}_{1m} \\ -\mathbf{A}_{21} & \mathbf{I}-\mathbf{A}_{22} & \cdots & -\mathbf{A}_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ -\mathbf{A}_{m1} & -\mathbf{A}_{m2} & \cdots & \mathbf{I}-\mathbf{A}_{mm} \end{pmatrix}^{-1} \begin{pmatrix} \sum_i \mathbf{y}_{1i} \\ \sum_i \mathbf{y}_{2i} \\ \vdots \\ \sum_i \mathbf{y}_{mi} \end{pmatrix} \tag{2}$$

where the inverse on the right hand side is called the Leontief inverse. Given an arbitrary vector of final demand, using the Leontief inverse, we can readily recover output in each country induced by the production of that final demand. For example, let $y_{ij,p}$ denote the final demand for product p sold from country i to country j where it's consumed. Then the outputs induced by the demand for this final product can be calculated as

$$\begin{pmatrix} \mathbf{x}_{1,ij,p} \\ \mathbf{x}_{2,ij,p} \\ \vdots \\ \mathbf{x}_{m,ij,p} \end{pmatrix} = \begin{pmatrix} \mathbf{I}-\mathbf{A}_{11} & -\mathbf{A}_{12} & \cdots & -\mathbf{A}_{1m} \\ -\mathbf{A}_{21} & \mathbf{I}-\mathbf{A}_{22} & \cdots & -\mathbf{A}_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ -\mathbf{A}_{m1} & -\mathbf{A}_{m2} & \cdots & \mathbf{I}-\mathbf{A}_{mm} \end{pmatrix}^{-1} \begin{pmatrix} \mathbf{0} \\ y_{ij,p} \\ \vdots \\ \mathbf{0} \end{pmatrix} \tag{3}$$

where $\mathbf{x}_{s,ij,p}$ is output of country s induced by final consumption $\mathbf{y}_{ij,p}$. Note that $y_{ij,p}$ is a scalar which is the p-th element of vector $\mathbf{y}_{ij}$. Emissions are the by-product of industrial output. If we further know emissions intensity (emissions per unit of output) in each sector, then based on equation (3), we are able to estimate the emissions induced by the final demand for $y_{ij,p}$, which is the accounting procedure under CRP.

A MRIO model described above is also call Leontief model (or demand-side model) which is widely used to allocate environmental responsibility under CRP. However, responsibility allocation under DRP is carried out using a different input-output model called Ghosh model (Marques et al., 2012). [1] While a Leontief model asks how much output would be induced by given final consumption, a Ghosh model asks how much output would be supported (enabled) by given primary input, i.e., labor and capital input value at the beginning of production process. The counterpart of the Leontief inverse in the Ghosh model is the Ghosh inverse, **G**. Suppose $v_{r,q}$ is the primary input to sector q in country r, then the output in each country *enabled* by this primary input can be calculated as

[1] Ghosh model is also called supply-side model. For detailed introduction on Ghosh model, see Miller and Blair (2009, chapter 12).

$$\begin{pmatrix} \mathbf{x}_{1,r,q} \\ \mathbf{x}_{2,r,q} \\ \vdots \\ \mathbf{x}_{m,r,q} \end{pmatrix}' = \begin{pmatrix} \mathbf{0} \\ v_{r,q} \\ \vdots \\ \mathbf{0} \end{pmatrix}' \begin{pmatrix} \mathbf{I}-\mathbf{B}_{11} & -\mathbf{B}_{12} & \cdots & -\mathbf{B}_{1m} \\ -\mathbf{B}_{21} & \mathbf{I}-\mathbf{B}_{22} & \cdots & -\mathbf{B}_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ -\mathbf{B}_{m1} & -\mathbf{B}_{m2} & \cdots & \mathbf{I}-\mathbf{B}_{mm} \end{pmatrix}^{-1} \quad (4)$$

where $\mathbf{B}_{ij} \equiv (\hat{\mathbf{x}}_i)^{-1}\mathbf{Z}_{ij}$, $\mathbf{x}_{s,r,q}$ is the output of country s enabled by the primary input $v_{r,q}$. Therefore, the final demand is regarded as an external variable (the 'cause') in Leontief model, whereas the primary input is an external variable in Ghosh model. The output (the 'effect') is the response variable in both models. Thus using the emissions intensity (emissions per unit of output) data and Ghosh model, we also can assess the emissions responsibility of workers and investors who provide the primary input $v_{r,q}$.

2.2 Emissions inventories under different allocation principles

2.2.1 Emissions inventory under PRP

Let $\mathbf{f}_s \equiv (\hat{\mathbf{x}}_s)^{-1}\mathbf{e}_s$ denote emissions intensity vector of country s. $\mathbf{e}_s$ is the vector of emissions whose elements represent emissions level in each sector. According to PRP, country s only needs to bear the responsibility for emissions generated directly. Therefore, the responsibility of country s for emissions generated in the supply chain of $y_{ij,p}$ is

$$E^{\mathrm{PRP}}_{s,ij,p} = \mathbf{f}_s{}'\mathbf{x}_{s,ij,p} \quad (5)$$

Aggregating across products, we obtains the emissions inventory of country s based on PRP, that is

$$E^{\mathrm{PRP}}_{s} = \sum_i \sum_j \sum_p E^{\mathrm{PRP}}_{s,ij,p} = \sum_i \sum_j \sum_p \mathbf{f}_s{}'\mathbf{x}_{s,ij,p} = \mathbf{f}_s{}'\mathbf{x}_s = \mathbf{i}'\mathbf{e}_s \quad (6)$$

Equation (6) indicates that inventory under PRP is just the total direct emissions of all sectors in country s. This inventory is often called production-based emissions.

2.2.2 Emissions inventory under CRP

According to CRP, country s needs to bear the responsibility for *global* emissions induced by its final demand. For $y_{ij,r}$, the responsibility of country s is defined by following equations

$$E^{\mathrm{CRP}}_{s,ij,p} = \begin{cases} \sum_k \mathbf{f}_k{}'\mathbf{x}_{k,ij,p}, & if\ \ j = s \\ 0, & if\ \ j \neq s \end{cases} \quad (7)$$

Equation (7) indicates that first, if the product $y_{ij,r}$ is not consumed in country *s*, it would bear no responsibility for emissions. Second, if $y_{ij,r}$ is consumed in country s, it would bear responsibility for emissions in every country caused by the production of the product. $\sum_k \mathbf{f}_k{}'\mathbf{x}_{k,ij,p}$ is total upstream emissions of the product $y_{ij,r}$, also known as carbon footprint of its consumption. Therefore, CRP states that one country should bear responsibility for the environmental footprint of its consumption.

Aggregating across products consumed in country *s*, we obtains the emissions inventory under CRP as following

$$E_s^{\mathrm{CRP}} = \sum_i \sum_p \sum_k \mathbf{f}_k{}'\mathbf{x}_{k,is,p} \tag{8}$$

This inventory is widely known as consumption-based emissions (Davis and Caldeira, 2010; Peters, 2008; Peters et al., 2011). It is also called national carbon footprints (Andrew et al., 2009).

2.2.3 Emissions inventory under DRP

Country *s* should bear responsibility for downstream emissions enabled by its primary inputs. For given primary input $v_{r,q}$, the emissions responsibility of country *s* is,

$$E_{s,r,q}^{\mathrm{DRP}} = \begin{cases} \sum_k \mathbf{f}_k{}'\mathbf{x}_{k,r,q}, & if\ r = s \\ 0, & if\ r \neq s \end{cases} \tag{9}$$

where $\mathbf{x}_{k,r,q}$ is calculated using the Ghosh model (equation (4)). Equation (9) shows if primary input comes from country *s*, it would responsibility for emissions in every country enabled by this primary input; otherwise, it would bear no responsibility.

The inventory under DRP also known as income-based emissions is calculated by aggregating across primary inputs from country *s*

$$E_s^{\mathrm{DRP}} = \sum_q \sum_k \mathbf{f}_k{}'\mathbf{x}_{k,s,q} \tag{10}$$

2.2.4 Emissions inventory under VCRP

Although the idea behind VCRP is different from CRP, the reallocation of emissions under the former is connected to that under the latter. The emissions 'pie' before reallocation under VCRP is the same as that under CRP which is the total upstream emissions of a specific product. VCRP allocates a part of the pie into a country according to a continuous ‘responsibility-coefficient’, i.e., the proportion of captured value (economic benefit) from the product, whereas CRP does it according to a dichotomous coefficient, i.e., whether or not the product is consumed in the country under consideration.

Therefore, we can establish emissions inventory under VCRP by three steps. First, we calculate the total upstream emissions (i.e., carbon footprints) of a product which can be done using equations (3) and (7). Second, we computed the proportions of captured value for each country from the production of the product. Third, we divide the upstream emissions of the product to each country in proportion to its share of captured value.

For the product $y_{ij,p}$ abovementioned, the value captured by country s can be estimated using the ratios of primary input (value added) to gross output in each sector. Define the vector of value-added ratio in country s as $\mathbf{u}_s \equiv (\hat{\mathbf{x}}_s)^{-1}\mathbf{v}_s$ where $\mathbf{v}_s$ reflects value added (wage, capital input, net tax) in each sector of country s. Then, value captured by country s from producing $y_{ir,p}$ is

$$u_{s,ij,p} = \mathbf{u}_s'\mathbf{x}_{s,ij,p} \tag{11}$$

Induced output $\mathbf{x}_{s,ij,p}$ is obtained from equation (3). $u_{\mathrm{s,ij,p}}$ is also known as global value chain income for country s from producing $y_{ij,p}$ (Timmer et al., 2015). If $i \neq j$, $u_{s,ij,p}$ is also called value-added exports from country i to country j (Johnson and Noguera, 2012). Adding up value captured by each country equals the total value of the final product, i.e., $y_{ij,p} = \sum_k \mathbf{v}_k'\mathbf{x}_{k,ij,p}$. [1]The share of captured value for country s is simply

$$\varphi_{s,ij,p} \equiv \frac{\mathbf{u}_s'\mathbf{x}_{s,ij,p}}{\sum_k \mathbf{u}_k'\mathbf{x}_{k,ij,p}} = \frac{u_{s,ij,p}}{y_{ij,p}} \tag{12}$$

Thus, the emissions responsibility for participating in the production of $y_{ij,p}$ and the whole emissions inventory of country s under VCRP can be established by the following equations

$$E_{s,ij,p}^{\mathrm{VCRP}} = \varphi_{s,ij,p} \sum_k \mathbf{f}_k{}'\mathbf{x}_{k,ij,p} \tag{13}$$

$$E_s^{\mathrm{VCRP}} = \sum_i \sum_j \sum_p E_{s,ij,p}^{\mathrm{VCRP}} = \sum_i \sum_j \sum_p \sum_k \varphi_{s,ij,p} \mathbf{f}_k{}'\mathbf{x}_{k,ij,p} \tag{14}$$

[1] This is because given a final product, the associated gross output equals total intermediate output plus final output (the value of the final product) on the one hand, it equals total intermediate input plus total primary input (value added) on the other hand. Moreover, total intermediate output equals total intermediate input for a given final product.

Although national inventory under different principle is different in general, it's easy to see that total emissions aggregated across countries give the same world emissions, that is

$$\sum_s E_s^{\text{PRP}} = \sum_s E_s^{\text{CRP}} = \sum_s E_s^{\text{DRP}} = \sum_s E_s^{\text{VCRP}} = \sum_s \mathbf{f}_s{}' \mathbf{x}_s = \sum_s \mathbf{i}' \mathbf{e}_s \tag{15}$$

2.3 Data

Data used to empirical analysis in this paper including the global input-output tables and CO_2 emissions data is taken from the World Input-Output Database (WIOD) (Timmer et al., 2015). The world input-output tables in the WIOD cover the period of 1995-2011, while the emissions data cover the period of 1995-2009. Therefore, our calculation is carried out to the year 2009. There are 41 countries and regions in the world input-output table, 35 sectors for each country. Therefore, for $y_{ij,p}$, both index i and index j runs from 1 to 41, while for given i and j, index p runs from 1 to 35. However, calculation can be simplified by matrix operation.

3. Results

3.1 Emissions responsibilities for selected product groups

Based on equations (5), (7), and (13), we can calculate emissions responsibility from producing a given final product (group) under different allocation principles. Table 1 presents responsibility allocation results for selected product groups and selected economies and for the year 2007 under PRP, VCRP, and CRP.[1] We will mainly analyze responsibility changes from PRP to VCRP since the changes from PRP to CRP are very straightforward depending on the consumption location of a given product group.

Table 1 shows that 38.54 Mt CO_2 emissions were generated globally due to the production of textiles and textile products exported from China to the US. These emissions were total upstream emissions from producing those textile products. Under the RPR, emissions responsibility of China was 35.2 Mt, accounted for 91% of total emissions, indicating that most emissions were emitted by firms in China. The VCRP reallocated emissions to countries based on proportion of captured value in each country. Compared to direct emissions, under VCRP, China's responsibility reduced by 8.5% (3 Mt), to 32.2 Mt. About 2.2 Mt emissions (73% of reduction in China's responsibility) were reallocated to the

[1] Using equation (9), we can also calculate emissions responsibility for each sector from its primary input. But these results cannot be directly compared with those under the other three principles which assess responsibility related to a specific final product rather than a sector. Therefore, only product-level results under PRP, CRP, and VCRP are reported and compared in this subsection. But we can compare national inventories across countries and principles which is done in the next subsection.

US, EU, Japan, and South Korea.

The result for electrical and optical equipment exported from China to the US is similar. Total upstream emissions for this product group were 106.1 Mt. Major responsibility went to China under either PRP or VCRP, accounting for 85% or 65% of total upstream emissions. However, the responsibility changes from PRP to VCRP much more significantly than the textile case. For this product group, China’s responsibility decreased from 90.05 Mt under PRP to 69.27 Mt under VCRP, or by 23%. In contrast, the responsibility for the US, EU, Japan, and South Korea combined increased from 5.4 Mt to 20.5 Mt, or by 276%. The increase of Japan and South Korea is prominent since they are major suppliers of intermediates (key parts and components) to China in the East Asia production network. These reallocation affects are much greater than that in the textile case. The major reason is that the proportion of captured value in China for electrical and optical equipment is much lower than that for textile products. We can easily recover value proportion based on the emissions under VCRP. The proportion of captured value (equals the emissions responsibility share) of China for textile products was 83.5%, while the proportion for electrical and optical equipment was only 65.3%. This difference may be mainly due to difference in degree of international production fragmentation between textile products and electrical products. In general, the degree of production fragmentation for electrical products (e.g., mobile phones, computers) is greater than that for textile products. Therefore, compared to the production of textile products, more parts and components are imported to China for producing electrical and optical equipment, resulting in lower proportion of captured value. Moreover, many firms in the industry of electrical equipment in China engage in low value-added activities like assembling and processing of electrical products, which further lower the proportion of captured value.

The upstream emissions for electrical and optical equipment exported from Japan to the US were 4.28 Mt, which were much lower than those for producing second group of products (i.e., electrical and optical equipment exported from China to the US). China participated in the production of these products by supplying intermediates (to Japan or the other countries). Now the major responsibility went to Japan whose emissions share of Japan increased from 60% under PRP to 85% VCRP. In contrast, China’s responsibility decreased from 0.6 Mt (14%

by emissions share) under PRP to 0.1 Mt (2.4%) under VCRP. Responsibilities changes only slightly for the other advanced economies other than Japan.

The last two columns in table 1 show the allocation results for transport equipment consumed in China and produced by the US or China itself. Similar phenomenon can be observed. For transport equipment exported to China from the US, emissions responsibility of the US increased from 1.09 Mt (62%) to 1.37 Mt (78%), whereas China's responsibility decreased from 0.22 Mt (12.3%) to 0.05 Mt (2.7%). And for transport equipment produced and consumed in China, China's emissions responsibility decreased from 173.76 Mt (89.6%) according to PRP to 146.95 Mt (77.9%) under VCRP. Again, the responsibility for advanced economies increased significantly. Emissions allocated to the US, EU, Japan, and South Korea combined rose from 7.3 Mt under PRP to 28.1 Mt under VCRP, or by 285%.

To summarize, for five groups of selected final products, the allocation results in Table 1 indicate that carbon responsibility for China eased under VCRP, that is, if emissions from production are borne among countries in the supply chains based on their respective proportion of captured value. In contrast, carbon responsibility allocated to major advanced economies increased due to their greater ability to capture value in the supply chains. In fact, it's not a phenomenon for particular product groups. Instead, those cases in Table 1 are representative. In next subsection, we will compare national inventories under different principles which contain emissions from producing all types of final products. We will see that major conclusions shown in this subsection also applied in the national level.

Table 1. Emissions responsibility for selected product groups under different allocation principles (Mt CO_2; year: 2007)

	Product group	Textiles and textile products	Electrical and optical equipment	Electrical and optical equipment	Transport equipment	Transport equipment
	Trade direction	China to US	China to US	Japan to US	US to China	China to China
E_PRP						
US		0.25	1.21	0.10	1.09	1.49
EU		0.27	1.33	0.09	0.07	2.17
Japan		0.26	1.50	2.55	0.03	2.00
South Korea		0.30	1.40	0.09	0.02	1.63
China		35.18	90.05	0.60	0.22	173.76

Russia	0.27	1.02	0.10	0.04	1.58
India	0.11	0.55	0.03	0.02	0.81
Brazil	0.04	0.13	0.01	0.01	0.22
Others	1.86	8.91	0.72	0.27	10.20
World	38.54	106.10	4.28	1.76	193.86
E_VCRP					
US	0.65	4.73	0.09	1.37	5.12
EU	1.32	6.82	0.09	0.10	12.13
Japan	0.80	5.54	3.64	0.04	7.41
South Korea	0.53	3.38	0.05	0.01	3.45
China	32.20	69.27	0.10	0.05	146.95
Russia	0.19	0.69	0.01	0.01	1.13
India	0.11	0.39	0.01	0.01	0.57
Brazil	0.14	0.43	0.01	0.01	0.75
Others	2.60	14.86	0.28	0.17	16.36
World	38.54	106.10	4.28	1.76	193.86
E_CRP					
US	38.54	106.10	4.28	0.00	0.00
EU	0.00	0.00	0.00	0.00	0.00
Japan	0.00	0.00	0.00	0.00	0.00
South Korea	0.00	0.00	0.00	0.00	0.00
China	0.00	0.00	0.00	1.76	193.86
Russia	0.00	0.00	0.00	0.00	0.00
India	0.00	0.00	0.00	0.00	0.00
Brazil	0.00	0.00	0.00	0.00	0.00
Others	0.00	0.00	0.00	0.00	0.00
World	38.54	106.10	4.28	1.76	193.86

Note: EU includes 27 member countries.

3.2 National inventories under different allocation principles

The national emissions inventory is the aggregation of emissions responsibility for every final product. Table 2 presents national inventories and their global shares for major emitters in the year 2007 under four allocation principles. It shows that the national inventories under CRP, DRP, or VCRP were significantly different from inventory under traditional PRP. For major developed countries except for South Korea, national inventories under CRP were significantly larger than those under PRP, whereas for China and Russia, their inventories under CRP were significantly lower than those under PRP, indicating that substantial emissions of China and Russia were induced by consumption in developed countries. Similar results have been shown by many existing studies (e.g., Davis and Caldeira, 2010; Peters et al., 2011; Wiebe, et al., 2012;Wilting and Vringer, 2009).

Table 2 shows that similar pattern exists when comparing inventories under VCRP and PRP. For example, national emissions of the US under VCRP were 5061 Mt, 7.8% greater than emissions under PRP (4694 Mt). For the US, this responsibility adjustment is smaller than CRP compared to PRP. However, for the EU, Japan, and South Korea, the responsibility changes under VCRP were much greater than CRP compared to PRP. For example, emissions of the EU under CRP were 4656 Mt, 27.2% greater than emissions under PRP, whereas emissions under VCRP were 31.7% greater than emissions under PRP. If we look at results for individual countries in the EU, we found that the responsibility changes under VCRP are particularly sharp for large member countries, such as Germany, the UK, and, France, whose inventories under VCRP were 43.7%, 42.7%, and 66.5% respectively larger than their inventories under PRP. For Japan, the national inventory under VCRP was 25.9% greater than inventory under PRP. While emissions of South Korea under CRP were lower than those under PRP, emissions under VCRP were 8.8% larger than the latter. For G7 countries (Canada, France, Germany, Italy, Japan, the UK, and the US) as a whole, total emissions under VCRP were 19% greater than emissions under PRP.

In contrast, national inventories under VCRP for China, Russia, India, and Indonesia were lower than their inventories under PRP. For example, China's emissions under VCRP were 4279 Mt, 22.5% lower than emissions under PRP. However, China's emissions under VCRP were greater than emissions under CRP. National emissions of Russia and India under VCRP were 20.9% and 13.2% respectively lower than those under PRP. Yet, like major developed countries, Brazil and Mexico had larger inventories under either CRP or VCRP than those under PRP. Responsibility for BRIC as a whole under VCRP decreased 19.4% compared to that under PRP.

Table 2 also reports allocation results under DRP. For most economies in the table, inventories under DRP were also significantly different from those under traditional PRP. For major developed countries except for the US and South Korea, emissions under DRP were also larger than those under PRP, whereas emissions of China and India under DRP were lower than emissions under PRP. Moreover, for most countries, inventories under DRP were also significantly different from inventories under VCRP (or CRP). For example, national emissions of the US under DRP were 4554 Mt, 10% lower than emissions under VCRP, and China's emissions under DRP were 4760 Mt, 11.2% greater than emissions under VCRP. For the US, South Korea, Russia, and Indonesia, the direction of responsibility adjustment by DRP compared to PRP is opposite to the adjustment by VCRP.

Shares of national inventories in the global emissions also reported in Table 2, indicating contribution of each country to the global carbon emissions. The pattern of changes in shares was similar to the changes in emission levels, only normalized by the global total. Major carbon emitters according to traditional PRP like the US, the EU, and China were still major players after responsibility adjustments under different allocation principles.

Table 2. CO_2 emissions inventories for selected economies under different allocation principles (year: 2007)

	E_PRP	E_CRP	E_DRP	E_VCRP	E_PRP	E_CRP	E_DRP	E_VCRP
	Mt CO2				Share in global emissions (%)			
US	4694	5563	4554	5061	18.6	22.0	18.0	20.0
EU	3535	4496	3929	4656	14.0	17.8	15.6	18.4
Germany	703	872	893	1010	2.8	3.5	3.5	4.0
UK	460	648	577	657	1.8	2.6	2.3	2.6
Italy	388	526	398	528	1.5	2.1	1.6	2.1
France	279	467	340	464	1.1	1.8	1.3	1.8
Japan	1080	1247	1169	1360	4.3	4.9	4.6	5.4
South Korea	510	500	483	554	2.0	2.0	1.9	2.2
Canada	476	488	582	532	1.9	1.9	2.3	2.1
G7	8080	9811	8512	9612	32.0	38.8	33.7	38.1
China	5522	4132	4760	4279	21.9	16.4	18.8	16.9
Russia	1525	1108	1734	1206	6.0	4.4	6.9	4.8
India	1281	1242	1106	1112	5.1	4.9	4.4	4.4
Mexico	364	421	415	428	1.4	1.7	1.6	1.7
Indonesia	329	296	360	315	1.3	1.2	1.4	1.2
Brazil	256	295	301	325	1.0	1.2	1.2	1.3
BRIC	8584	6776	7900	6922	34.0	26.8	31.3	27.4
World	25261	25261	25261	25261	100.0	100.0	100.0	100.0

Note: EU includes 27 member countries. G7 consists of seven major advanced nations, i.e., Canada, France, Germany, Italy, Japan, the UK, and the US.

Figure 1 shows the trend of discrepancies between inventories under VCRP and inventories under PRP. In every year of the period of 1995-2009, inventories under VCRP had been greater than those under PRP for the US, the EU, and Japan. For the EU, gap between two types of inventories had grown from 594 Mt to 1211 Mt during 1995-2008 and dropped to 962 Mt in 2009 due to the global financial crisis. For the US, the gap also grew from 195 Mt to 465 Mt during 1995-2006 and fell after 2006. However, the gap for Japan had shrunken from 413 Mt to 271 Mt in the study period. In contrast, for China, Russia, and India, inventories under VCRP had been lower than their inventories under PRP in every year of the study period. The gap for China had grown sharply, from 470 Mt in 1995 to 1517 Mt in 2008 and fell to 1261 Mt in 2009. It's evident that increase of gap for China began after 2001, the year China joined the World Trade of Organization (WTO), which significantly promote the participation of Chinese firms in the global value chains.

The evident growing gap between inventory of China under VCRP and that under PRP during 2001-2008 came from the fact that the proportion of value captured by Chinese firms had been decreased significantly after China's entry into the WTO. Table 3 present proportions of captured value for China in 2007 and their changes compared to those in 2000. Each group of final products is divided into three subgroups: products produced and consumed in China and outside China (exports of final products), products produced outside China and consumed in China (imports of final products), and products produced and consumed outside China.[1] For manufacturing products in the first subgroup, except for textiles and textile products, leather, leather and footwear, China's proportion of captured value had decreased by 2 to 9 percentage points. For example, for basic metals and fabricated metal, the proportion of captured value decreased 9 percentage points. The decrease of proportions for machinery, electrical and optical equipment, and transport equipment was also over 8 percentage points. While China is a major producer and exporter of these finished manufactured goods, China also depends on imports of critical raw material (e.g., crude oil and iron ore), parts and components (e.g., electronic chips, car parts), designs and innovations (e.g., various patent licensing). Chinese firms enjoyed much larger foreign markets of manufacturing products after China' entry into the WTO, their dependence on high value-added imports lower average proportions of value captured. In fact, for some service products, the proportions of captured value by China also fell. For example, the proportion of

[1] Note that proportion of captured value for final products produced and consumed in China is the same as value proportion for products produced in China and consumed outside China. The proof see appendix.

captured value for air transport service decreased by 10 percentage points, and the proportion for ‘renting of M&Eq and other business activities’ decreased by 3.6 percentage points.

For the other two subgroups of products (final products produced outside China), China’s proportion of captured value had increased about 0.1 to 4 percentage points during 2000-2007, indicating that exports of intermediate products in China also increased after its entry in the WTO. Table 3 shows that proportions of captured value for these products are much lower than proportions for those products produced in China, which is naturally true since intermediate inputs are mainly sourced from domestic suppliers for a large country like China while at the same time it’s only one small supplier (compared to rest of the world) of intermediate inputs to the other countries. For the same reason, the changes by percentage points in proportion of capture value for these subgroups of products are also much smaller compared to changes for the first subgroup of product. Therefore, the effect of changes in proportion of captured value in China for the final products produced in China had dominated the dynamic of national inventory of China under VCRP during 2000-2008.

Finally, Figure 2 illustrates changes in cumulative responsibility of the 15 years (1995-2009) under VCRP, CRP, and DRP for selected economies compared to that under PRP. The results are similar to the results for the year 2007. For major advanced countries, their cumulative emissions under VCRP, CRP, and DRP had increased compared to emissions under PRP, while for China, Russia, and India, cumulative emissions under VCRP and CRP had decreased. The reallocation of cumulative responsibility by VCRP was relatively greater for EU countries, China and Russia.

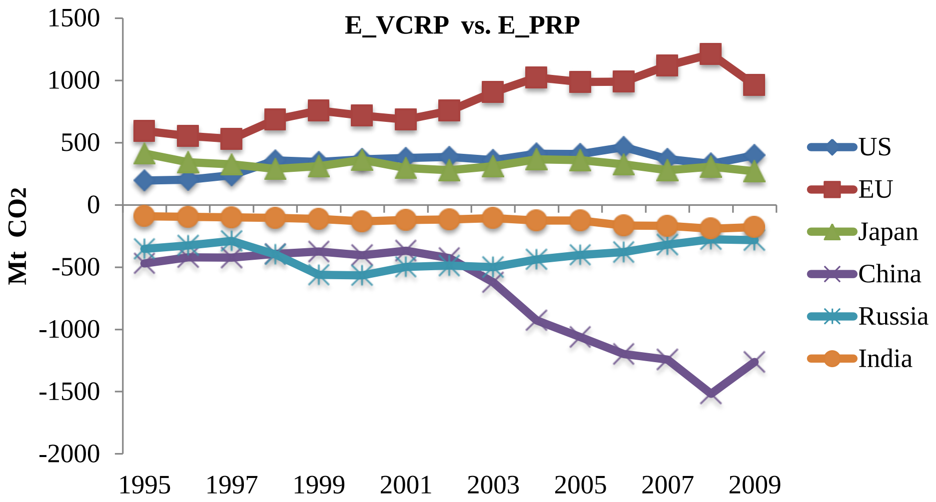

Figure 1. Annual differences between inventories under VCRP and inventories under PRP during 1995-2009 for selected economies

Table 3. Proportions of captured value of China in 2007 and their changes compared to those in 2000 (%)

	Products produced and consumed in/outside China	Products produced outside China and consumed in China	Products produced and consumed outside China
1.Agriculture, Hunting, Forestry and Fishing	92.5 (-1.3)	0.9 (0.4)	0.7 (0.4)
2.Mining and Quarrying	85.3 (-5.8)	0.8 (0.5)	0.6 (0.3)
3.Food, Beverages and Tobacco	89.1 (-3.0)	1.4 (0.6)	1.1 (0.5)
4.Textiles and Textile Products	83.5 (1.4)	3.7 (1.7)	4.1 (2.3)
5.Leather, Leather and Footwear	83.5 (1.3)	2.0 (0.9)	1.5 (0.5)
6.Wood and Products of Wood and Cork	82.3 (-4.3)	1.1 (0.5)	1.1 (0.7)
7.Pulp, Paper, Paper , Printing and Publishing	80.5 (-5.1)	1.3 (0.7)	1.0 (0.6)
8.Coke, Refined Petroleum and Nuclear Fuel	62.6 (-7.4)	1.2 (0.3)	0.7 (0.1)
9.Chemicals and Chemical Products	75.8 (-6.2)	1.9 (1.1)	1.3 (0.7)
10.Rubber and Plastics	75.4 (-5.8)	2.3 (1.3)	2.0 (1.2)
11.Other Non-Metallic Mineral	83.3 (-4.8)	1.4 (0.7)	0.9 (0.4)
12.Basic Metals and Fabricated Metal	74.5 (-9.0)	2.0 (1.0)	1.7 (1.0)
13.Machinery, Nec	75.4 (-8.7)	2.7 (1.7)	2.2 (1.5)
14.Electrical and Optical Equipment	65.3 (-8.8)	5.2 (3.6)	3.9 (2.9)
15.Transport Equipment	75.8 (-8.2)	2.2 (1.4)	2.8 (1.9)
16.Manufacturing, Nec; Recycling	84.6 (-2.1)	5.2 (4.0)	2.2 (1.6)
17.Electricity, Gas and Water Supply	82.9 (-7.6)	0.9 (0.3)	0.7 (0.3)
18.Construction	81.3 (-4.4)	2.0 (1.1)	1.5 (0.9)
19.Sale, Maintenance and Repair of Motor Vehicles and Motorcycles; Retail Sale of Fuel	NA.	1.0 (0.4)	0.9 (0.6)

20.Wholesale Trade and Commission Trade, Except of Motor Vehicles and Motorcycles	91.9 (0.0)	1.1 (0.2)	0.7 (0.5)
21.Retail Trade, Except of Motor Vehicles and Motorcycles; Repair of Household Goods	91.9 (0.0)	0.7 (0.4)	0.5 (0.3)
22.Hotels and Restaurants	90.9 (-2.7)	0.8 (0.3)	0.6 (0.3)
23.Inland Transport	88.3 (-3.3)	0.7 (0.4)	1.0 (0.6)
24.Water Transport	84.1 (-2.5)	5.1 (4.2)	1.9 (1.1)
25.Air Transport	77.1 (-10.0)	1.4 (0.8)	1.0 (0.5)
26.Other Supporting and Auxiliary Transport Activities; Activities of Travel Agencies	86.3 (-5.6)	0.9 (0.2)	0.9 (0.5)
27.Post and Telecommunications	88.0 (0.3)	1.3 (0.8)	1.0 (0.7)
28.Financial Intermediation	94.4 (-0.2)	0.6 (0.3)	0.4 (0.2)
29.Real Estate Activities	96.1 (-0.3)	0.5 (0.4)	0.2 (0.2)
30.Renting of M&Eq and Other Business Activities	82.6 (-3.6)	0.7 (0.3)	0.7 (0.4)
31.Public Admin and Defence; Compulsory Social Security	90.6 (-1.7)	1.1 (0.6)	0.6 (0.4)
32.Education	89.6 (-3.1)	0.7 (0.6)	0.4 (0.2)
33.Health and Social Work	81.0 (-3.5)	1.2 (0.8)	0.6 (0.4)
34.Other Community, Social and Personal Services	86.8 (-2.0)	1.1 (0.5)	0.7 (0.4)
35.Private Households with Employed Persons	NA.	0.2 (0.1)	0.1 (0.0)

Note: Value in the bracket is change (by percentage points) in proportion compared to that in 2000, i.e., proportion in 2007 less proportion in 2000.

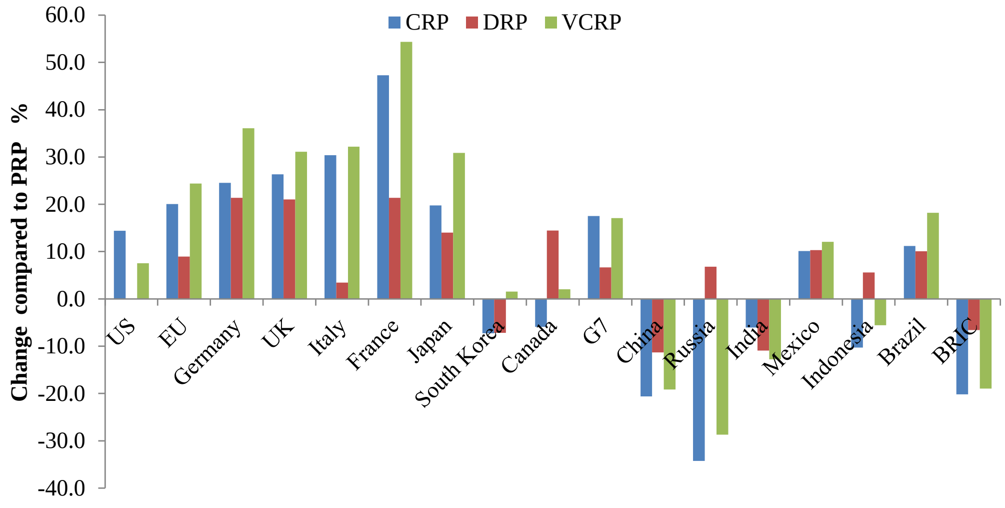

Figure 2. Changes in cumulative emissions responsibility in the period of 1995-2009 compared to PRP (%)

4. Discussion

4.1 Strengths of VCRP

Under traditional PRP, direct polluters have to pay for their pollution. However, there usually exists unbalance between environmental burden and economic benefit for direct polluters, which makes it inefficient to clean up supply chains. For direct polluters, the ability to pay may be very weak because they usually engage in activities with low value-added ratios and only obtain relative small proportion of income from participation in global value chains. Moreover, most direct polluters in global value chains come from developing countries with lax environmental regulation and are lack of efficiency technologies for emissions mitigation. In other words, financial and technological position may be very weak for direct polluters to deal with emissions. In contrast, producers engage in activities with high value-added ratios generally capture most of income from global value chains and therefore have better ability to pay. They may be also in a better position to develop efficiency technologies to deal with emissions from supply chains. Compared to PRP, the first major strength of VCRP is environmental responsibility and economic benefit was rebalanced. Under VCRP, *all* producers in supply chains share environmental responsibility for production of finished products and producers with better ability to pay pay more. Therefore, more resources will be available for tackling environmental problems and make the mitigation of emissions more efficiency and fair compared to traditional PRP.

As mentioned in the section 1, the basic idea underpinning VCRP is to closely connect ‘beneficiary pay’ and ‘ability-to-pay’ principles, two of major principles for sharing burdens of climate change among countries. Previous responsibility-allocation approach under ability-to-pay principle usually uses national wealth index (GDP share, GNP share, or per capita GDP share) as measurement of ability to pay (Mattoo and Subramanian, 2012; Rose et al., 1998; Smith et al., 1993). Thus, a country with larger share of GDP will bear larger share of mitigation cost. Unlike this approach, VCRP not only consider the ability to pay but the cause of emissions. According to VCRP, although a producer does not generate emissions directly, it should bear a part of environmental responsibility because it participates in the production and obtains economic benefit from emissions (‘beneficiary pay’ principle). For emissions from producing a specific product, a country with big share of GDP will not bear responsibility for these emissions if it does not at all participate in the production of that product. If it does participate in the production, its share of responsibility is then proportional to its share of captured value from the supply chains rather than proportional to its world share of national wealth (e.g., GDP share). [1]Therefore, VCRP improve the previous approach which reallocates national burden of climate change simply based on GDP share although both of their core idea is ability-to-pay principle.

The second advantage of VCRP compared to PRP is to provide stronger incentive for producers to cooperate in cleaning up the supply chains. Under PRP, there is weak incentive for a producer to care about emissions generated by its upstream suppliers or downstream buyers. However, under VCRP, downstream and upstream emissions will affect environmental responsibility of the producer given its proportion of captured value. Under VCRP, a producer with cleaner technology is more willing to transfer its cleaner technology to the other producer in the supply chain to reduce emissions which can reduce its environmental responsibility given its share of captured value. For this reason, a leader in the global value chain would put more resources into development and innovation of clean technologies and transfers them to upstream and downstream producers in the supply chain.

Third, like CRP, VCRP reallocates emissions responsibility of a country going beyond its territorial boundary and therefore can reduce carbon leakage. The PRP is often criticized for the problem of carbon leakage (Peters and Hertwich, 2008; Peters, 2008). That is, energy-intensive activities could be relocated from advanced countries with emissions binding commitments to developing countries with lax emissions regulation and therefore compromise the effect of climate policy. CRP is regarded as one possible solution for the carbon leakage. We argue that VCRP can also alleviate the problem of carbon leakage. Under VCRP, advanced countries engaging in design, development, innovation, and marketing of new products will bear a part of environmental cost for emissions generated in developing countries that supply raw materials and engage in assembling, processing, and manufacturing of those products. In fact, the relocation of energy-intensive activities from developed

[1] In fact, responsibility allocation based on GDP share can be seen as a simplified version of VCRP, in which a single share, i.e., GDP share is used to allocate national responsibility for emissions from producing any final product.

countries to developing countries usually increases whole emissions of the supply chains because relatively lax environmental regulation and dirtier technology in the developing countries, which may increase the emissions responsibility for producers in developed countries according to VCRP. Therefore, under VCRP, the incentive to find a pollution haven is much weaker than that under PRP.

4.2 Weaknesses of VCRP

There are weaknesses too. First, compared to PRP, the accounting of responsibility under VCRP is much more complex and therefore less transparent. Emissions accounting under PRP only need to compile direct emissions from each sector within a country. However, like CRP or DRP, emissions accounting under VCRP need information on production technology of both domestic producers and trade partners. It also needs information on international trades in intermediate and finished products. Therefore, the accounting under VCRP is a far more data-intensive activity than accounting under PRP. Recent developments of MRIO databases have provided great opportunities for emissions accounting under VCRP (also CRP, and DRP).[1] However, accounting under VCRP is prone to uncertainties from original input-output data, trade data, and environmental data and various uncertainties from the processes of compiling MRIO tables and emissions data. Accounting results under VCRP can also be affected by the resolution of sectors and regions in the MRIO model. In theory, the more detailed of the resolution of sectors and regions, the better precision of the emissions accounting for a specific product. However, in reality, this would require more data inputs and therefore more financial resources. And uncertainties may increase due to the lack of detailed raw data and various estimations in compiling processes. In general, emissions accounting approaches under VCRP, CRP, DRP and the other principles all subject to the problem of increasing uncertainties and less transparency compared to traditional emissions accounting based on PRP.

Second, while CRP provides strong incentive for consumers to decarbonize their consumption behaviors, such incentive is weak in VCRP since no environmental responsibility is directly allocated to final consumers.[2] However, we can first allocate

[1] See Tukker and Dietzenbacher(2013) for an overview of recent MRIO database programs.
[2] Of course, in a perfect market where any environmental cost is reflected in product prices, consumers will finally share

emissions among producers according to VCRP and then transfer a part of emissions of each producer with the same ratio to final consumers. Suppose country A and country B produce together a product and bear emissions e_1 and e_2 respectively according to VCRP. The product is consumed in country C. Suppose the proportion of responsibility that is borne by consumers is c. Then the emissions responsibility for country C is $c\times(e_1+e_2)$, while emissions of country A and country B reduce to $(1-c)\times e_1$ and $(1-c)\times e_2$, respectively. The difficulty is how to determine the responsibility share for consumers at the beginning. The method proposed by Lenzen et al.(2007) may be useful to divide emissions responsibility into producers and final consumers.

Third, at the first glance, it seems that producers with greater ability to capture value in the supply chains will be punished under VCRP and therefore discourage their participation in the supply chains. Although greater ability of value capture provide a producer with more resource to deal with environmental cost, VCRP can still discourage their entry into high value activities if the environmental cost is substantial part of cost from production. However, if this is the case, then it's even more difficult for producers with less resource including direct polluters to tackle the environmental problem from production. Moreover, if the environmental cost for producing a product (e.g., ivory) is so high that discourage of production is actually desirable. In general, environmental cost is only small part of cost for producing final products. Producers in advanced countries participate in the global value chains to exploit labor and market resources in developing countries. Therefore, the effect of VCRP for their willingness to participation in the global value chains is likely to be weak. However, VCRP will indeed encourage a leader in the global value chains to search for cleaner suppliers in the developing countries. Producers with dirty technologies may be squeeze out of the supply chains. While a supply chain with fewer emissions is a good thing, there may be negative impact for developing countries without both clean technology and attractive resources (e.g., cheap labor, good infrastructure, large domestic market, or close to a large market). The international transfer of technology may reduce this impact.

5. Conclusions

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some environmental burden in the way of higher prices even though producers pay for the environmental cost.

In the present paper, we discuss how producers engaging in production sharing in the global value chains can share their environmental responsibility for environmental impacts. We propose a value-capturer responsibility principle for responsibility allocation among producers in the supply chains, according to which the environmental responsibility of a producer participating in producing a product is proportional to its share of captured value from that product. VCRP has combined the 'beneficiary pays' principle and the 'ability to pay' principle when allocating environmental responsibility for each supply-chain participator.

Based on dataset from the WIOD, we calculated carbon emissions responsibility for major economies under VCRP in the period of 1995-2009 and compared it to their responsibilities under producer responsibility principle, consumer (upstream) responsibility principle, and downstream responsibility principle. The results show that, compared to traditional inventories according to PRP, emissions inventories for major advanced economies, like the US, the EU, and Japan, increased under VCRP, while inventories for major developing economies, like China, Russia, and India, decreased. The gap between inventory under VCRP and inventory under PRP had grown significantly since China joined the WTO in 2001 due to the fact that China's proportion of captured value had fell significantly, particularly for mechanical and electrical products.

We don't suggest in this paper that VCRP is unconditionally better in terms of fairness and efficiency than PRP, CRP, DRP and the other responsibility-sharing approaches. We had discussed some advantages and disadvantages of VCRP. In fact, it's difficult for any new principle to replace traditional PRP in the near future which is more transparent, simpler and has lower cost for implementation. However, we believe that responsibility accounting approach under VCRP, together with other approaches under CRP, DRP and other principles, can be a useful and beneficial supplement to accounting under traditional PRP, which will improve the efficiency of emissions mitigation, strengthen cooperation among producers in dealing with supply-chain environmental impacts and promote the decarbonization of supply chains.

Appendix

Under VCRP, the proportion of captured value for a country is only determined by production technology of a final product but not affected by where the product is consumed.

Proof:

Denote l_{ab}, as the element in the a-th row and b-th column of Leontief inverse in equation (3). According equation (3), the induced output of country s can be written as

$$\mathbf{x}_{s,ij,p} = \begin{pmatrix} l_{1+(s-1)\times K,\, p+(i-1)\times K} \\ l_{2+(s-1)\times K,\, p+(i-1)\times K} \\ \vdots \\ l_{sK,\, p+(i-1)\times K} \end{pmatrix} y_{ij,p} \equiv \begin{pmatrix} z_1 \\ z_2 \\ \vdots \\ z_K \end{pmatrix} y_{ij,p} \qquad \text{(A.1)}$$

Then, value captured by country s can be written as

$$u_{s,ij,p} = \mathbf{u}_s' \mathbf{x}_{s,ij,p} = y_{ij,p} \sum_{h=1}^{K} u_{s,h} z_h \qquad \text{(A.2)}$$

Thus, the share of captured value of country s is

$$\varphi_{s,ij,p} = \frac{u_{s,ij,p}}{y_{ij,p}} = \sum_{h=1}^{K} u_{s,h} z_h \equiv F(s,i,p) \qquad \text{(A.3)}$$

Equation (A.3) shows that the share changes with index, s (supply chain participator considered), i (supplier of the final product), and p (product), but does not change with index, j (consumer of the product).

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