

Graduate School of Economics
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Ph.D. Thesis

Global Footprints in International Trade: Application to
Carbon Productivity Decomposition and Construction
of Output Accounting Frameworks as a Foundation for
Footprint Calculation

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This doctoral research stands in the interaction of two fields: trade in value added and global footprint. Through the concept of “embodied in trade” and output coefficients, any factor embodied in trade could be analyzed in a similar way to value added. Benefiting from the development of global multi-regional input-output model, the calculation of footprints in trade has become simpler and more accurate.

This dissertation comprises three chapters. Chapter 1 applies consumption-based labor and CO₂ emissions to investigate the nature of carbon productivity. A country’s carbon productivity could be divided into the part of true carbon productivity (consumption-based labor productivity and population-sustaining power of CO₂) and the part with zero-sum nature (labor exploitation, carbon emission exploitation, and trade surplus). By computing carbon productivity and its decomposed terms for 66 regions and the ROW in 2018, it is found that the difference in carbon productivity between developed and developing regions shrinks drastically after excluding exploitation parts. The results for typical countries and country groups reveal that the structure of labor and carbon emission exploitation remained relatively stable from 1995 to 2018. The LMDI analysis shows that the improvement in carbon productivity is mainly from true carbon productivity.

Chapter 2 is closely related to Chapter 1 as it further explores factors increasing a country’s possibility of becoming labor- and GHG emission- exploiters. Labor/GHG emission coefficients, industrial structure and source consumption structure from the viewpoint of labor/GHG emission intensity are considered for determining labor/GHG emission exploitation, respectively. The results of related indices for 77 regions in 2020 demonstrate that low sectoral coefficients and less biased production structure significantly increase the likelihood of exploiting, while the impact of source industry consumption structure is the opposite of expectation. The analysis of temporal changes in exploitation and the three factors for typical regions from 1995 to 2020 confirm the strength of the three aspects in explaining the values and relative position of exploitation, however, some variations have not been clarified.

Chapter 3 is a theoretical work that constructs a unified output accounting framework to calculate global footprints along global value chains. After getting rid of the total value added multiplier, a framework that discusses all relations in terms of output rather than value added is proposed. Under the world perspective, an output accounting of breaking down aggregate,

bilateral, and sectoral exports is developed. In this framework, the inconsistent definitions for foreign value added in previous studies are addressed by a counterpart criterion, replacing the perimeter criterion. In addition, global footprint measurements are decomposed concerning trade complexity, and the difference between the multi-regional input-output and emissions embodied in bilateral trade methods for consumption-based accounting is mathematically clarified.

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Introduction

Recent developments in global production networks are characterized not only by the growing scale of international trade but also by its unprecedented complexity. The enhancement in trade complexity, exemplified by the international fragmentation of production processes, has raised the number of intermediate goods crossing borders. This has resulted in repeated recording of upstream intermediate flows and challenged the ability of existing customs statistics to accurately capture the true information of supply and demand between economies.

The concept of “value-added trade” has been proposed to address this problem. It accounts only for the value added created at each production stage, excluding the parts already counted upstream. Measuring value-added is equivalent to identifying the value-added embodied in traded goods. In addition to value-added, the “embodied” concept, which is also referred to as “footprint” or “consumption-based accounting”, can be applied to any factors accompanying production, such as energy, CO₂ emissions, employment, and other natural resources. The development of global multi-regional input-output tables has enabled more precise calculation of footprints.

This doctoral research studies the calculation of embodied factors in production based on international input-output analysis. Chapter 1 and Chapter 2 apply the concept of embodied labor and CO₂ emissions to investigate the nature of carbon productivity. Chapter 3 deals with some theoretical issues surrounding footprints in global value chains.

In Chapter 1, we focus on the disparity between global labor embodied in a country’s final consumption and the domestic labor utilized in its production, as well as the disparity between global CO₂ emissions embodied in final demand and the CO₂ emitted within its territory. The two disparities are measured by the difference between consumption-based and production-based employment and CO₂ emissions of a country, respectively. Building on the theories of international labor exploitation, we define the ratio of consumption-based to production-based amounts as labor and CO₂ emission exploitation. Accordingly, we decompose carbon productivity, defined as gross domestic product (GDP) divided by CO₂ emission, into “true carbon productivity” and zero-sum components that include the two exploitation indices.

In Chapter 2, we investigate labor and GHG emission exploitation, which were defined and observed in Chapter 1, and analyze factors that increase a country’s likelihood of becoming exploiter. For labor exploitation, three aspects are assessed, including labor coefficients, the bias

of industrial structure and source consumption structure with respect to labor intensity. Similarly, GHG emission coefficients, the bias of industrial structure and source consumption structure in terms of GHG emission intensity are studied for GHG emission exploitation. We examined whether the three factors can explain the real exploitation status of 77 regions in 2020 and the time-varying trend of some selected regions from 1995 to 2020.

In Chapter 3, we make bridge between the trade in value added study and the global footprint study. The field of trade in value added has concerned to identify true value added in trade from the double-counted part. This concern is common to other factors accompanying production, but the trade in value added study has the convenient trait that the value-added coefficient vector multiplied by the Leontief inverse matrix produces a vector with all the elements equal to unity. To solve the problem that this unity property can not be used by other factors other than value added, we construct an output-based accounting framework. We also tackled the question about different and inconsistent identification of foreign value added in existing methods by proposing a counterpart criterion.

1

The decomposition of carbon productivity under the context of international trade

1.1 Introduction

Nearly 90% of carbon dioxide (CO₂) emissions are from the combustion of fossil fuels, which are also key driving forces for economic growth (OECD, 2017). How to reduce CO₂ emissions without impeding economic growth thus becomes a great challenge for humankind in tackling climate change. Carbon productivity, which is defined as the amount of gross domestic product (GDP) produced per tonne of carbon emissions, is considered an important indicator of a country's performance in mitigating global warming.

Understanding what factors determine the value of carbon productivity of a country or region has become a critical concern. Breaking down this indicator into the determinants and identifying which parts contribute to its enhancement can offer valuable insights for sustainable development. Building on the Kaya identity (Kaya et al., 1997), which pioneeringly linked anthropogenic activities to the environment, a range of carbon productivity decomposition has been suggested. These approaches decompose carbon productivity into energy intensity and CO₂ intensity of an economy or focus on the sectoral level drivers, dissecting carbon productivity into industrial structure adjustment and technological innovation (Meng and Niu, 2012), or carbon emissions intensity into sectoral energy intensity, industrial composition and final energy consumption structure (Zhang and Da, 2015). In a nutshell, the above methods address decomposition with domestic economic factors.

However, given the increasing importance of international trade, examining its impact on carbon productivity is essential. By substituting the denominator and/or numerator with the consumption-based metrics, OECD (2017) and Simas et al. (2015) redefined carbon productivity. Meanwhile, based on the input-output model, other scholars have explored the decomposition of production-based carbon emissions by isolating exports (Wood, 2009), as well as the decomposition of consumption-based carbon emissions and other variables by breaking down the final

demand matrix (Arto and Dietzenbacher, 2014; Dietzenbacher and Los, 1998; Lan et al., 2016; Malik et al., 2016). Nevertheless, none of the above studies provided a breakdown of carbon productivity.

This chapter, on the back of trade globalization, proposes a new decomposition of carbon productivity. To better understand how international trade would affect a seemingly domestic indicator, carbon productivity is regarded as the decomposition object and is not converted into the consumption-based measure. While the consumption-based metrics are incorporated into the breakdown, they are not decomposed but used to construct two measures of exploitation – one for labor and the other for carbon emissions – alongside other determinants. Consequently, carbon productivity is decomposed into the part of “true” carbon productivity (consumption-based labor productivity, and population-sustaining power of CO₂) and the part characterized by the “zero-sum” nature (carbon emission exploitation, labor exploitation and trade surplus). In contrast to previous literature, which placed equal weight on each determinant, from a global viewpoint, it can be argued that an increase in one country’s exploitation inevitably leads to a decrease in another country’s exploitation ratio, highlighting the zero-sum nature of such interactions. Indeed, the real improvement of carbon productivity is only reflected in the rising values of consumption-based labor productivity and the population-sustaining power of CO₂.

1.2 Background

The new decomposition is a result of combining the studies of carbon footprint and international labor exploitation. In this subsection, two research fields are reviewed and how the insights from one field could be integrated into the other is presented.

1.2.1 Footprint studies

Under the United Nations Framework Convention on Climate Change (UNFCCC), the ratified parties are obliged to submit the greenhouse gas (GHG) emission inventories every year (UNFCCC, 2004). Emissions here are defined as the amount of GHG emissions from activities that take place within the territory of each country. The obligations under the Kyoto Protocol as well as the Nationally Determined Contributions (NDCs) under the Paris Agreement are also defined as territorial-based emissions. Another concept of emissions has been developed, however, responding to the deepening of global production networks, which is the emissions from all the production stages to produce final goods consumed by a country’s residents. This concept of emissions was required considering the question of whether a country actually cut its emissions or not when it reduced the territorial emissions by offshoring some production processes and continues to enjoy the same consumption by increasing imports.

This concept came to be called “consumption-based emissions” whereas territorial-based emissions were called “production-based emissions”¹. In the early stages of consumption-based emissions research, it was defined as total emissions embodied in domestically produced final consumption goods plus imports (Peters and Hertwich, 2008). The production-based emissions were symmetrically defined as emissions embodied in exports and domestically produced final products. These concepts indicate that the difference in production-based and consumption-based emissions is equivalent to the difference in the embodied emissions in exports and imports. The method used to estimate the above production-based and consumption-based emissions was called emissions embodied in bilateral trade (EEBT) model (Peters, 2008). However, emissions embodied in imports here included those embodied in imported intermediate goods that might be used to produce final consumption products to be exported to satisfy other countries’ final demands. The consumption-based emissions thus calculated did not represent the previously defined one. Therefore, taking into account the vast volume of intermediates in global production chains, multi-regional input-output (MRIO) analysis was proposed to distinguish intermediate and final consumption trade. In MRIO analysis, the consumption-based emissions were defined as the row vector of emission coefficient multiplied by the Leontief inverse matrix and multiplied by the column vector of final demands of a country (Peters, 2008; Peters et al., 2011). Both EEBT and MRIO methods required the calculation of the Leontief inverse matrix, but due to data availability, early estimations were based on harmonized national input-output tables and bilateral trade statistics (Tukker and Dietzenbacher, 2013). Specifically, the estimation of the Leontief inverse matrix in MRIO analysis was to split the exports and imports into intermediates and final consumption components by using trade shares, which was not as precise as we desire. The construction of global multi-regional input-output (GMRIO) tables have solved this problem. The calculation of the global Leontief inverse matrix and consumption-based emissions have become more accurate and feasible on the basis of GMRIO (Reimer, 2011). Meng et al. (2018) further integrated embodied emissions in trade into the accounting framework of trade in value-added, which cannot only estimate embodied emissions from the common perspectives of production and consumption but also emissions embodied in different production stages along global production chains.

The concept of “embodied in products” is not restricted to CO₂ emissions. Everything embodied in trade or production can be calculated by MRIO tables. A bunch of literature involving GMRIO analysis focuses on the material aspects of international trade and the environmental and social impacts that carry, such as GHG emissions, water, land use and biodiversity, employment displacement, gender equality, governance, and access to sanitary facilities. Wiedmann and

¹In most studies, territorial-based and production-based emissions are interchangeable. The most important thing is to differentiate from consumption-based emissions. However, the definitions of production-based and territorial-based emissions differ slightly across studies (Peters, 2008; Yamano and Guilhoto, 2020). The UNFCCC and the International Energy Agency (IEA) adopt territorial-based principles to account for fuel purchased and combusted within the territory, basically, fuels combusted by non-residents are included (Yamano and Guilhoto, 2020). By contrast, production-based emissions are differentiated from territorial emissions by reallocation of fuels combusted by non-residents in the Organisation for Economic Co-operation and Development (OECD) database.

Lenzen (2018) provided a holistic literature review of the above issues. In this study, employment embodied in final demand is relevant; production-based and consumption-based employment are connected with the concept of labor exploitation.

1.2.2 Theory of labor exploitation

Marx (1867) established the theory of labor exploitation on the basis of the labor theory of value, which he had inherited from Classical Economists. Under the labor theory of value, the (exchange) value of a commodity is determined by the amount of labor embodied in it. This encompasses the amount of labor expended directly in the production process of the commodity plus the amount of labor embodied in the inputs consumed in the process, which in turn consist of the direct labor expense and the embodied labor in their inputs. In other words, the value of a commodity is determined as the sum of the direct and the indirect labor.

The profit from the production of a commodity is identified as the surplus value, which is the difference between the value of the product and the sum of the value of the inputs plus the wage payment. The wage payment is identified as the value of the workforce that exercises labor, and the value of the workforce is defined as the labor embodied in the commodities that can be purchased by the wage paid for the labor.

Labor exploitation is defined as the difference between the amount of labor expended and the amount of labor embodied in the commodities that are purchased by the wage paid for that labor. In the labor theory of value, since this difference is equal to the surplus value, it is straightforward that the existence of profit is identical to the existence of labor exploitation.

Okishio (1954) liberated the theory of exploitation from the labor theory of value. He established a theorem, which is called the Fundamental Marxian Theorem (Morishima, 1973), that the existence of exploitation is the sufficient and necessary condition for the existence of profit, even if commodities are exchanged at the relative prices that are not proportional to the amount of embodied labor when exploitation is defined as the state that the labor expended by workers is greater than the labor embodied in the commodities that can be purchased by the wage paid to the workers.

Hagiwara (2017) expanded the notion of labor exploitation to an open economy – the situation where international trade takes place. He defined the state where a worker is exploited as the state where the amount of labor expended is greater than the amount of the world labor embodied in the commodities purchased by the worker, which includes domestic products and imported products, both produced with domestic and imported inputs.

In measuring embodied employment, a crucial consideration is whether to regard labor across countries as homogeneous or heterogeneous. Hagiwara (2017) took into account the possibility of labor heterogeneity across countries, introducing a country-specific “conversion rate of labor” as a weight to measure the amount of labor. His main proposition posits that positive profits in the global economy require a set of conversion rates that ensure labor is exploited in every

country. In this framework, the assumption of homogeneous labor is a special case with an identical conversion rate for all countries. However, Hagiwara neither specified any particular values for the conversion rate nor provided a basis for determining them; his concern was about the existence of a particular set of conversion rates that ensure labor is exploited in every country when positive profits exist. Under other sets of conversion rates, it is possible that labor in certain countries is not exploited, in the sense that the laborers purchase commodities embodied with more amount of labor than they exercised. Under the assumption of homogeneous labor (with an identical conversion rate), it is likely that laborers in some countries are not exploited but instead exploit labor in other countries.

The idea of treating different countries' labor as of different quality was adopted by Leontief (1953) to resolve the discrepancy between actual U.S. trade patterns and the prediction by the Heckscher-Ohlin model. Utilizing input-output tables, he found that the United States exported labor-intensive goods and imported capital-intensive ones, contrary to what was expected given the assumption that the United States is relatively abundant in capital. This contradiction has become famously known as the "Leontief paradox"². The human capital concept has also been used to mitigate the paradox (Baldwin, 1971; Stern and Maskus, 1981); the United States can be regarded as exporting goods intensive in human capital, rather than labor. Tsaliki (2008) and Paraskevopoulou et al. (2016) have, however, criticized the notion of human capital, as it can hardly be thought of as a proper primary factor of production.

Pasinetti (1981) argued that the "Leontief paradox" was not a paradox. He explained this seeming paradox without introducing heterogeneous labor, focusing instead on the fact that the capital-output ratio was not necessarily higher in industries of developed countries with huge capital per worker, since wages are included in the denominator and the numerator of the capital-output ratio. Pasinetti's argument is in the tradition of attributing variations in wages to differences in technology rather than to labor itself. If technology is seen as embodied in capital equipment, this is a view that attributes differences in wages to differences in capital³.

In reality, it is commonly seen that labor of the same quality receives higher compensation in developed countries than in developing ones. Efforts to ascribe wage disparities to variations in labor quality or human capital amount often result in a tautological definition of quality or human capital. Considering these factors, we assume labor in all countries is homogeneous.

In closed economies, if capitalists earn profits and workers earn wages, capitalists are the exploiters, and workers are exploited. In economies with international trade, the class that earns

²A similar paradox has been observed for trade patterns concerning environmental burdens which were regarded as a factor of production (Dietzenbacher and Mukhopadhyay, 2007)

³Marx (1867) argued that technological progress in capitalist societies is mainly driven by the adoption of machinery, leading to the removal of many skills from workers because "workers become subsumed to the operation of machines rather than the other way round" (Tsaliki, 2008, 367). Marx detailed how the machinery production system facilitated the employment of child and women labor. Thus, technological advances may result in either the skilling or deskilling of workers, but irrespective of the skillfulness of labor, wages tend to increase with technological advances as noted by Pasinetti (1981). Keynes also "subsumed, so to speak, the non-homogeneity of equally remunerated labor units in the equipment" (Keynes, 1936, 42).

profits must be the exploiting class, but some workers can exploit other workers in foreign countries. This study does not distinguish capitalists and laborers in a country, and regard all the residents in a country as a group, but distinguish the residents in different countries. By doing so, it focuses on the exploitation by the residents of a country of those in other countries and regard the ratio of consumption-based employment to production-based employment as an index of labor exploitation for a country. If the ratio is larger than 1, it means this country is exploiting the rest of the world with respect to employment.

To summarize, this section has connected consumption-based and production-based employment with labor exploitation. This connection can be applied to any other quantity, of which consumption-based and production-based are distinguished. It can be considered that residents of a country exploit CO₂ emissions of other countries when the consumption-based CO₂ emissions exceed the production-based ones.

1.3 Methodology and data

The following section provides the derivation of the new decomposition of carbon productivity, explains the choice of GDP and how to construct the constant GDP with real exchange rates, demonstrates the calculation of consumption-based indicators, and mentions the data sources.

1.3.1 The new decomposition of carbon productivity

The carbon productivity of a country is defined as GDP divided by CO₂ emissions from the activities carried out by its residents. Provided that Y represents GDP and E_p represents CO₂ emissions, a country's carbon productivity is Y/E_p . If the amount of labor used to produce Y is expressed as L_p , then

$$\frac{Y}{E_p} = \frac{Y}{L_p} \frac{L_p}{E_p}, \quad (1.1)$$

which represents a decomposition of Y/E_p into the components of labor productivity and the inverse of CO₂ emissions per capita. Y/L_p is in the form of territorial productivity⁴.

⁴The definitions of territorial-based and consumption-based productivity are from Simas et al. (2015). Territorial productivity is GDP per domestic factor requirements, while consumption-based productivity based on the consumption-based accounting approach is the requirements to satisfy a country's total demand (final consumption of domestic and imported products) and is measured by gross national expenditure per global factor requirements. In this study, territorial-based productivity is later called production-based productivity to keep in line with the factor requirements estimated by the residence principle.

In a global economy, a country's GDP is not necessarily equal to its final demand⁵. Thus let us assume D represents final demands of a country and denote the labor embodied in final demand as L_c , then we have a decomposition of Y/L_p as⁶:

$$\frac{Y}{L_p} = \frac{D}{L_c} \frac{L_c}{L_p} \frac{Y}{D}. \quad (1.2)$$

The first component on the right-hand side of the equation describes the productivity of labor embodied in final consumption to produce the final demand of a country. The second represents the ratio of the amount of labor embodied in the final demand to the amount of labor expended to produce the GDP and can be interpreted as the ratio of the amount of world labor that is commanded by domestic labor. Therefore, it can be called the index of labor exploitation through international trade. The last component is the trade surplus ratio which indicates the ratio of a country's net exports to final demand plus 1. This equation represents the decomposition of production-based labor productivity into consumption-based productivity, labor exploitation and trade surplus.

Similarly, L_p/E_p can be decomposed as:

$$\frac{L_p}{E_p} = \frac{L_p}{E_c} \frac{E_c}{E_p}, \quad (1.3)$$

where E_c represents the global CO₂ emissions to produce the final demands of a country. Since the amount of domestic labor would be proportional to the total population, the first component on the right-hand side is the inverse of per capita consumption-based CO₂ emissions, which can be regarded as representing the inverse of how much CO₂ emissions are necessary to produce the commodities that sustain the population. We thus call it population sustaining power of CO₂ emissions. The second component is the ratio of consumption-based and production-based carbon emissions which represents the ratio of the CO₂ emissions embodied in the final demand to CO₂ emissions producing GDP. It indicates the amounts of global emissions commanded by

⁵By the national expenditure approach, a country's GDP is calculated as $Y = C + I + G + X - M$, where $C + I + G$ (denoting as D) is the summation of the final demand of the country, which represents the requirements (no matter from domestic production or imports) to satisfy domestic demand. Self-evidently, in an open economy, a country's GDP is not equal to its final demand. We further explain why a country's GDP is not equal to its total final goods production (denoting as D' , the row summation of final consumption demanded by this country and foreign countries) to provide insight for readers. Let $D = D_d + D_m$ and $D' = D_d + D_f$, where D_d is the final products used for domestic demand while D_m is the imports of final products and D_f is the exports of final products. Since X and M are gross trade statistics, but D_m and D_f are final product imports and exports, therefore $X - M \neq D_f - D_m$. As a result, $Y \neq D'$.

⁶Another possible decomposition form is $Y/L_p = (Y/L_c)(L_c/L_p)$. Wiedmann et al. (2015) offered adjusted land productivity by looking at GDP per land footprint, which is similar to Y/L_c . The denominator is a consumption-based indicator that lies on the demand side, while the numerator is a production-based one that lies on the supply side. Simas et al. (2015) pointed out the importance of consistency when constructing territorial-based productivity and consumption-based productivity. Hybridized productivity is still looking at the efficiency of supply, only pure consumption-based productivity reflects the efficiency of demand. Considering the uniformity, we follow Simas et al. (2015) and decompose Y/L_p into $(D/L_c)(L_c/L_p)(Y/D)$.

domestic emissions through international trade. We can regard it as an index of exploitation of carbon emissions, following the concept of labor exploitation. This is a decomposition of the inverse of CO₂ emissions per capita into the population-sustaining power of CO₂ emissions and carbon emission exploitation.

By combining Eqs. (1.1)–(1.3), we have:

$$\frac{Y}{E_p} = \frac{D}{L_c} \frac{L_p}{E_c} \frac{L_c}{L_p} \frac{E_c}{E_p} \frac{Y}{D}. \quad (1.4)$$

The first two terms of the right-hand side, $(D/L_c)(L_p/E_c)$ can be regarded as the true carbon productivity, and the $(L_c/L_p)(E_c/E_p)$ represents the exploitation components, while the last term Y/D is the trade surplus ratio. The last three components have zero-sum nature, that is, the global sums of $L_c - L_p$, $E_c - E_p$ and $Y - D$ equal 0 respectively.

1.3.2 GDP measurements

Existing literature chose different GDP indexes to calculate carbon productivity (Mir and Storm, 2016; Murshed et al., 2022; OECD, 2017). For time series data, researchers have reached a consensus for using deflated monetary values to get rid of the inflation effect (De Freitas and Kaneko, 2011; Lan et al., 2016; Zhang and Da, 2015). But for panel data, two additional problems emerge – currency exchange rates and price level discrepancy.

The World Development Indicator (WDI) provides several kinds of GDP indicators, in which two are most relevant to our analysis. The first one is PPP-GDP (constant 2017 international \$). The calculation is very simple: first, collect each country's GDP in local currency, deflate it by the best available domestic deflator, and then convert the local currency into international \$ by the PPP conversion rates. This calculation method focuses on welfare, for PPP conversion rates reflect the volume of goods and services purchased (OECD, 2012). The second one is GDP (constant 2015 \$), which differs from PPP-GDP by using the currency exchange rate of 2015. This calculation method keeps the price difference in each country's GDP. Since the occurrence of international trade is partly due to the price level discrepancy existing in different countries and undoubtedly the price level is a key factor affecting the volume and degree of international flows. We care about the actual flow rather than the welfare. Although the second GDP (we then call it constant GDP with fixed exchange rates) reserves the price issues, it fails to contain each year's currency exchange rate which is also very important in international trade (Chinn, 2019). From 1995 to 2018, constant GDP with fixed exchange rate only utilizes one year's currency exchange rate. Therefore, we newly compute a GDP indicator which we call constant GDP with real exchange rates. It would reflect the currency exchange rate in every country's GDP to the best. We first collect the current GDP data in USD of our sample countries/regions and then use the United States deflator (base year: 2015) to eliminate the inflation effect. This new GDP indicator is the most suitable one for our study, because the actual trade flow, which

is the cause of carbon emission and labor exploitation, is affected by the real exchange rate rather than the hypothetical constant exchange rate that is only real for one year. In addition, each year's GMRIO table is constructed on the currency exchange rate of each year. The GDP based on a fixed exchange rate is not consistent with the consumption-based CO₂ emissions and employment calculated with the GMRIO tables.

Besides GDP, another monetary indicator in our new decomposition also needs to solve the currency exchange rates and the price level discrepancy problems. Since a country's domestic demand for final products can not be directly obtained from open databases. We employ the GMRIO tables to calculate each country's final demand:

$$D^r = \sum_{s=1}^g F D^{sr}, \quad (1.5)$$

where $F D^{sr}$ is the final consumption products from country s to country r . Considering the uniformity of GDP and final demand, we do not use the current GDP data from the WDI, but compute it from the GMRIO tables:

$$Y^r = \sum_{i=1}^n V_i^r + \sum_{i=1}^n T_i^r, \quad (1.6)$$

where V_i^r is the value added created in domestic industry i and T_i^r is the tax less subsidy from industry i country r .

Fig. 1.1 displays the carbon productivity calculated by four GDP measurements of six regions (EU15, Japan, the United States, EU13, India and China)⁷ in 1995 and 2018. Since the production-based carbon emissions are physical quantities, the difference among the four bars is solely from the four different GDP measuring methods. The two indexes using constant GDP with real exchange rates (Real1 and Real2) were very close but the Real2 was always smaller. Except for Japan and China in 1995, the values of the Fixed, Real1 and Real2 were very similar for other regions. In 2018, the PPP was larger and the gap between the PPP and the other three varies with regions. Particularly, the difference within developed regions (EU15, the United States, and Japan) is not significant, while in developing economies (EU13, China, India), the gaps are outstanding. For India, the PPP was three times as big as the Fixed.

Fig. 1.2 further plots carbon productivity in four GDP measurements of India and EU15 from 1995 and 2018. For India, the varying trends of the four lines are very stable. Lines of the Fixed, Real1 and Real2 are adjacent and they are lower than PPP-GDP measured carbon productivity by around 2000 \$/tonne. By contrast, EU15's lines of the PPP and the Fixed show similar and ascending trends and the PPP line locates above the line of the Fixed. The fluctuations in Real1 and Real2 were greater than in PPP and Fixed GDP measurements. The distance between EU15 and India expands when GDP measurement changes from the PPP-GDP to the other three.

⁷EU13 are the European countries that joined the European Union in and after 2004, while EU15 are the countries that entered before 2004.

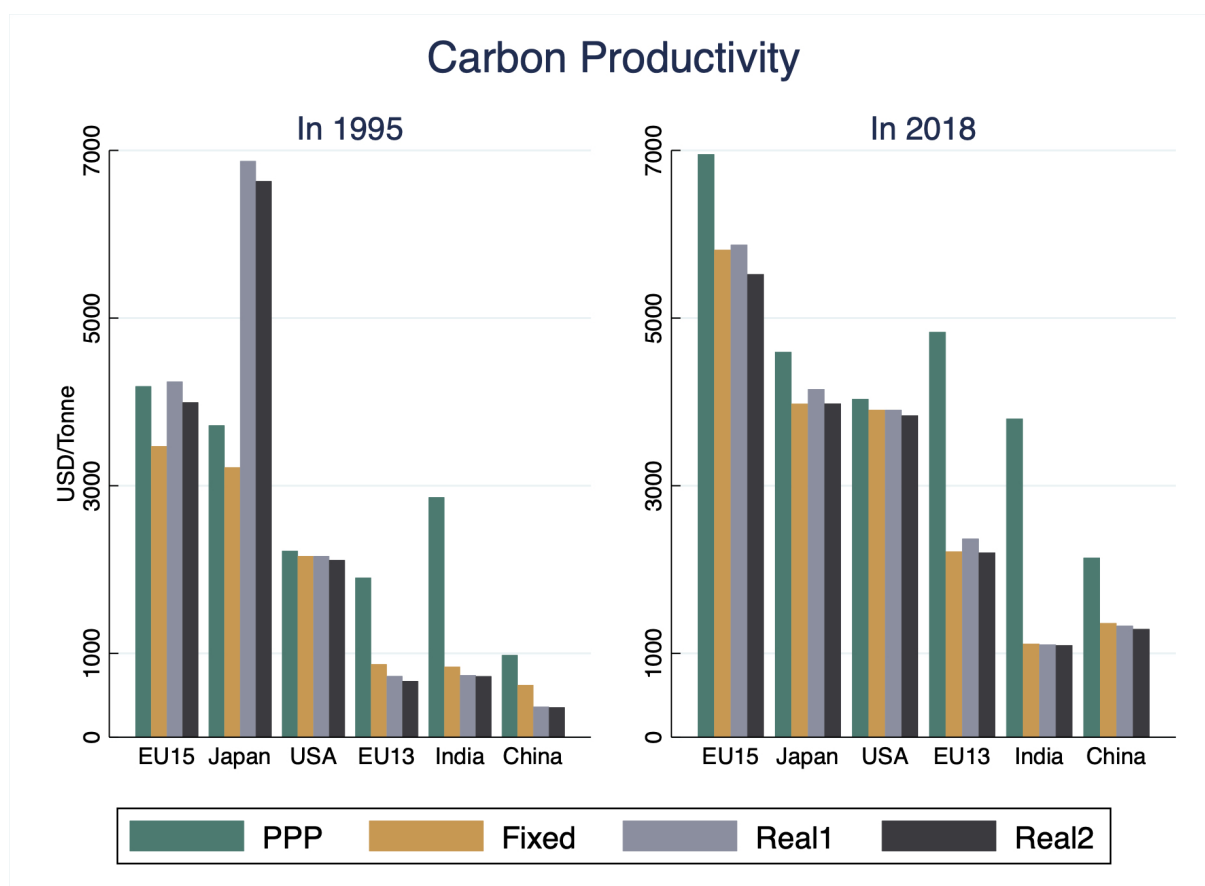


Figure 1.1 PPP means that the corresponding carbon productivity is calculated by PPP-GDP from WDI. Fixed uses GDP (constant 2015 \$) from WDI. Both Real1 and Real2 use GDP with real exchange rates but from different current GDP data sources. Real1 uses data from WDI, while Real2 is from GMRIO tables.

Therefore, it is very important to choose an appropriate GDP indicator that is compatible with the research purpose.

1.3.3 Measuring consumption-based employment and the LMDI decomposition

In the presence of international trade, production-based carbon emissions or employment need not coincide with consumption-based ones (Aichele and Felbermayr, 2012). To measure consumption-based employment⁸, the GMRIO tables is used.

⁸“Employment is defined as persons engaged in production activity within the National Accounts boundary of the resident institutional units (domestic concept) and includes both employees and self-employed”, page 10 in Horvát et al. (2020).

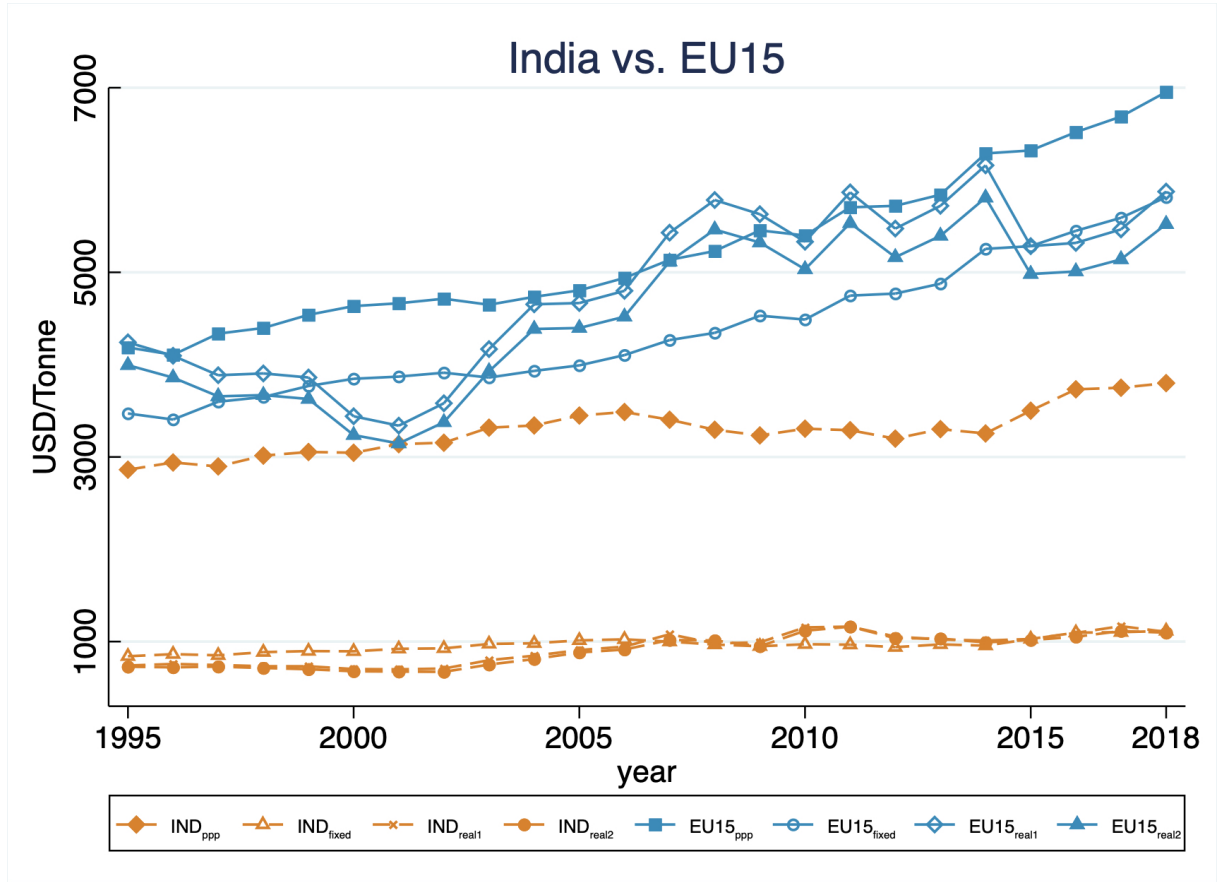


Figure 1.2 Carbon productivity by four GDP measurements of India and EU15.

Let a_{ij}^{sr} be the input coefficient from industry i of country s to industry j of country r , then the global input coefficients matrix A is defined as

$$A = \begin{bmatrix} A^{11} & \dots & A^{1G} \\ \vdots & \ddots & \vdots \\ A^{G1} & \dots & A^{GG} \end{bmatrix}, \text{ where } A^{sr} = \begin{bmatrix} a_{11}^{sr} & \dots & a_{1N}^{sr} \\ \vdots & \ddots & \vdots \\ a_{N1}^{sr} & \dots & a_{NN}^{sr} \end{bmatrix},$$

and let us express the global Leontief inverse matrix $B = (I - A)^{-1}$ in its block matrix representation as:

$$B = \begin{bmatrix} B^{11} & \dots & B^{1G} \\ \vdots & \ddots & \vdots \\ B^{G1} & \dots & B^{GG} \end{bmatrix}.$$

Let y_j^{sr} represent the final good j that is produced in country s and consumed in country r and the final demand matrix is defined as:

$$Y = \begin{bmatrix} y^{11} & \dots & y^{1G} \\ \vdots & \ddots & \vdots \\ y^{G1} & \dots & y^{GG} \end{bmatrix}, \text{ where } y^{sr} = \begin{bmatrix} y_1^{sr} \\ \vdots \\ y_N^{sr} \end{bmatrix},$$

and let us define a $GN \times G$ matrix $\mathbf{X}$ as $\mathbf{X} = \mathbf{B}\mathbf{Y}$; with its block expression:

$$\mathbf{X} = \begin{bmatrix} \mathbf{x}^{11} & \dots & \mathbf{x}^{1G} \\ \vdots & \ddots & \vdots \\ \mathbf{x}^{G1} & \dots & \mathbf{x}^{GG} \end{bmatrix} = \begin{bmatrix} \mathbf{B}^{11} & \dots & \mathbf{B}^{1G} \\ \vdots & \ddots & \vdots \\ \mathbf{B}^{G1} & \dots & \mathbf{B}^{GG} \end{bmatrix} \begin{bmatrix} \mathbf{y}^{11} & \dots & \mathbf{y}^{1G} \\ \vdots & \ddots & \vdots \\ \mathbf{y}^{G1} & \dots & \mathbf{y}^{GG} \end{bmatrix}.$$

If $\mathbf{l} = [\mathbf{l}^1 \dots \mathbf{l}^G]$, where $\mathbf{l}^r = [l_1^r \dots l_N^r]$ ($r = 1, 2, \dots, G$), is the row vector of industry employment per unit of production, then the consumption-based employment of country r defined as the r -th element of $\mathbf{l}\mathbf{X}$, which is $\sum_{u=1}^G \mathbf{l}^u \mathbf{x}^{ur} = \sum_{u=1}^G \sum_{t=1}^G \mathbf{l}^u \mathbf{B}^{ut} \mathbf{y}^{tr}$. On the other hand, the production-based employment of country r is $\mathbf{l}^r \mathbf{x}^r$, where $\mathbf{x}^r = [x_1^r \dots x_N^r]^T$ is the output vector of country r ⁹.

The new decomposition of carbon productivity could further reveal what effects are crucial in the improvement of carbon productivity. Following a period-wise analysis, it is possible to compare the performance of those effects from one base year to the determined year. Careful consideration of the chosen time period is essential, as results can be highly sensitive to this selection. The study period spans from 1995 to 2018, and the results would be too redundant if the annual time series analysis is conducted. As such, the change in carbon productivity is going to be decomposed into five effects for two periods: 1995-2006 and 2006-2018 by using the LMDI method.

According to Ang (2005); Ang and Liu (2001); Moutinho et al. (2015); Xu and Ang (2013), the LMDI method has the desirable properties of no residuals and consistency in aggregation. Based on our new decomposition (Eq. (1.4)), we decompose the change in carbon productivity over a certain interval as:

$$\Delta \left(\frac{Y}{E_p} \right) = \frac{\Delta(Y/E_p)}{\Delta \ln(Y/E_p)} \left[\Delta \ln \left(\frac{D}{L_c} \right) + \Delta \ln \left(\frac{L_p}{E_c} \right) + \Delta \ln \left(\frac{L_c}{L_p} \right) + \Delta \ln \left(\frac{E_c}{E_p} \right) + \Delta \ln \left(\frac{Y}{D} \right) \right] \quad (1.7)$$

in additive formula, and as:

$$\frac{(Y/E_p)^t}{(Y/E_p)^0} = \frac{(D/L_c)^t}{(D/L_c)^0} \frac{(L_p/E_c)^t}{(L_p/E_c)^0} \frac{(L_c/L_p)^t}{(L_c/L_p)^0} \frac{(E_c/E_p)^t}{(E_c/E_p)^0} \frac{(Y/D)^t}{(Y/D)^0} \quad (1.8)$$

in multiplicative formula for the change from period 0 to period t .

1.3.4 Data source

The GMRIO tables are taken from OECD Inter-Country Input-Output (ICIO) Tables (2021 edition) (OECD, 2021a), which provides for 66 regions and the rest of the world (ROW) from 1995 to 2018¹⁰. We obtain the production-based and demand-based CO₂ emissions data directly

⁹Production-based and consumption-based carbon emissions are similarly defined by using the CO₂ emissions coefficients vector.

¹⁰Region list sees Table A.1 in Appendix.A.1

from the OECD's Trade in embodied CO₂ (TECO2) database (OECD, 2021b), in which the dimensions of countries and industries comply with the ICIO tables. For the employment data, we combine the data from the OECD's Trade in employment (TiM) (OECD, 2021c)¹¹ and the International Labor Organization (ILO) databases (ILO, 2020)¹². The GDP data and the US deflators (base year: 2015) are taken from World Bank (2022).

1.4 Results

The following first presents the global overview of carbon productivity and its two components: true carbon productivity and exploitation measures in 2018; then provides a time series analysis of carbon productivity and its determinants for the selected country (the United States, Japan, China and India) and country groups (EU15 and EU13) from 1995 to 2018. Furthermore, the driving forces behind changes in carbon productivity are quantified.

1.4.1 Carbon productivity decomposition

(1) All regions in 2018

The carbon productivity of the 66 countries and the ROW in 2018 is shown together with the true carbon productivity in Fig. 1.3. It reveals that carbon productivity tends to be greater in high-income countries than in middle- and low-income countries, but the distance is significantly reduced for true carbon productivity. For instance, in 2018, Switzerland exhibited the highest carbon productivity at 13,790 USD per tonne (\$/t), compared to Mexico's 2,591 \$/t. However, when adjusted for true carbon productivity, Switzerland's figure significantly declined to 3,673

¹¹The ICIO tables have distinguished exporting from the non-exporting economic activities of China and Mexico. However, the TiM database only provides the employment statistics of China (CHN) and Mexico (MEX), not distinguishing between exporters and non-exporters. To solve this problem, this study tried two ways: 1) before getting B , first aggregate MX1&2 to MEX, CN1&2 to CHN. Then the regions will be converted to 67; 2) keep the dimension as $GN \times GN$ and get B , but for the employment coefficient, use the employment coefficient of MEX for MX1&2, CHN for CN1&2. Both methods could accurately estimate the consumption-based employment of countries except China and Mexico. But compared with method 1, the absolute error of method 2 is larger. This paper finally chooses the first method to deal with this estimation problem.

¹²For the employment data, the TiM database only provides employment data for 51 countries, which is not in line with that in OECD's TECO2 database. In order to fill this gap, we combine the TiM and ILO databases together to obtain production-based employment of 66 economies and the ROW. The employment indicators of the TiM database are presented for 45 industries of 51 countries covering the time period 1995 to 2018. Although the ILO database offers employment indicators for all the regions wanted, we still use the data of 51 countries from the TiM database and obtain the data of the other 15 countries and the Row from the ILO database, for we also use the ICIO tables and carbon emissions statistics of the OECD database, we take OECD's statistics as the benchmark. Another step is needed for completing the collection of production-based employment statistics. The ILO database only gives employment data for 14 sectors, while in the TiM database, 45 sectors are available. Luckily, both databases use ISIC rev.4 (United Nations, 2008) as the criterion of industrial classification. We use the share of value added of a sector to further break down the 14 sectors to 45 sectors (International Labour Organization, 2022). Morocco's value added (including tax and subsidy) is negative which could not be used as a ratio for allocation. We use the value-added ratio excluding tax and subsidy of Morocco to tackle this problem.

\$/t, while Mexico's value rose to 2685 \$/t. As a result, although Switzerland's carbon productivity was 5.3 times that of Mexico, this ratio narrows to 1.4 times under the true carbon productivity measure. Countries with relatively high carbon productivity often have smaller proportions of true carbon productivity. On average, the ratio of true carbon productivity to carbon productivity among the top 20 countries (by carbon productivity) is approximately 52.2%, in stark contrast to 120.1% for the bottom 20 regions.

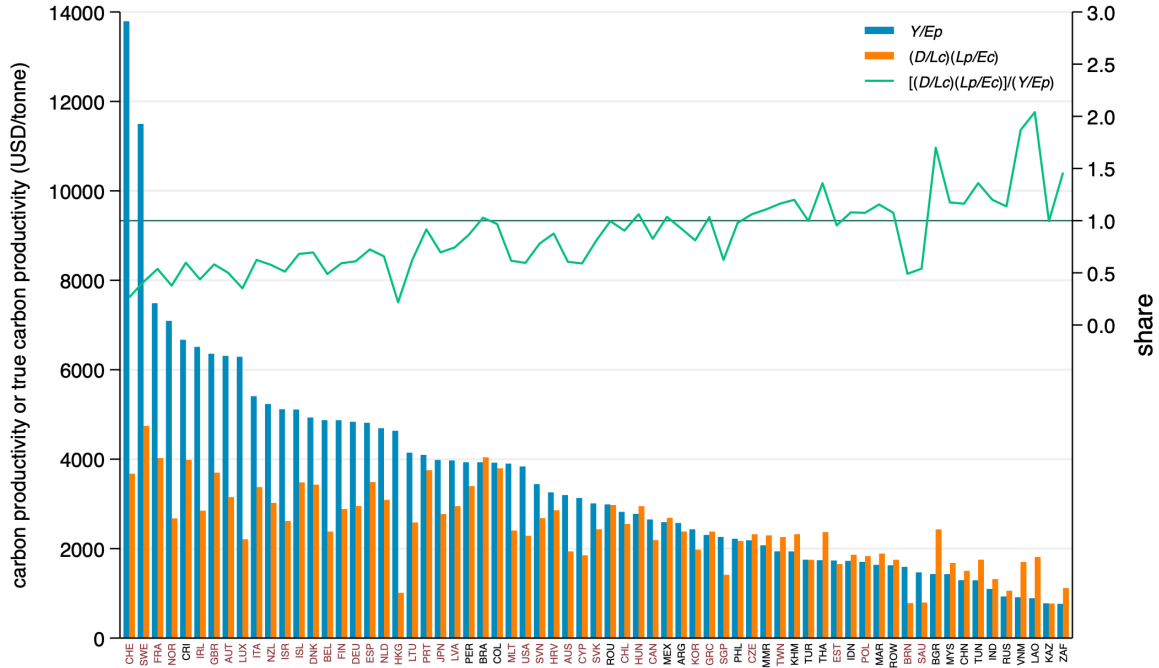


Figure 1.3 Carbon productivity (Y/E_p) and true carbon productivity ($(D/L_c)(L_p/E_c)$) in 2018 for 66 regions and the ROW, organized according to carbon productivity in descending order. The line shows the ratio of true carbon productivity to carbon productivity (right axis). The red x-labels indicate developed nations, while the black ones represent developing economies¹³.

The difference between carbon productivity and true carbon productivity is attributed to the labor and carbon emission exploitation. The degrees of the two exploitation are illustrated in Fig. 1.4 using the indices of $2(L_c - L_p)/(L_c + L_p)$ and $2(E_c - E_p)/(E_c + E_p)$, which better display the exploiting and exploited countries. Bars above the horizontal axis indicate that the consumption-based employment or carbon emissions for these countries exceed their production-based counterparts, suggesting exploitation. For Switzerland, the degrees of exploitation regarding employment and carbon emissions were 0.55 and 0.63, respectively. The corresponding values for L_c/L_p and E_c/E_p were 1.75 and 1.92. Conversely, in Vietnam, the degrees of labor and carbon emission exploitation were -0.42 and -0.24, respectively, and the related values for L_c/L_p and E_c/E_p were 0.65 and 0.79.

¹³Based on the World Bank's classification of income and lending groups (World Bank, 2019), we refer countries with high income ($> \$12375$) as developed nations.

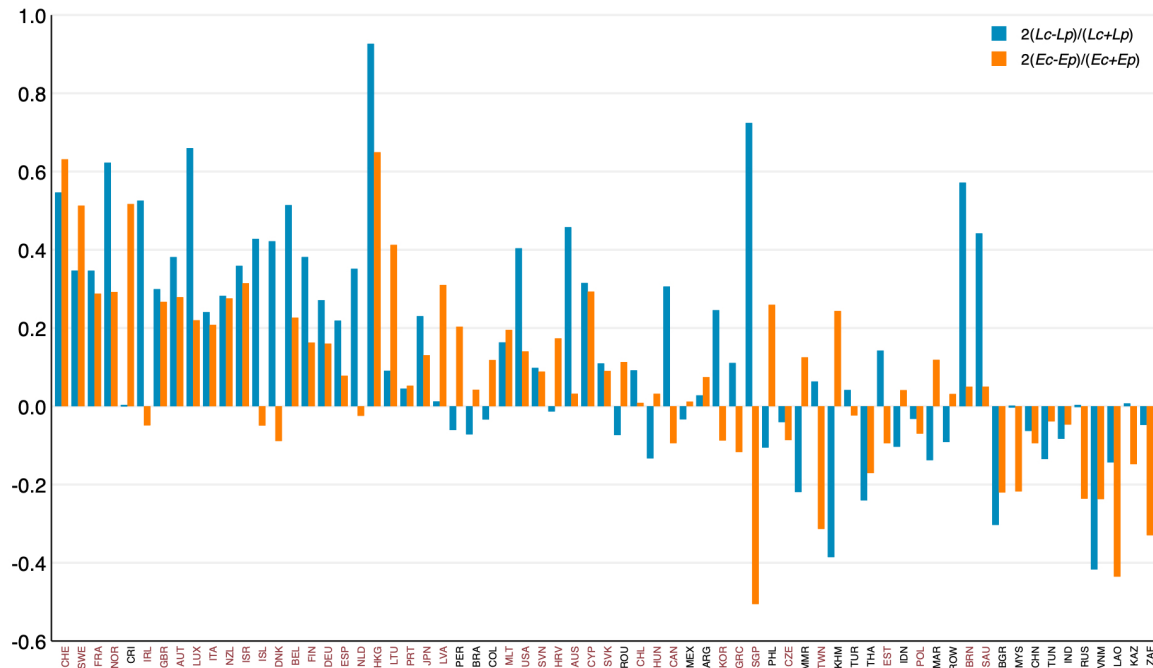


Figure 1.4 Labor and carbon emission exploitation in 2018 for all 66 economies and the Row. The country order on the horizontal axis complies with Fig. 1.3.

A pattern for exploitation according to carbon productivity is apparent. Countries with high carbon productivity, typically the developed countries, are often exploiter, whereas countries with low carbon productivity, represented by developing countries, tend to be exploited. Specifically, as shown in Table 1.1, among the 42 high-income nations, 28 engage in both labor and carbon emission exploitation, while only 2 of the 25 developing countries do so. Regarding single exploitation, labor exploitation is more prevalent in developed areas: with 10 countries exploiting labor while being exploited in terms of CO₂ emissions; conversely only 2 nations exploit carbon emissions while being exploited in labor. In developing regions, the situation is contrary; 4 countries exploit labor while being exploited in CO₂ emissions, and 11 exploit carbon emissions while facing labor exploitation. The underlying reasons is discussed later.

Table 1.1 Classification of the countries with respect to exploitation pattern

	I	II	III	IV	Total
Developed	28	10	2	2	42
Developing	2	4	11	8	25

Note: The numbers indicate the number of countries in each category: category I represents countries exploiting both labor and CO₂ emissions, category II countries exploiting labor while being exploited in CO₂ emissions, category III countries exploiting CO₂ emissions while being exploited in labor, and category IV countries being exploited in both labor and CO₂ emissions.

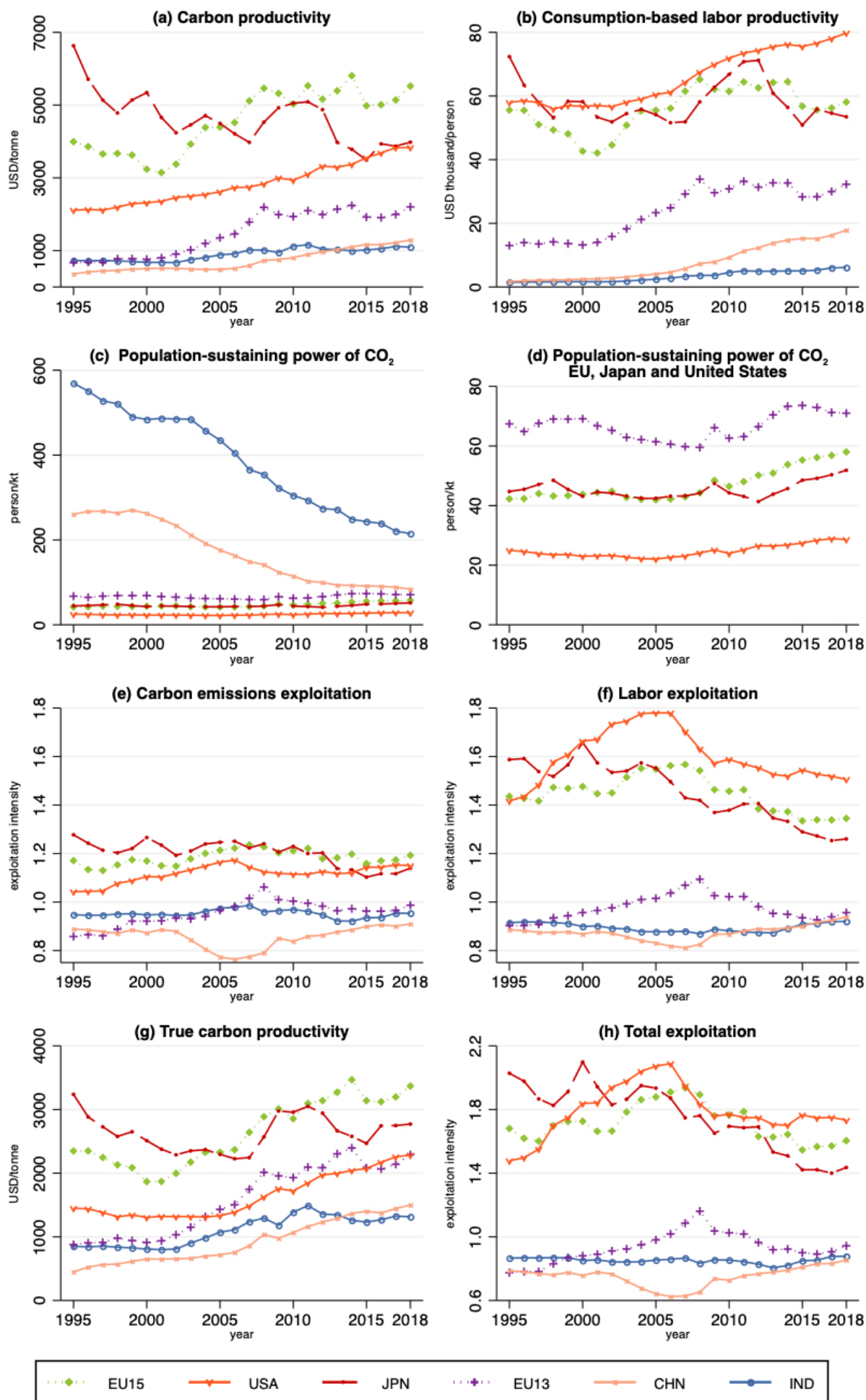
(2) Typical country and country groups ranging from 1995 to 2018

A detailed interpretation of our new decomposition, examining six regions from 1995 to 2018, is illustrated in Fig. 1.5. Panel (a) depicts the evolution of carbon productivity from 1995 to 2018. The EU15 demonstrated substantial enhancement in carbon productivity, although there was a decrease from 1995 to 2001, it surpassed Japan in 2005, reaching 5523 \$/t by 2018. Similarly, the United States showed steady improvement, increasing from 2133 in 1995 to 3838 \$/t in 2018. In contrast, Japan experienced dramatic fluctuations, with an overall declining trend. Starting at 6633 \$/t in 1995, Japan's carbon productivity dropped to a nadir of 3487 \$/t in 2015, followed by a slight increase thereafter. Meanwhile, the carbon productivity of EU13, China and India remained below 2300 \$/t throughout the period.

Fig. 1.5(b) illustrates the evolution of consumption-based labor productivity. Despite significant increases, the consumption-based labor productivity for EU13, India, and China has remained below 40 thousand USD per capita (k\$/p), while Japan, EU15, and the United States have consistently exceeded this value. Differing from its ranking in carbon productivity, the United States has led in consumption-based labor productivity since 2001, rising from 58.0 k\$/p in 1995 to 79.8 k\$/p in 2018. EU13's growth from 2000 to 2008 was prominent, reflecting their economic advancement after the collapse of the socialist system, and likely influenced by their affiliation with the EU. However, this growth has not continued beyond that period, in contrast to the ongoing increases seen in China and India. Furthermore, China's consumption-based labor productivity has begun to increase faster than that of EU15 and Japan, likely due to industrial transformation.

Fig. 1.5(c) displays the changing trend of the population-sustaining power of CO₂. We observe a great slump in India and China. This reflects a rapid increase in consumption-based CO₂ emissions per capita, resulting from heightened energy consumption due to economic development. Yet, the population-sustaining power of China has remained stable at around 90 persons/thousand tonne (p/kt) since 2013. EU, Japan and the United States locate at the bottom, with minimal variations observed. We zoom their curves in panel (d). The population-sustaining power of CO₂ of the United States have kept below 30 p/kt for the last two decades. Although Japan and EU15 have tried to improve their population-sustaining power, the values were still below 60 p/kt by 2018. Japan's decrease from 2010 to 2013 was due to the shutdown of nuclear power plants. EU13's population-sustaining power of CO₂ declined when their consumption-based labor productivity showed active growth from 2000 to 2008. Prior to 1995, under the socialist system, their population-sustaining power of CO₂ was likely even lower.

The situation of carbon emission exploitation is clearly reflected in Fig. 1.5(e). EU15's exploitation intensity fluctuates, which was kept at a high level and there is no sign of alleviation. Japan's carbon emission exploitation was the highest (1.28) in 1995 but gradually declined to 1.14 in 2018. The USA's exploitation intensity rose from 1.04 in 1995 to 1.17 in 2006, then decreased but gradually recovered close to its peak by 2018. China has been exploited during the last two decades. The exploitation intensity was steady (around 0.88) from 1995 to 2001.



19
Figure 1.5 Carbon productivity and its decomposed components, 1995-2018.

Subsequently, the ratio dropped to 0.76 in 2006 after China joined the World Trade Organization and experienced exponential growth in trade. Remarkably, the curves of the USA and China appear like a mirror image from 2002 to 2011. EU13 economies were the lowest (0.86) in 1995. However, it increased substantially, exceeded 1.0 in 2007, and soared to 1.06 in 2008. From 2007 to 2010, EU13 economies have changed to exploit other regions in the world with respect to embodied CO₂ emissions. In 2010, this ratio slightly decreased and dropped back to below 1.0 (about 0.97), indicating the exploitation of EU13 has been largely mitigated. The ratio of India was between 0.9 and 1.0 during the investigated periods.

Of the two kinds of exploitation, labor exploitation has been more intense than the exploitation of CO₂ emissions (Fig. 1.5(f)), especially for the developed regions. The intensities of labor exploitation for the USA, Japan and EU15 are consistently higher than those of carbon emission exploitation. The ratio in the USA rapidly increased from 1995 and reached 1.8 in 2006. Afterwards, it declined but remained as high as 1.5 by 2018. Japan's downward trend in labor exploitation intensity is more prominent than that in carbon emission exploitation. EU15 also showed a mild alleviation recently, although its ratio increased from 1995 to 2007. The mirror image of the USA and China is more pronounced for labor exploitation even for the whole period. China is distinctive because it is more exploited in carbon emissions than in labor since 2003. India's intensity of being exploited in CO₂ emissions is consistently milder than that in labor.

The multiplication of consumption-based labor productivity and the population-sustaining power of CO₂ produced the true carbon productivity (Fig. 1.5(g)). The fluctuation in true carbon productivity was less violent compared with its two components. Except for Japan, the true carbon productivity exhibited an upward trend. But Japan's declining tendency is much milder than that of carbon productivity. Surprisingly, the true carbon productivity values of the United States and EU13 were very close, especially in 2018 – 2286 \$/t and 2291 \$/t respectively. This result again highlights the importance of removing the exploitation part from the carbon productivity. Fig. 1.5(h) shows the development of the product of the two exploitation.

The trade surplus ratios of the typical countries were around 1.0 and the changes are very moderate.

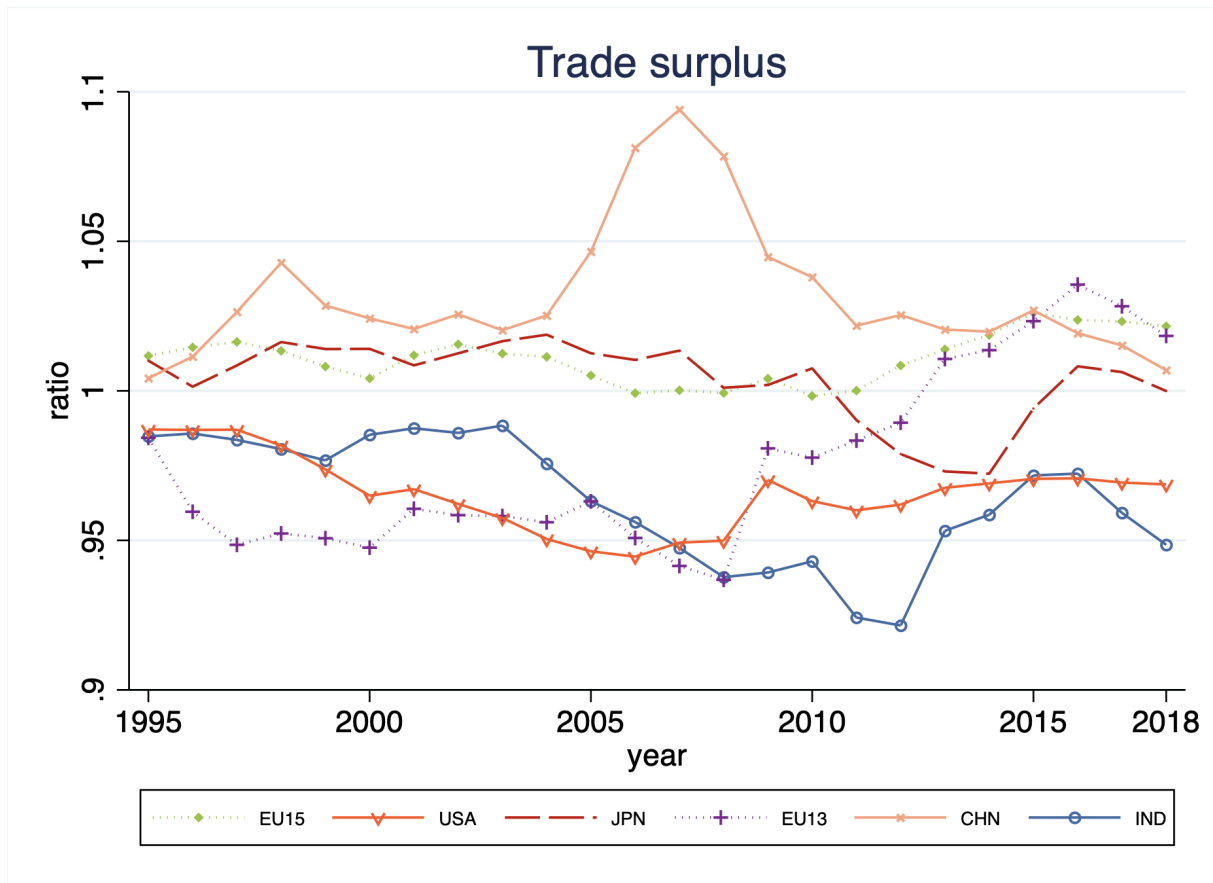


Figure 1.6 Trade surplus ratio for typical countries and country groups from 1995 to 2018

1.4.2 LMDI decomposition of change in carbon productivity

We decompose the change in carbon productivity into five causal determinants for two distinct periods: 1995-2006 and 2006-2018¹⁴. The results for each country and country group are combined and presented in Figs. 1.7-1.9.

The demand for fossil fuels in India escalated alongside its economic development, leading to increased carbon emissions. Consequently, in both periods, the net effect on carbon productivity was largely contingent upon the interplay of two offsetting impacts: positive consumption-based labor productivity and negative population-sustaining power of CO₂ effects. China displayed similar change patterns of true carbon productivity effects as India but to a more dramatic extent in the 2006-2018 phase. This radical variation may be caused by the rapid economic growth and tremendous energy utilization. During the second period, China overtook the United States

¹⁴We have also tried three periods (1995-2002, 2002-2010, 2010-2018) and four periods (1995-2000, 2000-2006, 2006-2012, 2012-2018) and their averages. But two periods are good enough to capture the most essential features of the selected samples, so we decide to take the concise one. The reasons why we choose the year 2006 as the cutting point are: 1) consider the balance of intervals, a middle point is preferred; 2) since the exploitation did not change greatly between 1995 and 2018, in order to show the exploitation effects in the LMDI decomposition, we try to pick the turning point during the exploitation change. China and the United States are the most important two countries in the world with respect to exploitation situations. The turning points of labor exploitation of the United States and China are 2006 and 2007 respectively and the peak and nadir years of carbon emission exploitation of the United States and China are both 2006.

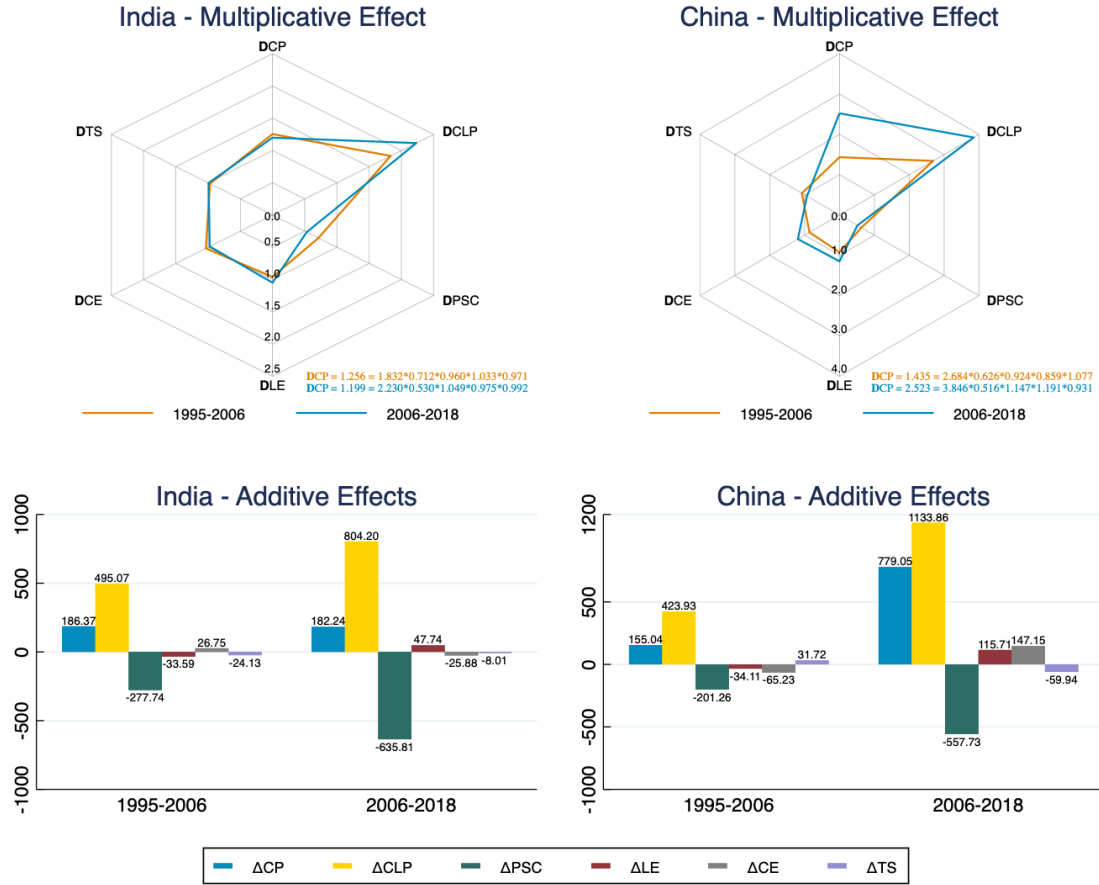


Figure 1.7 LMDI decomposition of the change in carbon productivity for India and China. CP, CLP, PSC, LE, CE and TS mean $Y/E_p, D/L_c, L_p/E_c, L_c/L_p, E_c/E_p$ and Y/D respectively. D means ratio between the beginning and the ending years respectively. Those with Δ represent the term on the left-hand side the five terms of the right-hand side of Eq. (1.7). The notation is followed in Figs. 1.7 to 1.9.

as the world's largest carbon emitter in 2008 and its GDP surpassed that of Japan to become the world's second-largest economy in 2010 (OECD, 2021b). The exploitation effects and the trade surplus impact were negligible for India, whereas in China, the exploitation effects had a negative effect in the first period, but alleviation in the second period led to an increase in carbon productivity. The positive effect in consumption-based labor productivity and the negative effect in the population-sustaining power of CO₂ emissions of China and India are the most telling confirmation of the view that affluence is the main driver of carbon footprint increase (Malik et al., 2016).

Between 1995 to 2006, EU13's carbon productivity increased by 788.38 \$/t. This significant increase is dominated by the positive and considerable effect of consumption-based labor productivity and supplemented by two positive exploitation effects, which differ from the case of China and India whose exploitation effects during the first period are either negative or minimal. Another difference from China and India is that EU13 managed to realize the positive population-

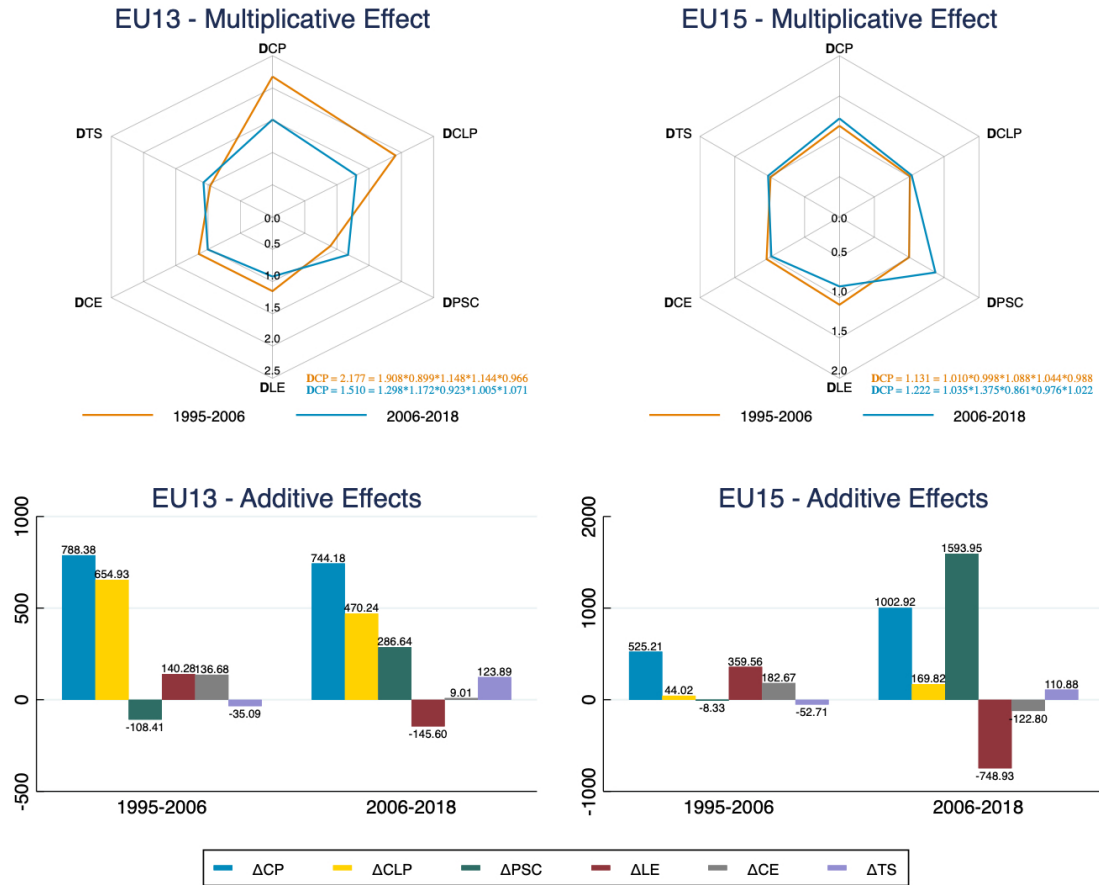


Figure 1.8 LMDI decomposition of the change in carbon productivity for EU13 and EU15.

sustaining power of CO₂ effect in the 2006-2018 period, which supported the change in carbon productivity by 286.64 \$/t. Nevertheless, the positive consumption-based labor productivity effect diminished over the two periods. The trade surplus effect for EU13 from 2006 to 2018 was rather outstanding compared with other areas.

Despite being geographically adjacent, the economic development of EU15 differ greatly in comparison with EU13. During the first period, the true carbon productivity effects were too tiny to be noticed, indicating that there was nearly no change of EU15's consumption-based labor productivity and high living standards at the expense of CO₂ emissions. In contrast, the exploitation degrees even expanded and provided a positive contribution to the change in carbon productivity. The most conspicuous feature during the second period is the surge of the population-sustaining power of CO₂ effect, which increased by 37.5%.

From 1995 to 2006, the United States increasingly exploited the rest of the world, as evidenced by the positive and significant effects of labor and carbon emission exploitation. These effects overpowered the negative impacts of the population-sustaining power of CO₂, contributing to an overall increase of 29.5% in carbon productivity. The variation in carbon productivity of the United States has displayed an increasing trend and the driving forces have changed from

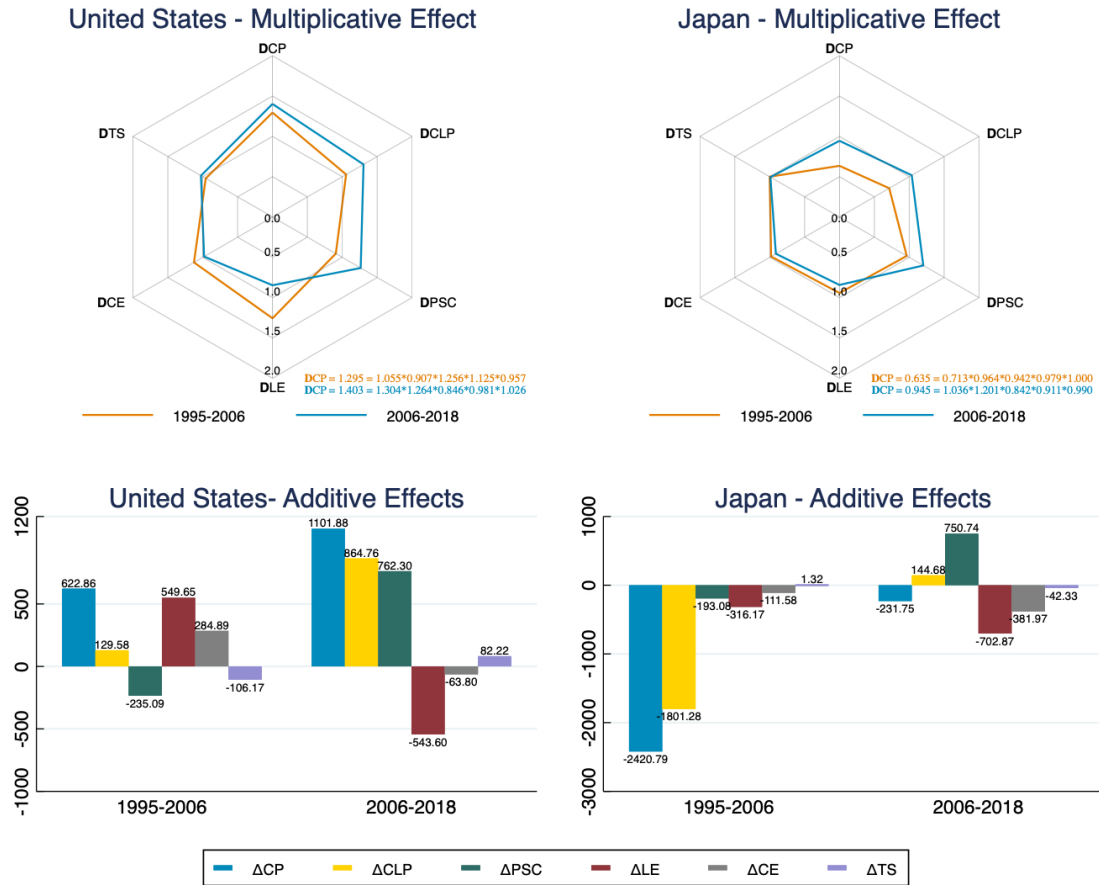


Figure 1.9 LMDI decomposition of the change in carbon productivity for the United States and Japan.

zero-sum to true carbon productivity effects in 2006 to 2018, but the labor exploitation rate still remained at a high level, and the carbon emission exploitation rate has increased again in recent years.

Among the selected countries and country groups, the results of Japan differ from other regions widely – Japan is the only country that saw a slump in carbon productivity during the investigated periods. From 1995 to 2006, except for the trade surplus effect, the others all contributed negatively to the change in carbon productivity which dropped by 2420.79 \$/t. This huge fall is dominated by the considerable and negative consumption-based labor productivity effect that accounted for 1801.28. The negative exploitation effects continued in the next period and even became larger. However, from 2006 to 2018, there was a recovery of consumption-based labor productivity, which contributed positively, though only 144.68, to the change in carbon productivity. The population-sustaining power of CO₂ effect was the principal power to improve true carbon productivity in the second period but this could not turn the carbon productivity into a positive result due to the reduced levels of exploitation.

1.5 Discussion

By excluding the exploitation—namely, how much world labor and CO₂ emissions a country's own labor and CO₂ emissions can command—from the carbon productivity, the discrepancies in carbon productivity between developed and developing countries have diminished. For instance, while EU15's carbon productivity was 4.3 times larger than China's in 2018, but in terms of true carbon productivity it reduced to 2.2. The gap between the two regions also decreased from 11.2 in 1995 to 4.3 in 2018, but the ratio of the difference of carbon productivity to the difference of true carbon productivity for EU15/China remained stable, changing slightly from 1.9 in 1995 to 2.1 in 2018. This fact suggests that the intensity of exploitation did not vary much between 1995 and 2018 (although higher around 2006 and 2007). The decrease in the discrepancy in carbon productivity was primarily caused by the narrowing of the gap in true carbon productivity. The intensity of exploitation appears to be stable.

We also observed that the intensity of labor exploitation is generally higher than that of CO₂ emission exploitation in Fig. 1.5, and found that more developed countries exploit labor than exploit CO₂ emissions, while more developing countries are exploited in labor than in CO₂ emissions in Table 1.1. Let us investigate the circumstances behind those facts. When country r is exploiting labor, then $L_p^r = l^r x^r < L_c^r = \sum_{u=1}^G l^u x^{ur} = \sum_{u=1}^G \sum_{t=1}^G l^u B^{ut} y^{tr}$. This occurs if

- i) $l_i^r < l_i^u$ for $u \neq r$ or
- ii) x^r is biased towards sectors with relatively smaller labor coefficients, and $x^u = \sum_{s=1}^G x^{us}$ ($u \neq r$) is biased towards sectors with relatively greater labor coefficients.

Since output x_i^r is measured in monetary price, the first scenario arises when output price per worker in a particular industry i of country r is larger, which is common in developed countries. If the higher output per worker is accompanied by higher wage rates, some of the other industries with larger labor coefficients may face comparative disadvantages. Consequently, these industries might be replaced by imports from foreign countries, bringing about the second scenario. This process will take place as a normal function of global market economy.

The same reasoning may be applied to carbon emission exploitation. The above argument about scenarios i) and ii) will be stated for carbon emission exploitation by replacing labor coefficients with CO₂ emission coefficients. However, one important difference is that labor has its own price, that is “wage”, whereas CO₂ emissions do not have any price. Therefore, there is no driving force that will cause the situation i) and ii) as a natural function of market. Certainly many countries have introduced artificial measures for pricing CO₂ emission, such as carbon taxes and emissions trading scheme, but the levels of price are relatively small compared to the fossil fuel prices, and in most cases measures have been adopted to ensure that industrial competitiveness is not undermined, which makes carbon prices ineffective. As a result, CO₂ emissions exploitation must have taken place only as an incidental consequence of the changes that have occurred with labor exploitation. This inference conforms with Peters et al. (2011), which indicated that

emission transfer was not caused by stricter environmental regulations in developed countries but by other preexisting policies or socioeconomic factors. In relation to this point, it is often asserted that changes in industrial structure, such as transformation from manufacturing to service industries, are crucial for mitigating CO₂ emissions. This transformation may have contributed to some improvement in consumption-based labor productivity, but it would not enhance population-sustaining power of carbon emissions and is likely to lead to an expansion of labor exploitation through scenario ii). When a country's carbon emissions are reduced solely through such industrial transformation, it must result from an expansion of carbon emission exploitation. We believe that the exploitation effects were manifested in the deepening of exploitation from 1995 to 2006.

We have decomposed carbon productivity into true carbon productivity and the zero-sum components. The true carbon productivity, constituting consumption-based labor productivity and population-sustaining power of CO₂ emissions, represents the positive-sum aspect of international economic relationships. When the positive-sum aspect of international trade is discussed, gains from trade have often been referred to. In fact, both gains from trade and exploitation are inherent in international trade, with the former belonging to the domain of efficiency and the latter to the domain of equity. However, we did not deal with gains from trade, because it is not relevant to our purpose. Meanwhile, although gains from trade and progress in labor productivity are positive-sum aspects in international economic relationships, they are different. According to Pasinetti (1981), the primary source of gains from international economic relationships is that underdeveloped countries "can learn the method of production which are being used already in" advanced countries, and trade is only a secondary source of international gains and plays "the subordinate role". The gains from trade has "once-for-all character" (Pasinetti, 1981, 250-261). In general, technological development enhances consumption-based labor productivity, but knowledge spillovers to any country can also improve this form of productivity, benefiting not only the learning nation but also countries that import value added from it. This impact on productivity is distinct from gains from trade, with the latter belonging to the domain of static efficiency.

The population-sustaining power of CO₂ pertains to the domain of climate policy. The recent rise in the population-sustaining power in the developed world has been mainly caused by the growth of the use of renewable energies (Moutinho et al., 2015). Substitution of fossil fuels with renewable and nuclear energy seems to be the only well-established method to increase the population sustaining power of CO₂ without decreasing the consumption-based labor productivity. If net CO₂ emissions have to be reduced to zero at some point of time to stabilize global temperature (IPCC, 2023). The population-sustaining power of CO₂ has to move toward infinity. However, the recent annual growth rates of the population sustaining power of CO₂ for the developed countries are only around 2%. If this rate continues, the population-sustaining power in 2030 will be only 1.3 times larger than those in 2018, and those in 2050 will be only 2 times larger than those in 2018.

1.6 Concluding remarks

This chapter revealed the complex relationship between trade, economic growth and the environment by proposing a new decomposition of carbon productivity. A country's carbon productivity could be divided into the part of true carbon productivity and the part with zero-sum nature. Consumption-based labor productivity and population-sustaining power of CO₂ represent the true carbon productivity. Labor and carbon emission exploitation and trade surplus show the nature of zero-sum games. By investigating 66 regions and the ROW in 2018 and typical country and country groups from 1995 to 2018, we found that the wedge in carbon productivity between developed and developing regions shrinks drastically after separating out the exploitation. Besides, labor and carbon emission exploitation tend to be stable between 1995 and 2018. The increase in carbon productivity is mainly from the improvement in true carbon productivity. We identified the consumption-based labor productivity and population-sustaining power of CO₂ effects as the main driving forces of change in carbon productivity, which are very important for tackling global warming.

2

Exploring the factors influencing labor and GHG emission exploitation

2.1 Introduction

In Chapter 1, a new decomposition on carbon productivity is proposed and discussed. The two exploitation indices - labor and carbon emission exploitation - represent the part with “zero-sum” nature and explain the difference between a country’s carbon productivity and true carbon productivity. We found that there is a pattern for exploitation by the level of economic development. Among 42 high-income countries, 40 engage in exploitation, with 28 involved in both labor and carbon emission exploitation, and 12 exploit either labor or carbon emissions alone. In contrast, of the 25 developing countries, 8 experience exploitation in both labor and carbon emissions; 4 countries exploit labor while being exploited in CO₂ emissions, and 11 exploit carbon emissions while facing labor exploitation. Additionally, we observed that more developed countries exploit labor than exploit CO₂ emissions and more developing countries are exploited in labor than in CO₂ emissions; the intensity of labor exploitation is generally higher than that of CO₂ emission exploitation. This chapter aims to further explore the influencing factors behind the two exploitation ratios.

The OECD has updated its ICIO tables, replacing the TECO2 database with the Greenhouse gas footprint indicators (OECD, 2024a). To obtain the latest insights, this chapter will use the most recent OECD ICIO tables (2023 edition) and the corresponding environmental accounts. However, the Greenhouse gas footprint indicators only provide data on greenhouse gas emissions. Consequently, the focus shifts to GHG productivity, especially its two components: labor exploitation and GHG emission exploitation.

The major GHGs include carbon dioxide (CO₂), methane (CH₄), nitrous oxide (N₂O) and industrial gases. A significant amount of CH₄ and N₂O is emitted from agricultural sectors, therefore the importance of agriculture has been increased in the new database.

2.2 Methods and data

This section focuses on analyzing the factors contributing to the extent of exploitation by constructing indices from different aspects.

2.2.1 Factors influencing exploitation of labor and GHG emissions

In Chapter 1, labor exploitation is identified when the global labor embodied in a country's consumed goods exceeds the domestic labor utilized in its production output. The ratio of consumption-based employment to production-based employment within a country is defined as the degree of labor exploitation. This definition can be easily applied to GHG emissions.

To better explain the difference between a country's consumption-based and production-based employment or GHG emissions, it would be useful to revisit the consumption-based measurement, even though it was introduced in Chapter 1.

Based on the ICIO model, the matrix of output generated in all countries by final consumption in one country is defined as $\mathbf{X} = \mathbf{B}\mathbf{Y}$:

$$\mathbf{X} = \begin{bmatrix} \mathbf{x}^{11} & \dots & \mathbf{x}^{1G} \\ \vdots & \ddots & \vdots \\ \mathbf{x}^{G1} & \dots & \mathbf{x}^{GG} \end{bmatrix} = \begin{bmatrix} \mathbf{B}^{11} & \dots & \mathbf{B}^{1G} \\ \vdots & \ddots & \vdots \\ \mathbf{B}^{G1} & \dots & \mathbf{B}^{GG} \end{bmatrix} \begin{bmatrix} \mathbf{y}^{11} & \dots & \mathbf{y}^{1G} \\ \vdots & \ddots & \vdots \\ \mathbf{y}^{G1} & \dots & \mathbf{y}^{GG} \end{bmatrix}, \text{ where } \mathbf{x}^{rs} = \begin{bmatrix} x_1^{rs} \\ \vdots \\ x_N^{rs} \end{bmatrix}.$$

$\mathbf{x}^{rs}$ is the output produced in country r to meet the final demand of country s . By multiplying the global employment coefficient vector ($\mathbf{l} = [\mathbf{l}^1 \dots \mathbf{l}^G]$) or the GHG emission coefficient vector ($\mathbf{g} = [\mathbf{g}^1 \dots \mathbf{g}^G]$) by the bilateral absorbed output matrix, we can estimate the employment or GHG emissions embodied in final demand of each country:

$$\mathbf{L}_c = \mathbf{l}\mathbf{X} = \mathbf{l}\mathbf{B}\mathbf{Y}, \quad \mathbf{G}_c = \mathbf{g}\mathbf{X} = \mathbf{g}\mathbf{B}\mathbf{Y}.$$

The r -th element of $\mathbf{L}_c$, $L_c^r = \sum_{u=1}^G \mathbf{l}^u \mathbf{x}^{ur} = \sum_{u=1}^G \sum_{t=1}^G \mathbf{l}^u \mathbf{B}^{ut} \mathbf{y}^{tr}$, is the consumption-based employment of country r . Similarly, G_c^r denotes country r 's consumption-based GHG emissions. Additionally, let L_p^r and G_p^r represent country r 's production-based employment and GHG emissions, respectively. These values can be calculated as $\mathbf{l}^r \mathbf{x}^r$ and $\mathbf{g}^r \mathbf{x}^r$, where $\mathbf{x}^r = [\mathbf{x}_1^r \dots \mathbf{x}_N^r]^T = \sum_u^G \mathbf{x}^{ru}$ is the output vector of country r . Consequently, the labor exploitation ratio for country r is calculated as L_c^r/L_p^r and the GHG emission exploitation ratio is given by G_c^r/G_p^r .

With regard to labor, the possibility that country r exploits other countries would increase,

- i) when the labor coefficients for many sectors of country r are lower than those in the corresponding sectors of other countries,
- ii) when the industrial structure is biased toward non-labor-intensive direction, and

iii) when the source structure of consumption is biased toward labor-intensive direction.

In the following subsections, these three aspects will be discussed in succession with a focus on labor. However, a similar discussion could also be applied to GHG emissions.

2.2.2 Labor coefficients

It is possible to compare the labor coefficient of any industry in country r with that of the corresponding sector in any other country. However, the analysis includes 45 industries and 77 regions. Accordingly, in pairwise comparisons between countries, country r may have smaller labor coefficients for some sectors but larger coefficients for others. Additionally, for a given sector, country r 's labor coefficient may be lower than that of some countries while higher than that of others. It would be helpful if we can construct a country-level index for labor coefficients that represents labor intensity.

A country's average labor coefficient evidently reflects the country-level labor intensity. Nevertheless, it is intertwined with a country's output composition. For example, country r 's labor intensity is computed as:

$$l^r = \frac{\sum_i l_i^r x_i^r}{\sum_i x_i^r}, \quad (2.1)$$

which can be viewed as an average of country r 's sectoral labor coefficients, weighted by each sector's output share. It is a mixture of aspect 1 and aspect 2.

To extract the aspect of labor coefficients, it is necessary to remove the influence of each country's unique industrial structure. By applying the industrial structure of the world, labor coefficients differences can be assessed effectively, without conflating them with variations in national economic compositions. Let us define S_i as

$$S_i = \frac{\sum_u x_i^u}{\sum_i \sum_u x_i^u}, \text{ for } i = 1, 2, \dots, N,$$

then $\sum_i S_i = 1$ and $S_1, S_2, \dots, S_N$ represent the production structure of the world. By using S_i as the averaging weight, country r 's aggregated labor intensity evaluated by the world's industrial structure can be calculated as:

$$l^r(S) = \sum_i l_i^r S_i. \quad (2.2)$$

Since all countries use the same weights, differences in the index result solely from variations in labor coefficients. If $l^r(S)$ is higher than that of another country, it indicates that country r has relatively higher labor intensity as far as it is reflected to labor coefficients compared to that country.

2.2.3 Industrial structure

The industrial structure of country r can be expressed by $s_1^r, s_2^r, \dots, s_N^r$, which are defined as:

$$s_i^r = \frac{x_i^r}{\sum_i x_i^r} \quad (i = 1, 2, \dots, N).$$

However, we need a country-level index which reflects whether a country's production structure is biased to the labor-intensive direction. To obtain such an index, we must exclude the aspect of labor coefficients from l^r defined by (2.1). It would be convenient to have a set of sectoral coefficients common to all countries. The averaged sectoral labor coefficients of the world, which are defined as

$$L_i = \frac{\sum_u l_i^u x_i^u}{\sum_u x_i^u} \quad (i = 1, 2, \dots, N),$$

can be used for that purpose. By using L_i as the weight, we can measure country r 's industrial structure from the standpoint of labor intensity as

$$s^r(L) = \sum_i L_i s_i^r, \quad (2.3)$$

which is comparable among countries. If the value for (2.3) of country r is larger than that of country u , then country r 's industrial structure is more biased to labor-intensive production.

The world's labor intensity can be defined as

$$L = \sum_i L_i S_i = \frac{\sum_u l_i^u x_i^u}{\sum_u x_i^u} \frac{\sum_u x_i^u}{\sum_i \sum_u x_i^u} = \frac{\sum_i \sum_u l_i^u x_i^r}{\sum_i \sum_u x_i^u}.$$

L represents the average of global sectoral labor coefficients, weighted by the corresponding industrial structure, and can also be viewed as the average of world's sectoral production structure weighted by labor coefficients. $l^r(S)$ as well as $s^r(L)$ can be compared with L . When $s^r(L) > L$, country r 's production structure is more biased to labor-intensive direction compared to the world average level. When $l^r(S) > L$, country r has bigger labor intensity with respect to labor coefficients than the world average.

A country's production-based employment consists of employment that satisfies the final demand of its own residents, i.e. employment absorbed domestically, and employment that fulfills the final consumption of foreign countries, i.e. employment absorbed abroad. This can be expressed by $L_p^r = l^{rr} \mathbf{x}^{rr} + \sum_{u \neq r}^G l^r \mathbf{x}^{ru}$. Likewise, a country's consumption-based employment includes labor employed in this country and labor employed in the foreign countries, that is $L_c^r = l^{rr} \mathbf{x}^{rr} + \sum_{u \neq r}^G l^u \mathbf{x}^{ur}$.

Since $l^{rr} \mathbf{x}^{rr}$ is common to both production-based employment and consumption-based employment, we can construct another index for labor exploitation by subtracting the common

part,

$$\frac{L_{c,out}^r}{L_{p,out}^r} = \frac{\sum_{u \neq r}^G \mathbf{l}^u \mathbf{x}^{ur}}{\sum_{u \neq r}^G \mathbf{l}^r \mathbf{x}^{ru}}. \quad (2.4)$$

This index must show exploitation more sharply, because the difference between consumption-based and production-based employment stems from the output that is not absorbed by the producing country. We call it “external labor ratio”.

Corresponding to the new index (2.4), we can consider the production structure of the output absorbed by foreign consumers. Specifically, the bilateral foreign absorbed output matrix is defined as:

$$\mathbf{X}^F = \begin{bmatrix} \mathbf{0} & \mathbf{x}^{12} & \dots & \mathbf{x}^{1G} \\ \mathbf{x}^{21} & \mathbf{0} & \dots & \mathbf{x}^{2G} \\ \vdots & \vdots & \ddots & \vdots \\ \mathbf{x}^{G1} & \mathbf{x}^{G2} & \dots & \mathbf{0} \end{bmatrix},$$

then a country’s output absorbed abroad equals

$$\mathbf{x}^F = \mathbf{X}^F \mathbf{u} = \begin{bmatrix} \sum_{g \neq 1} \mathbf{x}^{1g} \\ \sum_{g \neq 2} \mathbf{x}^{2g} \\ \vdots \\ \sum_{g \neq G} \mathbf{x}^{Gg} \end{bmatrix},$$

where $\mathbf{u}$ is an $G \times 1$ vector, of which all elements are one. The industrial structure of country r ’s output which meets foreign final demand can be expressed as:

$$s_{i,out}^r = \frac{\sum_{u \neq r} x_i^{ru}}{\sum_i \sum_{u \neq r} x_i^{ru}}.$$

Similarly, by using the world sectoral labor coefficients, the extent to which country r ’s industrial structure of output absorbed by foreign countries is biased toward a labor-intensive direction can be measured as

$$s_{out}^r(L) = \sum_i L_i s_{i,out}^r. \quad (2.5)$$

Evidently, variations in $s_{out}(L)$ across countries are more drastic compared to those in $s(L)$.

2.2.4 Source structure of consumption

In this subsection, we will discuss two types of source structure of consumption: source industry structure and source country structure.

(1) Source industry structure

Obviously, the r -th column of $\mathbf{X}$, which is the global output induced by country r 's final demand, divided by the column summation can be regarded as country r 's consumption source structure:

$$\boldsymbol{\delta}^r = \begin{bmatrix} \delta^{1r} \\ \delta^{2r} \\ \vdots \\ \delta^{Gr} \end{bmatrix} = \begin{bmatrix} \mathbf{x}^{1r} \\ \mathbf{x}^{2r} \\ \vdots \\ \mathbf{x}^{Gr} \end{bmatrix} / \mathbf{t} \begin{bmatrix} \mathbf{x}^{1r} \\ \mathbf{x}^{2r} \\ \vdots \\ \mathbf{x}^{Gr} \end{bmatrix}, \text{ where } \mathbf{t} = \overbrace{\begin{bmatrix} 1 & 1 & \cdots & 1 \end{bmatrix}}^{GN}.$$

$\mathbf{l}\boldsymbol{\delta}^r$ can be regarded as representing the source structure of country r in terms of labor intensity, as vector $\mathbf{l}$ is common across all countries. However, since the self-sufficiency rates are very high for most countries, the value of $\mathbf{l}\boldsymbol{\delta}^r$ is largely determined by country r 's own labor coefficients.

Therefore, we consider country r 's source industry consumption structure, ensuring the use of world sectoral labor coefficients (L_i). To get the source industry consumption structure, it is necessary to rearrange $\mathbf{X}$ as first by sector, and within each sector by country:

$$\boldsymbol{\chi} = \begin{bmatrix} \chi_1^1 & \chi_1^2 & \cdots & \chi_1^G \\ \chi_2^1 & \chi_2^2 & \cdots & \chi_2^G \\ \vdots & \vdots & \ddots & \vdots \\ \chi_N^1 & \chi_N^2 & \cdots & \chi_N^G \end{bmatrix}, \text{ where } \chi_i^g = \begin{bmatrix} x_i^{1g} \\ x_i^{2g} \\ \vdots \\ x_i^{Gg} \end{bmatrix} \quad (g = 1, 2, \dots, G)$$

Then country r 's source industry consumption structure can be expressed as:

$$\mathbf{c}^r = \begin{bmatrix} c_1^r \\ c_2^r \\ \vdots \\ c_N^r \end{bmatrix} = \begin{bmatrix} \mathbf{u}^T \boldsymbol{\chi}_1^r \\ \mathbf{u}^T \boldsymbol{\chi}_2^r \\ \vdots \\ \mathbf{u}^T \boldsymbol{\chi}_N^r \end{bmatrix} / \mathbf{t} \begin{bmatrix} \chi_1^r \\ \chi_2^r \\ \vdots \\ \chi_N^r \end{bmatrix},$$

Consequently, multiplying by L_i , the extent to which country r 's source structure of consumption is biased toward labor-intensive direction is measured as:

$$c^r(L) = \sum_i L_i c_i^r. \quad (2.6)$$

Similar to the industrial structure of country r 's output meeting foreign final demand, we also construct the source structure of consumption from foreign countries. Rearranging $\mathbf{X}^F$ first

by sector and by country within each industry, we have

$$\mathbf{x}^F = \begin{bmatrix} \chi_1^{F1} & \chi_1^{F2} & \cdots & \chi_1^{FG} \\ \chi_2^{F1} & \chi_2^{F2} & \cdots & \chi_2^{FG} \\ \vdots & \vdots & \ddots & \vdots \\ \chi_N^{F1} & \chi_N^{F2} & \cdots & \chi_N^{FG} \end{bmatrix}, \text{ where } \chi_i^{F1} = \begin{bmatrix} 0 \\ x_i^{21} \\ \vdots \\ x_i^{G1} \end{bmatrix}, \chi_i^{F2} = \begin{bmatrix} x_i^{12} \\ 0 \\ \vdots \\ x_i^{G2} \end{bmatrix}, \cdots, \chi_i^{FG} = \begin{bmatrix} x_i^{1G} \\ x_i^{2G} \\ \vdots \\ 0 \end{bmatrix}.$$

Accordingly, country r 's industrial source structure of consumption from foreign countries is defined as

$$\mathbf{c}_{out}^r = \begin{bmatrix} c_{1,out}^r \\ c_{2,out}^r \\ \vdots \\ c_{N,out}^r \end{bmatrix} = \begin{bmatrix} \mathbf{u}^T \chi_1^{Fr} \\ \mathbf{u}^T \chi_2^{Fr} \\ \vdots \\ \mathbf{u}^T \chi_N^{Fr} \end{bmatrix} / \mathbf{t} \begin{bmatrix} \chi_1^{Fr} \\ \chi_2^{Fr} \\ \vdots \\ \chi_N^{Fr} \end{bmatrix},$$

By using L_i , we could also assess whether country r 's source structure of consumption from abroad shows a bias toward labor-intensive products by

$$c_{out}^r(L) = \sum_i L_i c_{i,out}^r. \quad (2.7)$$

(2) Source country structure

The source country structure represents the share of different suppliers within an industry. For industry i , the country source consumption structure of country r is defined as

$$\boldsymbol{\sigma}_i^r = \begin{bmatrix} \sigma_i^{1r} \\ \sigma_i^{2r} \\ \vdots \\ \sigma_i^{Gr} \end{bmatrix} = \chi_i^r / \mathbf{u}^T \chi_i^r,$$

from which we know the source country structure of consumption within a specific sector for country r . All countries' labor coefficients for sector i can be expressed as $\boldsymbol{\zeta}_i = [l_i^1 \ l_i^2 \ \cdots \ l_i^G]$. Applying $\boldsymbol{\zeta}_i$ as a weight to evaluate $\boldsymbol{\sigma}_i^r$, we get

$$l_{i,con}^r = \boldsymbol{\zeta}_i \boldsymbol{\sigma}_i^r,$$

which can be viewed as the source country consumption structure of a sector evaluated by source country's labor coefficients. While this index can also be computed at country level, we focus on the sectoral level for it is feasible and provides more detailed information.

Although using $\boldsymbol{\zeta}_i$ may appear to have a similar issue as $\mathbf{l}\delta^r$, the effect is less pronounced. When divided into 45 industries, the impact diminishes because countries have heterogeneous domestic-produced share across different sectoral goods. This effect is further mitigated by

applying the consumption structure within an industry specific to foreign country sources:

$$\sigma_{i,out}^r = \begin{bmatrix} \sigma_{i,out}^{1r} \\ \sigma_{i,out}^{2r} \\ \vdots \\ \sigma_{i,out}^{Gr} \end{bmatrix} = \chi_i^{Fr} / \mathbf{u}^T \chi_i^{Fr},$$

to measure the bias of the source country structure of sector i to satisfy country r 's consumption with respect to labor intensity,

$$l_{i,outcon}^r = \zeta_i \sigma_{i,out}^r. \quad (2.8)$$

2.2.5 Ratio of consumption-side to production-side within a country

In previous subsections, we have derived both the production structure of a country's output that meets foreign final demand and the industrial source structure of consumption from foreign countries. Cross-country comparisons of these indices can reveal relative labor-intensity biases. Furthermore, examining the ratio of these two indices for a single country allows us to determine if its consumption structure is more labor-intensive compared to its production structure.

Subsequently, at the country-level, we define the ratio of industrial foreign-source consumption structure to production structure of output that fulfills foreign demand from the perspective of labor intensity as:

$$\eta_{out}^r(L) = \frac{c_{out}^r(L)}{s_{out}^r(L)} \quad (2.9)$$

If the value of (2.9) is larger than 1, it means that country r 's consumption originating abroad is more concentrated on labor-intensive goods than its production for foreign countries.

At the sectoral level, it would be meaningful to compare $l_{i,outcon}^r$ with l_i^r , and to have the ratio:

$$\lambda_{i,out}^r = \frac{l_{i,outcon}^r}{l_i^r}. \quad (2.10)$$

This ratio represents the relative labor intensity of foreign countries' industry i to country r 's own industry i . The difference between the numerator and the denominator is brought about by the source country structure bias of country r 's consumption.

In brief, equations (2.2)–(2.10) collectively represent the indices we developed to investigate the factors influencing a country's labor exploitation ratio. This analysis can be readily applied to GHG emission exploitation by substituting labor coefficients with GHG emission coefficients. Specifically, for index (2.2), the GHG emission coefficients g are used, and the symbol changes from $l(S)$ to $g(S)$. For indices (2.3)–(2.9), the world sectoral GHG emission coefficients are applied, and accordingly, the symbol L is replaced by G . Finally, for index (2.10), $\gamma_{i,out}^r$ is used to represent the relative GHG emission intensity of foreign countries' industry i compared to country r 's own industry i . In the calculation of GHG emissions for all indices, household

greenhouse gas emissions are excluded because the ICIO model does not classify households as part of the production sectors within N .

2.2.6 Data

We use the regular version of the Inter-Country Input-Output (ICIO) Tables, 2023 edition (OECD, 2024b), which provides data for 76 economies and the rest of the world (ROW) across 45 industries from 1995 to 2020. To ensure data consistency, we directly use the country-level GDP figures derived from the ICIO tables. Production-based and demand-based GHG emissions, along with emission factors, are obtained from the Greenhouse gas footprint indicators. Although the Trade in Employment (TiM) indicators (OECD, 2024c) are integrated with the ICIO tables, employment data is available for only 66 countries. To address this limitation, we supplement the analysis with data from the International Labor Organization (ILO) database (International Labour Organization, 2023). The U.S. deflators (base year: 2015) are sourced from the World Bank (World Bank, 2024).

2.3 Result

In this section, the exploitation situation and indices about the three influencing factors for 77 regions in 2020 is first shown. Then, we select typical country and country group to observe time-varying trend of labor and GHG emission exploitation as well as the influencing factors from 1995 to 2020.

2.3.1 All regions in 2020

Fig. 2.1 illustrates the global overview of labor and GHG emission exploitation. Instead of using L_c/L_p and G_c/G_p , $2(L_c - L_p)/(L_c + L_p)$ and $2(G_c - G_p)/(G_c + G_p)$ better display the exploiting and exploited regions. Regarding exploitation structure, developed countries tend to be exploiters, while developing countries are often exploited. This trend is more prominent in labor exploitation. In 2020, 33 countries were exploited with respect to labor, of which only 3 were developed countries. By contrast, 14 out of 31 countries exploited with respect to GHG emissions were developed nations. Furthermore, among developed nations, it seems that degree of labor exploitation is greater than that of GHG emission exploitation.

As we analyzed in section 2.2, coefficients, industrial structure, and source consumption structure may explain these facts. To better analyze the impact of these influencing factors, we select countries near the division line of exploitation as reference points. In labor exploitation, these are Lithuania, a developed country, with a degree of 1.008, and Costa Rica, a developing

¹Based on the World Bank's classification of income and lending groups (World Bank, 2021), we refer countries with high income ($> \$12695$) as developed nations.

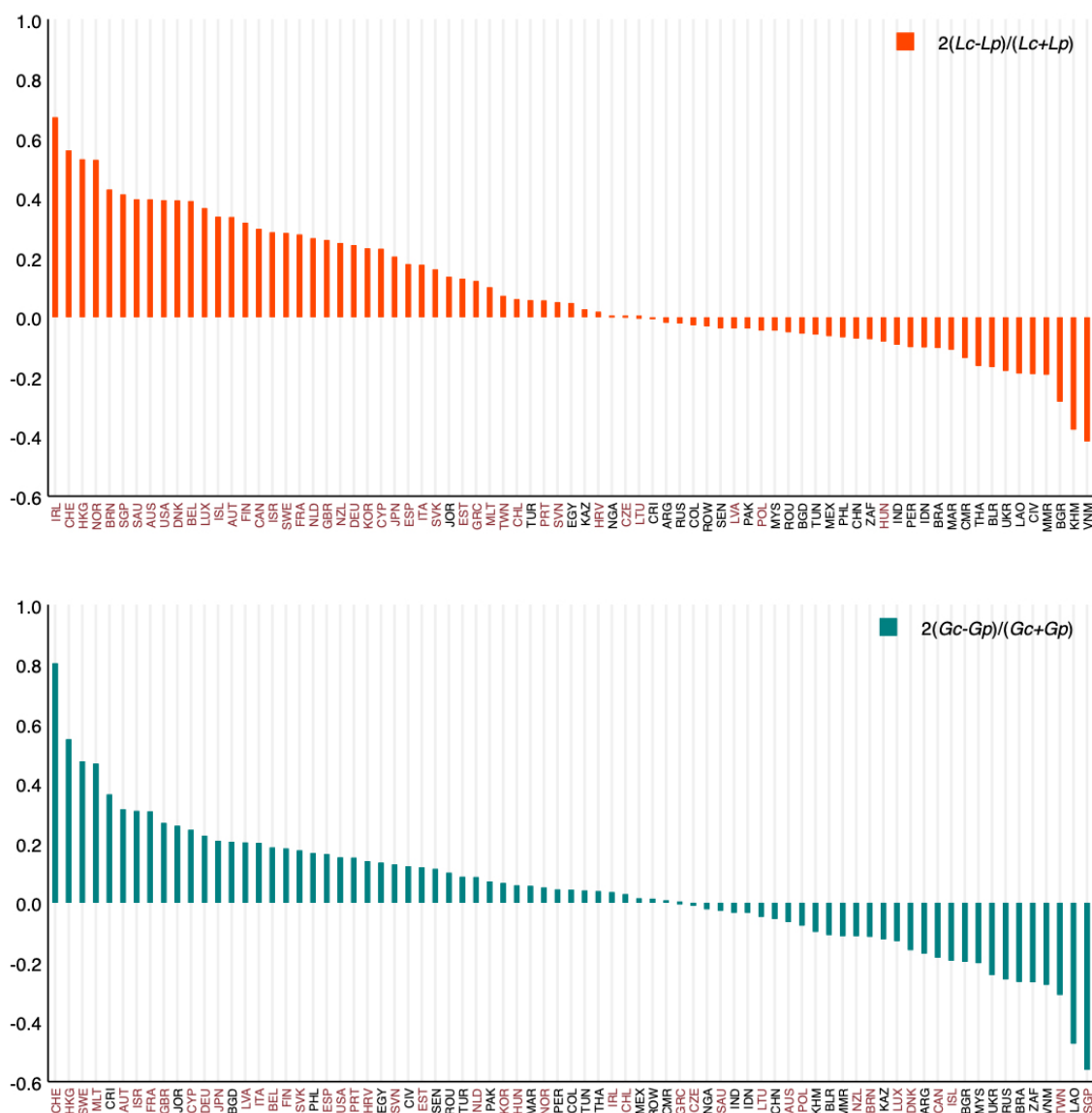


Figure 2.1 Labor and GHG emission exploitation in 2020 for 77 regions, arranged in descending order by their respective values. The red x-labels indicate developed nations, while the black ones represent developing economies¹.

country, with a degree of 0.9938. In GHG emission exploitation, the reference countries are Cameroon, a developing country, with a ratio of 1.008, and Greece, a developed country, with a ratio of 0.9987.

Fig. 2.2 demonstrates the indices of labor coefficients, industrial structure and source industry structure from the standpoint of labor intensity. It reveals that, among the three aspects, labor coefficients have the greatest impact on increasing the likelihood of a country exploiting others. Countries that exploit labor tend to have extremely smaller labor coefficients than countries being exploited. For example, Ireland's degree of labor exploitation was 2.01, and the value of $l(S)$ was 4.99 person per million USD (p/\$mln), while for Cambodia, the labor exploitation ratio

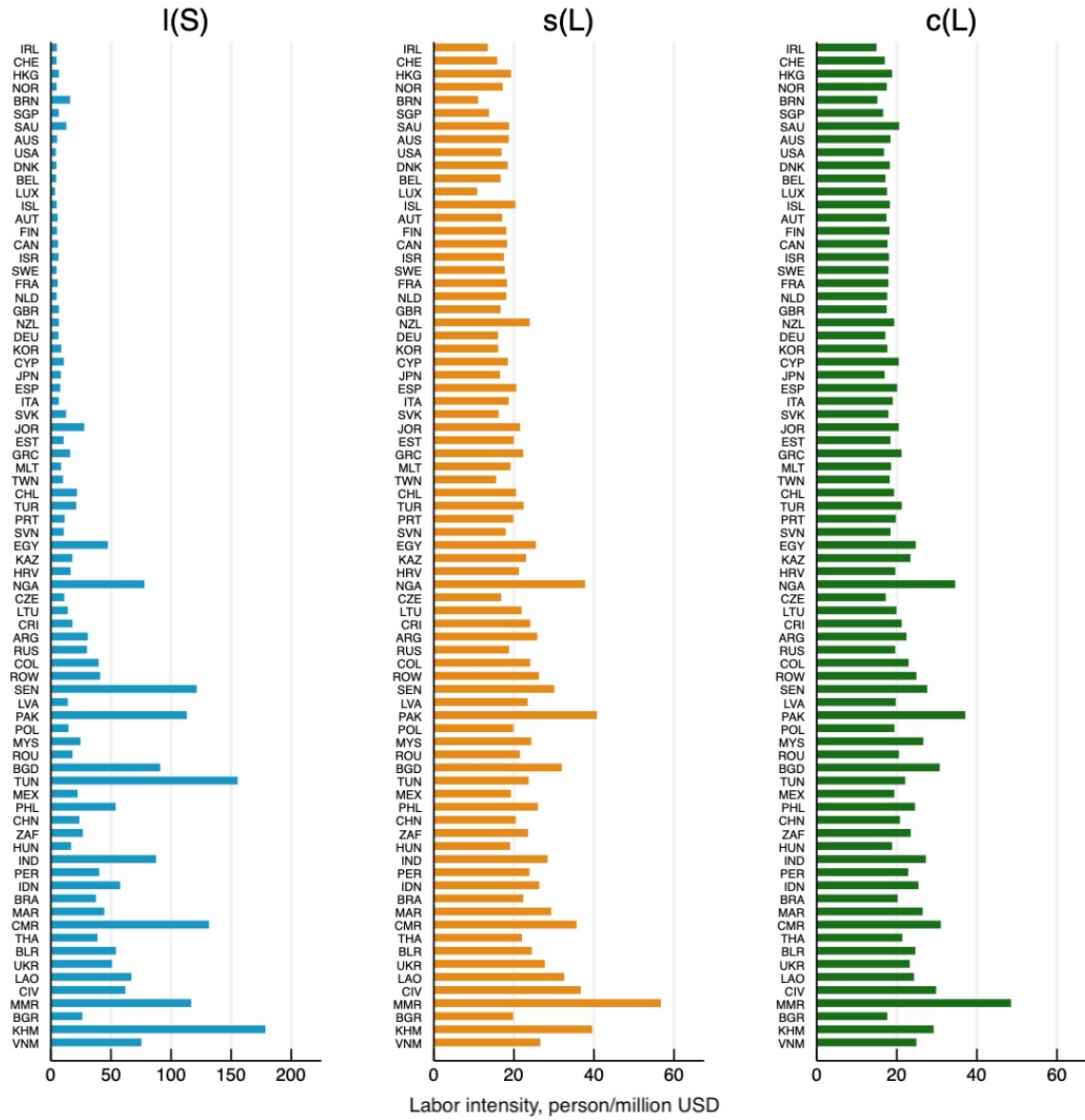


Figure 2.2 The indices $l(S)$, $s(L)$, and $c(L)$ for 77 regions in 2020; regions on the y-axis arranged in descending order of labor exploitation.

was 0.68 and the value of $l(S)$ was 178.5 p/\$mIn. Interestingly, the values of $l(S)$ for major high-income nations (the top 32 regions on the y-axis of Fig. 2.2) are similarly low.

The industrial structure, viewed from the perspective of labor intensity, also contributes to increasing the possibility of labor exploitation, though its influence is less pronounced than labor coefficients. Notably, the values of $s(L)$ for high-income nations generally remain below 20 p/\$mIn, whereas most developing countries exceed this threshold. In contrast, it is challenging to assess the role of the source industry consumption structure in influencing labor exploitation. The distinction between developed and developing countries is less clear in this regard. Specifically, $c(L)$ is lower in developed countries compared to developing ones, potentially due to the shift to

a tertiary economy in developed regions. Furthermore, the regional variation in $s(L)$ is greater than that observed in $c(L)$.

Fig. 2.3 shows the indices of GHG emission coefficients, industrial structure, and source industry consumption structure analyzed through the lens of GHG emission intensity. Similarly,

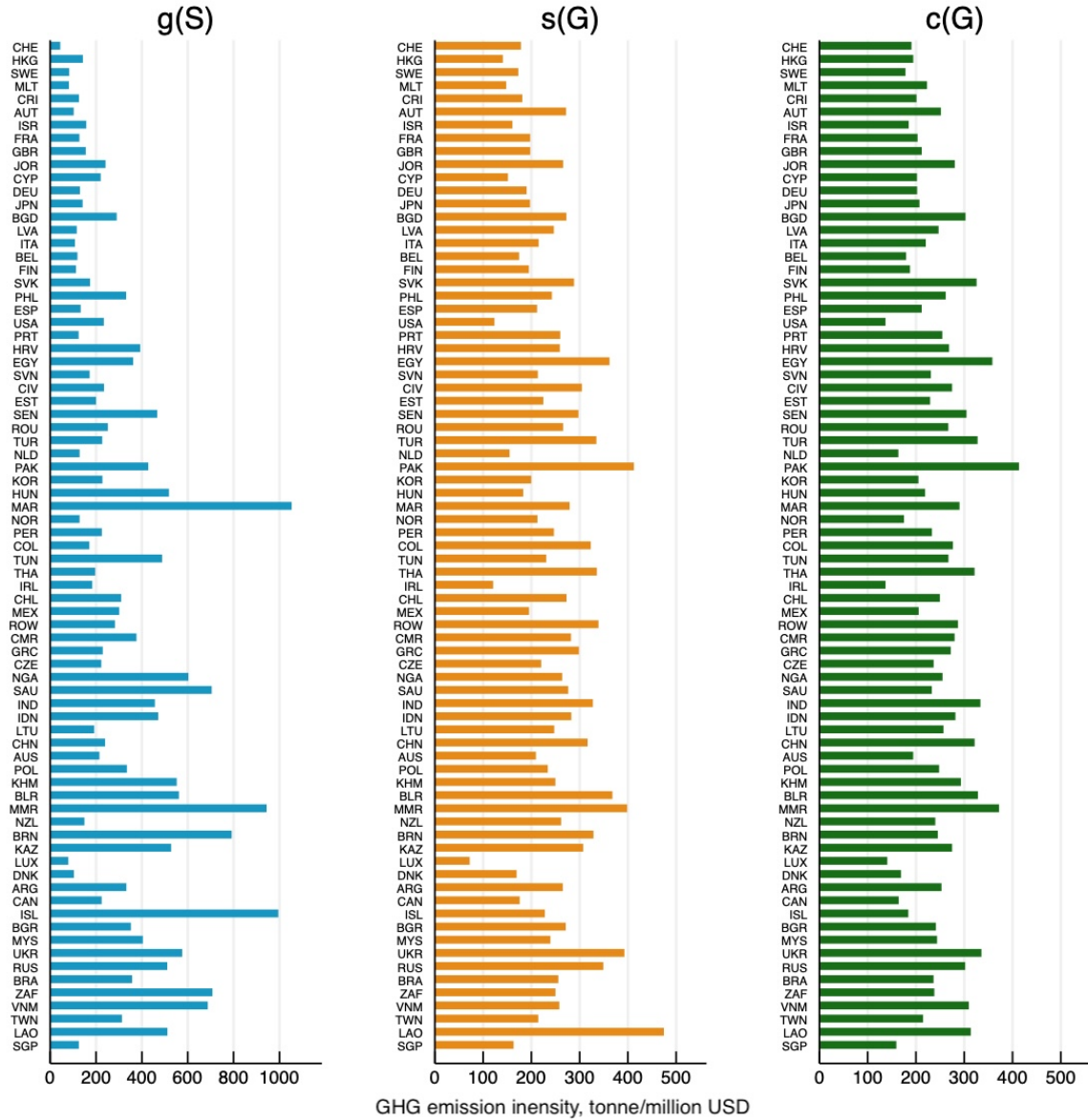


Figure 2.3 The indices $g(S)$, $s(G)$, and $c(G)$ for 77 regions in 2020; regions on the y-axis arranged in descending order of GHG emission exploitation.

the factor of GHG emission coefficients substantially plays a role in explaining the formation of GHG emission exploitation. However, unlike the case of labor exploitation, the effects of both $s(G)$ and $c(G)$ are ambiguous. While GHG emission coefficients for exploiting countries are generally low, the relationship with economic development differs from that observed in labor exploitation. Among the top 32 regions on the y-axis of Fig. 2.3, nine are developing countries,

including Costa Rica, Jordan, Bangladesh, Philippines, Egypt, Côte d'Ivoire, Türkiye, Romania, and Senegal.

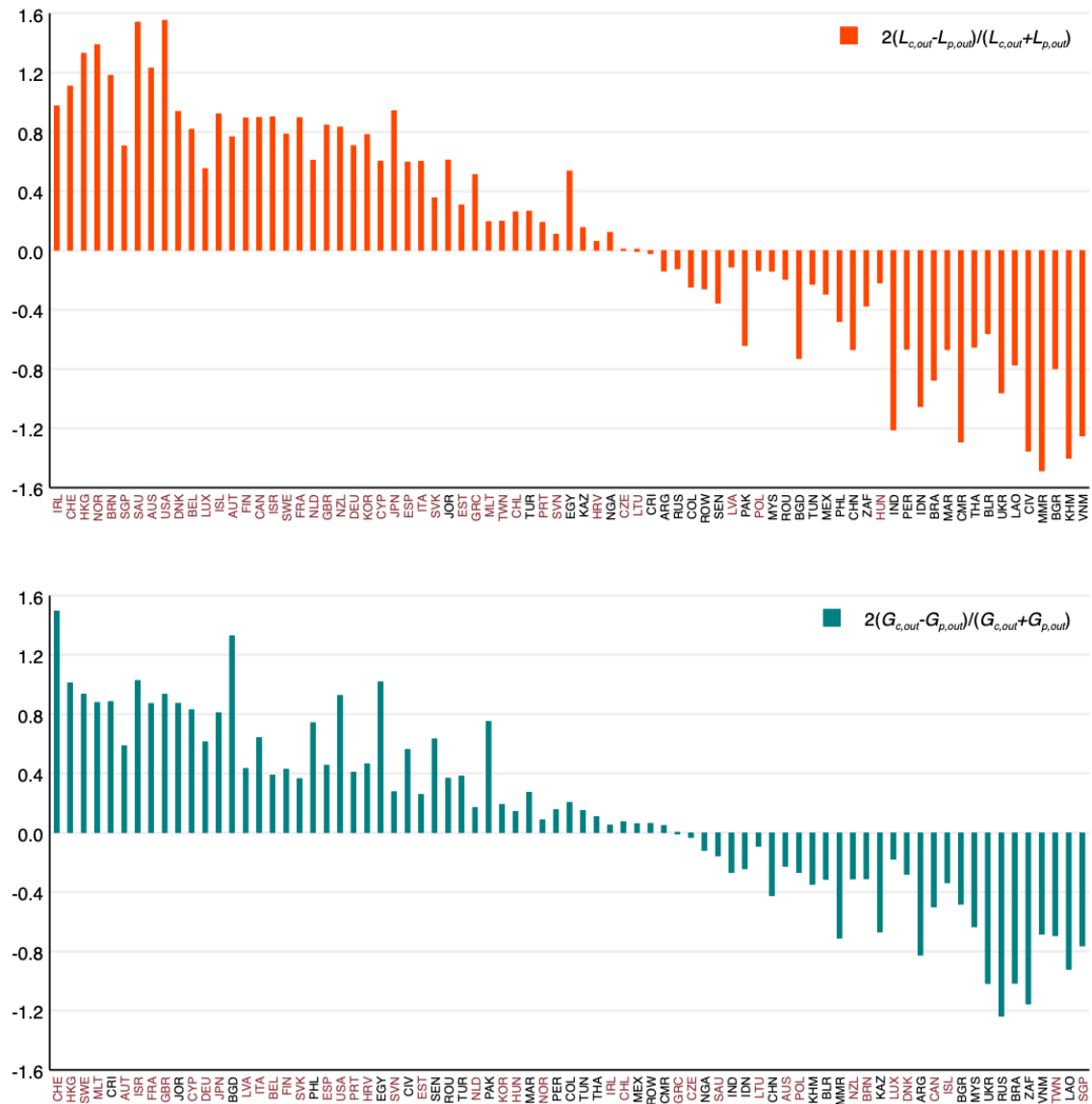


Figure 2.4 External labor and GHG emission ratio for 77 regions in 2020. The country order and label on the horizontal axes comply with those in Fig. 2.1.

As the difference in the indices of $s(L)$, $c(L)$, $s(G)$, and $c(G)$ between exploiting and exploited countries is not strong enough to explain a country's status in exploitation, it would be helpful to focus on the differentiated part of a country's production-based and consumption-based employment/GHG emissions and the corresponding indices. Fig. 2.4 displays the new indicators of labor and GHG emission exploitation calculated based on (2.4). Similar to Fig. 2.1, we use $2(L_{c,out} - L_{p,out}) / (L_{c,out} + L_{p,out})$ and $2(G_{c,out} - G_{p,out}) / (G_{c,out} + G_{p,out})$ instead of $L_{c,out} / L_{p,out}$ and $G_{c,out} / G_{p,out}$ to better indicate the exploitation sides. Apparently, the magnitude of the external ratio is larger than the original exploitation index in Fig. 2.1. For example, the degrees

of external labor ratio for Switzerland and Norway were 1.11 and 1.39, respectively. In contrast, the corresponding values for $2(L_c - L_p)/(L_c + L_p)$ were 0.56 and 0.53, respectively.

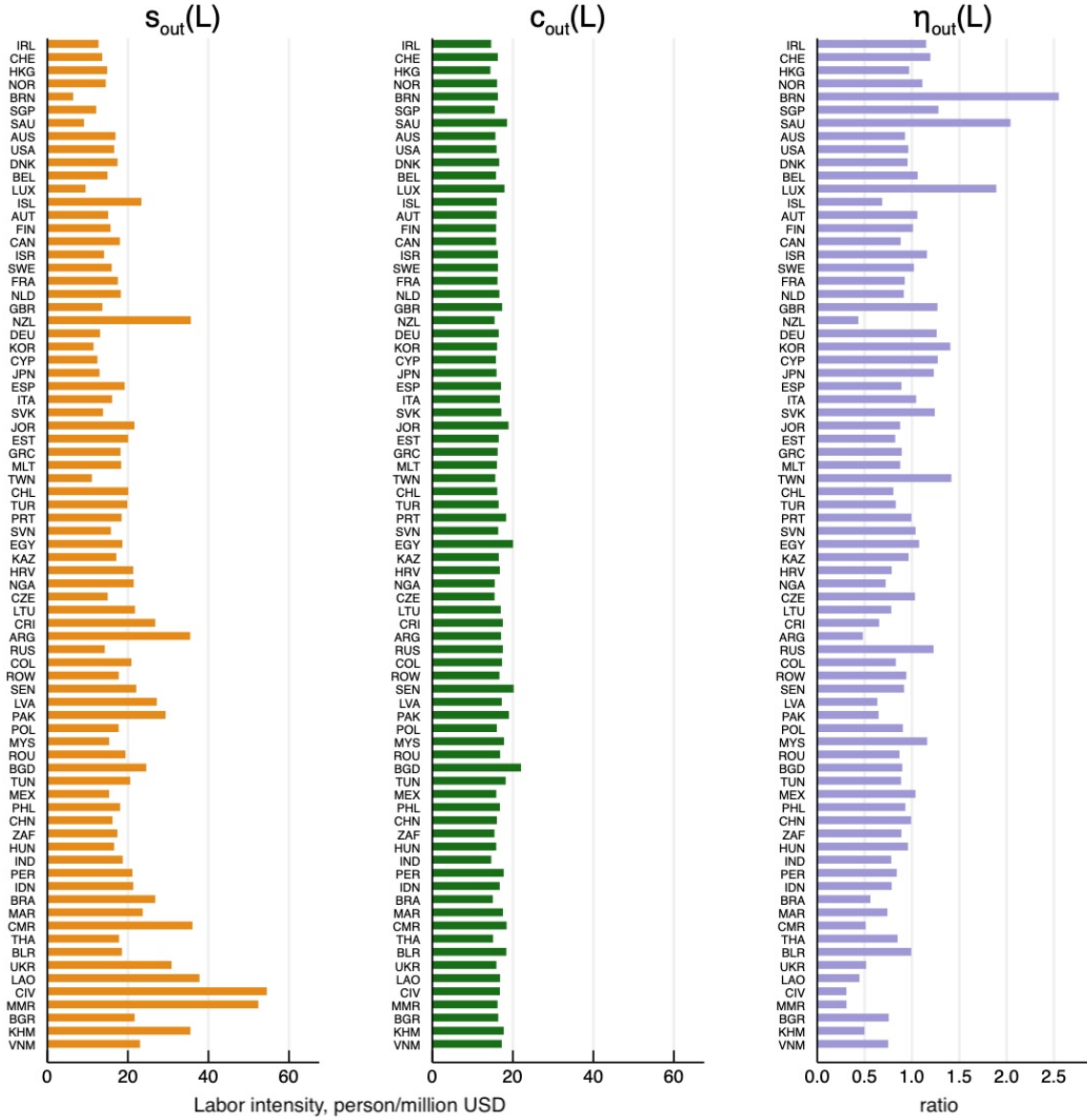


Figure 2.5 The indices of $s_{out}(L)$, $c_{out}(L)$, and $\eta_{out}(L)$. The country order on the y-axes comply with those in Fig. 2.2.

Fig. 2.5 illustrates the indices of the production structure of a country's output fulfilling foreign final demand, the industry consumption structure sourced abroad, and their ratio that are constructed using labor intensity. In 63 out of 77 regions, $s_{out}(L)$ values are smaller than $s(L)$ values, indicating a labor-light industrial structure in the output absorbed by foreign countries. The notable increase in $s_{out}(L)$ for New Zealand, Argentina, and Côte d'Ivoire can be attributed to significant changes in the share of the agriculture, hunting, and forestry sectors when shifting from total output to output absorbed abroad. Surprisingly, the $c_{out}(L)$ values across regions, with the exception of Brunei Darussalam and Luxembourg, are smaller and more similar compared to

$c(L)$ values. The minor difference in $c_{out}(L)$ highlights the predominant influence of production-side factors on a country's labor exploitation. The ratio $\eta_{out}(L)$ is moderately informative, as the values for most labor-exploited countries fall below 1.0.

The situation of $s_{out}(G)$, $c_{out}(G)$, and $\eta_{out}(G)$ is reflected in Fig. 2.6. In the analysis of GHG

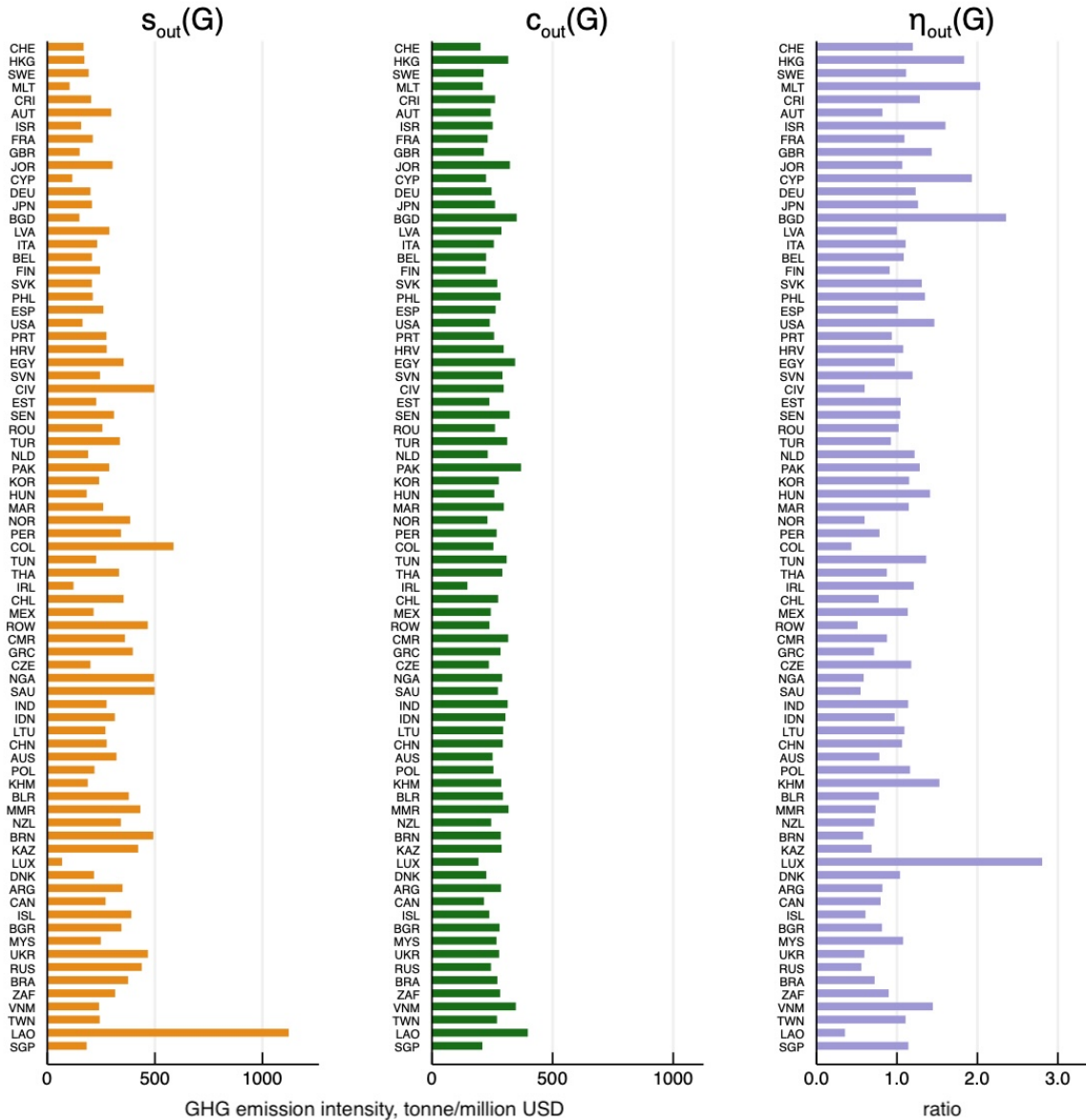


Figure 2.6 The indices of $s_{out}(G)$, $c_{out}(G)$, and $\eta_{out}(G)$. The country order on the y-axes comply with those in Fig. 2.3.

emissions, the electricity, gas, steam and air conditioning supply sector plays a crucial role. The exceptionally high value of $s_{out}(G)$ for Lao People's Democratic Republic (Laos) is due to the significant portion of electricity exports (nearly 23.6%) and the world average GHG coefficient of the electricity, gas, steam and air conditioning supply sector is 3486.24 tonnes per million USD. However, it is important to point out this result only reflects the production structure of Lao's output absorbed by foreign countries and does not necessarily indicate the actual GHG emissions.

In fact, Laos generates electricity primarily through hydropower (Kyophilavong et al., 2021). 59 out of 77 regions saw an increase in $c_{out}(G)$ compared to $c(G)$ values. It appears that the consumption sourced from abroad is more GHG emission-intensive than domestically produced output for most countries. $\eta_{out}(G)$ is also indicative like $\eta_{out}(L)$, though still not decisive. The extremely large value of $\eta_{out}(G)$ for Luxembourg results from the exceptionally low value of $s_{out}(G)$, due to the concentration of exports from the financial and insurance activities sector (54.9%), of which the world average GHG coefficient is 5.99 tonnes per million USD, as well as the high value of $c_{out}(G)$, due to the intensive absorption of output from the agriculture, hunting, forestry sector, the electricity, gas, steam and air conditioning supply sector, and the land transport and transport via pipelines sector.

Table 2.1 Sectoral consumption structure of foreign country sources evaluated by labor/GHG emission coefficients and original sectoral coefficients in 2020 for India and Japan (Units: tonne/million USD for g and person/million USD for l)

Sector code	g_i^{IND}	$g_{i,out}^{IND}$	$\gamma_{i,out}^{IND}$	g_i^{JPN}	$g_{i,out}^{JPN}$	$\gamma_{i,out}^{JPN}$	l_i^{IND}	$l_{i,out}^{IND}$	$\lambda_{i,out}^{IND}$	l_i^{JPN}	$l_{i,out}^{JPN}$	$\lambda_{i,out}^{JPN}$
A01_02	891.6	1094.5	1.23	117.4	980.2	8.35	457.2	134.5	0.29	20.3	93.9	4.63
A03	40.0	129.1	3.23	412.2	151.1	0.37	65.0	117.1	1.80	31.8	69.4	2.18
B05_06	1263.9	524.7	0.42	976.7	519.3	0.53	10.6	4.1	0.39	3.4	3.5	1.02
B07_08	262.9	178.7	0.68	11.8	205.3	17.36	74.0	5.4	0.07	5.4	6.0	1.12
B09	152.9	72.1	0.47	3.2	81.6	25.77	1.8	5.2	2.89	5.2	5.0	0.96
C10T12	66.1	39.0	0.59	28.9	37.0	1.28	27.3	12.1	0.44	6.3	8.2	1.29
C13T15	170.2	22.9	0.13	172.3	20.3	0.12	69.3	19.2	0.28	11.4	20.7	1.81
C16	46.0	71.3	1.55	17.3	79.3	4.57	141.5	16.7	0.12	6.0	24.6	4.08
C17_18	553.8	173.6	0.31	185.5	159.4	0.86	39.1	9.4	0.24	4.6	9.7	2.12
C19	594.2	345.2	0.58	386.3	348.3	0.90	1.7	5.0	3.02	0.3	2.6	7.61
C20	308.5	597.3	1.94	246.9	485.9	1.97	10.2	5.8	0.57	2.9	4.3	1.49
C21	95.9	27.8	0.29	52.2	12.2	0.23	11.8	6.4	0.54	1.3	2.1	1.70
C22	96.9	74.1	0.76	29.9	86.1	2.88	14.4	10.0	0.69	5.1	11.6	2.29
C23	2511.1	875.9	0.35	1161.7	938.6	0.81	49.6	10.1	0.20	7.0	9.9	1.41
C24	1522.4	697.1	0.46	471.0	854.1	1.81	9.5	4.5	0.47	1.6	4.5	2.79
C25	63.2	56.4	0.89	17.3	68.3	3.94	63.7	10.6	0.17	8.2	12.5	1.53
C26	31.2	7.8	0.25	5.2	7.6	1.47	4.7	6.1	1.29	3.6	6.4	1.78
C27	58.5	17.8	0.30	3.1	18.7	5.93	14.3	8.4	0.59	4.0	9.2	2.29
C28	172.7	28.5	0.17	12.4	34.1	2.74	13.1	7.7	0.58	5.9	8.1	1.38
C29	41.3	16.5	0.40	5.8	24.3	4.22	7.4	5.3	0.72	2.5	6.3	2.55
C30	31.9	25.3	0.79	8.7	24.3	2.78	7.4	6.1	0.82	3.4	4.4	1.31
C31T33	37.1	42.8	1.15	22.3	40.1	1.80	176.3	14.7	0.08	3.5	23.2	6.65
D	8820.3	3681.4	0.42	2067.1	3880.3	1.88	13.1	5.1	0.39	1.3	4.3	3.39
E	3081.2	2062.5	0.67	144.5	1939.4	13.42	55.9	8.8	0.16	3.1	9.8	3.15
F	93.2	48.1	0.52	7.6	48.2	6.36	84.0	17.1	0.20	7.9	15.6	1.98
G	98.5	39.3	0.40	3.5	35.1	10.17	134.9	32.7	0.24	10.2	33.1	3.26
H49	558.8	461.1	0.83	605.5	435.7	0.72	97.1	19.3	0.20	14.0	20.4	1.46
H50	1857.7	728.2	0.39	422.6	738.2	1.75	38.0	6.1	0.16	4.5	6.1	1.36
H51	963.1	742.0	0.77	605.1	739.3	1.22	11.2	10.8	0.96	3.8	10.3	2.70
H52	171.8	56.4	0.33	2.3	66.5	29.39	65.5	15.4	0.24	8.6	17.6	2.04
H53	354.0	98.5	0.28	1.8	110.1	60.47	88.3	19.3	0.22	21.1	19.8	0.94
I	52.2	30.9	0.59	36.5	31.5	0.86	77.4	37.1	0.48	19.0	41.8	2.20
J58T60	19.2	5.7	0.30	1.5	5.6	3.86	14.8	6.4	0.43	3.5	5.9	1.71
J61	34.8	7.5	0.22	0.7	7.7	10.85	7.9	8.5	1.07	1.2	6.5	5.25
J62_63	11.2	4.6	0.41	0.8	4.8	5.70	11.4	9.3	0.81	7.5	9.5	1.27
K	12.6	5.3	0.42	0.7	5.3	7.43	22.1	6.0	0.27	5.2	5.2	1.00
L	54.9	9.1	0.17	1.7	8.6	4.98	2.1	5.7	2.67	1.8	5.5	3.09
M	74.5	15.0	0.20	2.1	15.6	7.50	156.1	10.8	0.07	12.3	11.7	0.95
N	72.8	23.6	0.32	9.4	22.6	2.41	100.3	19.6	0.20	12.9	22.1	1.72
O	75.4	33.4	0.44	2.8	30.7	11.15	68.8	16.4	0.24	5.3	11.8	2.22
P	38.7	27.4	0.71	23.6	24.6	1.04	144.0	31.5	0.22	10.1	27.3	2.70
Q	25.1	26.2	1.04	12.1	19.6	1.62	133.5	26.1	0.20	14.9	20.9	1.40
R	45.9	21.6	0.47	12.5	19.9	1.59	293.1	44.9	0.15	20.4	33.6	1.64
S	104.0	32.0	0.31	36.6	27.5	0.75	552.4	60.3	0.11	48.3	52.0	1.08

For the sectoral index—source country consumption structure—India and Japan are chosen for analysis. For India, the degrees of exploitation in terms of labor and GHG emissions were 0.912 and 0.967, respectively, while for Japan, these values were 1.226 and 1.232. Table 2.1 provides the results of source foreign country consumption structure, sectoral production coefficients, and their corresponding ratio of 44 sectors² from the viewpoint of labor and GHG emission coefficients, respectively.

In contrast to the source industry consumption structure index, this sectoral source country consumption structure effectively explains the likelihood of a country becoming an exploiter. The larger the value of $\gamma_{i,out}^r$ and $\lambda_{i,out}^r$ and the greater the number of sectors with the two indices greater than one, the higher the likelihood. Regarding $\gamma_{i,out}^r$, India has only six sectors with a ratio greater than 1, the highest being 3.23 in the fishing and aquaculture sector. By comparison, 34 sectors in Japan have ratios exceeding 1, with the postal and courier activities sector reaching 60.47. The similar results can also be found in $\lambda_{i,out}^r$.

2.3.2 The three factors from 1995 to 2020

(1) Labor and GHG emission exploitation from 1995 to 2020

In this subsection, the aim is to examine the temporal change of the three aspects from 1995 to 2020. It is difficult to illustrate all 77 regions in this analysis and therefore we have selected some typical regions which are EU15, EU13, the United States, Japan, China, India, and Australia³. Fig. 2.7 shows the variation of GHG emission and labor exploitation for these regions. Compared to CO₂ emission exploitation, the ratio of GHG emission exploitation is consistently higher for developed economies such as the EU15 and Japan. For the United States, the GHG emission exploitation ratio was also higher than the CO₂ emission exploitation ratio from 1995 to 2011. However, after 2011, the two ratios became very close, with their relative magnitudes frequently switching. On the other hand, for the EU13, China, and India, although they remained exploited with respect to GHG emissions, the degree of exploitation was reduced (more close to 1.0) compared to CO₂ emissions. Australia, newly added in the analysis, was exploited in terms of GHG emissions from 1995 to 2004 and again from 2015 to 2020, unlike other developed economies. While Australia was also exploited with respect to CO₂ emissions from 1995 to 2003, it became and remained an exploiter thereafter. Between 1995 and 1999, Australia's labor exploitation ratio rose from 1.43 to 1.55, dipped slightly to 1.48 in 2001, and then increased again, surpassing the United States in 2005. It peaked at 1.89 in 2011 before beginning to decline, though it remained the highest level through 2019.

²To keep the table concise, only sector codes are provided; full sector names can be found in the Appendix A.2. Sector T (Activities of households as employers; undifferentiated goods- and services-producing activities of households for own use) is excluded as it involves no trade transactions and thus has no source country consumption structure.

³Compared to Chapter 1, we included Australia because the shift from CO₂ emissions to GHG emissions has altered its exploitation status in recent years, for which agriculture was responsible.

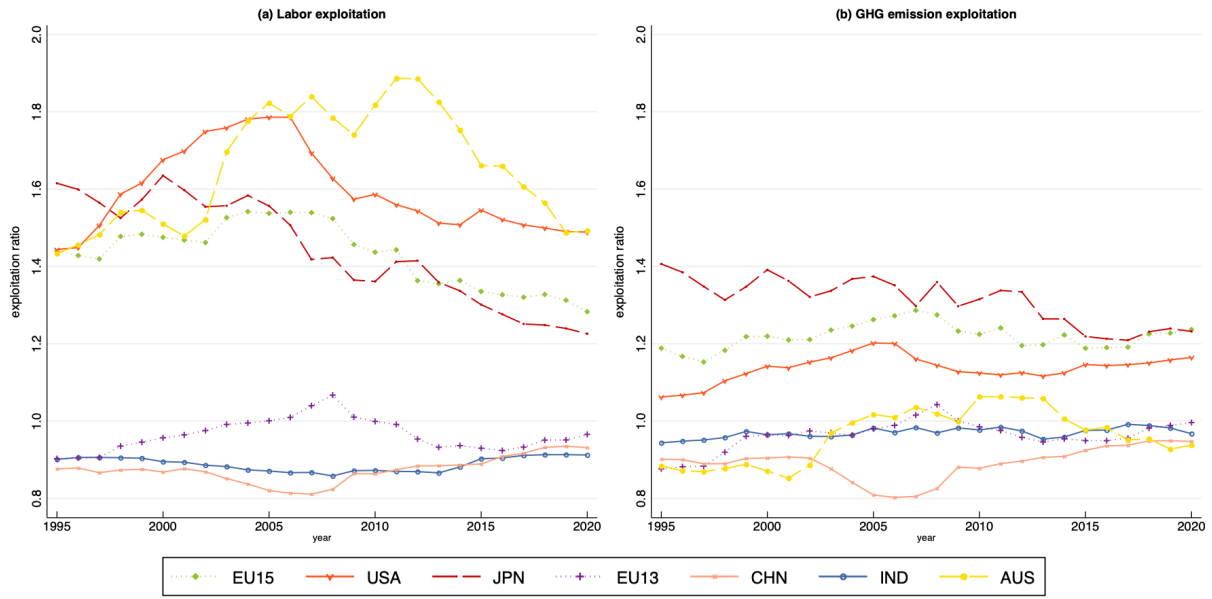


Figure 2.7 Labor and GHG emission exploitation for typical regions from 1995 to 2020

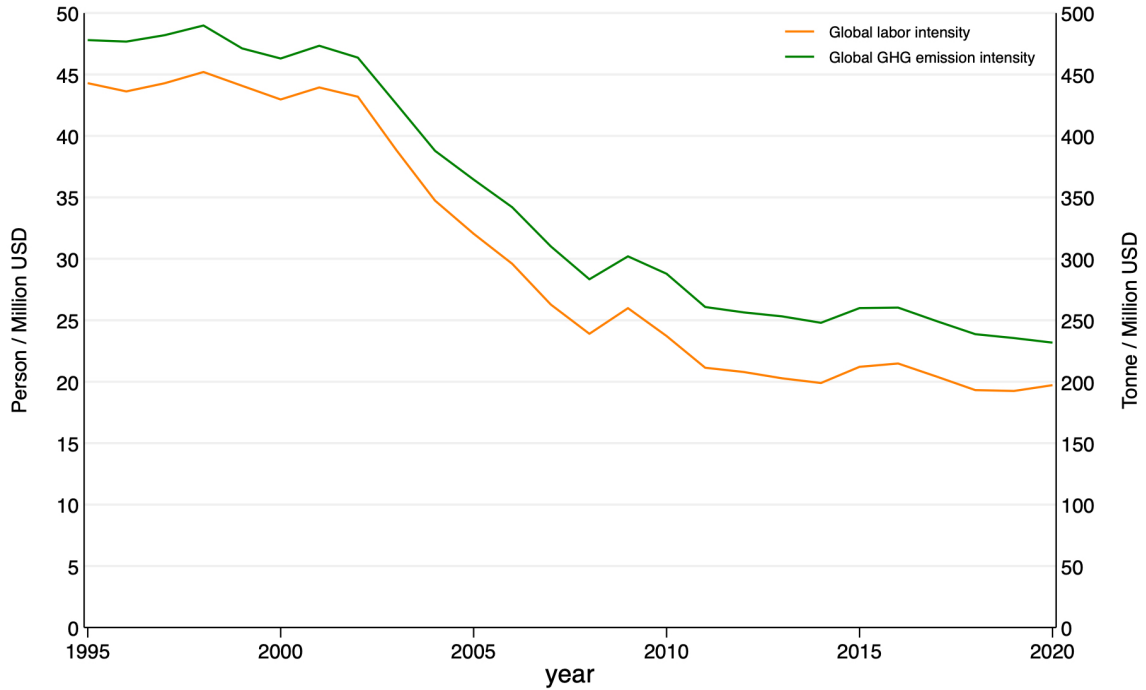


Figure 2.8 Labor and GHG emission intensity of the world from 1995 to 2020; the world GDP is deflated using the U.S. deflator (base year 2015).

We have calculated the coefficient factor by applying the world average industrial structure to all the countries. Similarly, we have applied the world average sectoral coefficients to extract production and consumption industrial structures. However, in the analysis of temporal changes, the world average indices also vary, which may affect the extracted factors. In fact, the world average coefficients must have been declined because of the improvement in labor productivity and GHG emission efficiency, as illustrated in Fig. 2.8. To exclude the effect of this time

trend in coefficients, it would be necessary to choose a particular year to analyze the change in the structures. Considering the fact that the global labor and GHG emission intensities have decreased from 2000 to 2015, as a consequence, these two years can be chosen as reference points for coefficients.

It is difficult to visualize industrial structure of 45 sectors. To observe the time trend, Table 2.2 has listed the world average industrial structure every 5 years since 1995. We can find that

Table 2.2 The world average industrial structure (%) in 1995, 2000, 2005, 2010, 2015, and 2020

Sector code	S1995	S2000	S2005	S2010	S2015	S2020
A01_02	3.182	2.888	2.865	3.357	3.713	3.837
A03	0.232	0.214	0.210	0.250	0.312	0.334
B05_06	1.201	1.535	2.018	2.439	2.060	1.842
B07_08	0.418	0.401	0.499	0.715	0.678	0.697
B09	0.169	0.165	0.251	0.307	0.303	0.228
C10T12	4.681	4.132	4.006	4.300	4.480	4.314
C13T15	1.898	1.620	1.407	1.474	1.760	1.721
C16	0.585	0.528	0.515	0.425	0.470	0.450
C17_18	1.675	1.461	1.170	1.040	0.971	0.921
C19	1.466	1.769	2.215	2.462	1.914	1.647
C20	2.342	2.236	2.144	2.386	2.514	2.211
C21	0.712	0.769	0.810	0.823	0.923	0.967
C22	1.247	1.167	1.094	1.077	1.122	1.078
C23	1.097	0.976	1.048	1.087	1.253	1.213
C24	2.119	1.833	2.142	2.532	2.431	2.374
C25	1.721	1.582	1.543	1.440	1.458	1.486
C26	2.608	3.068	2.321	2.260	2.283	2.412
C27	1.311	1.253	1.104	1.244	1.316	1.243
C28	2.320	2.108	2.047	2.050	2.162	1.978
C29	2.738	2.811	2.701	2.466	2.664	2.368
C30	0.706	0.718	0.707	0.746	0.781	0.675
C31T33	1.482	1.386	1.259	1.153	1.095	1.214
D	2.106	2.144	2.218	2.571	2.450	2.350
E	0.672	0.660	0.687	0.683	0.633	0.702
F	7.103	6.627	7.011	6.722	7.177	7.495
G	10.211	9.738	9.672	9.295	9.156	9.314
H49	2.331	2.216	2.326	2.373	2.419	2.348
H50	0.437	0.441	0.504	0.514	0.492	0.462
H51	0.571	0.617	0.566	0.547	0.570	0.408
H52	0.992	0.963	1.059	1.092	1.083	1.083
H53	0.418	0.429	0.400	0.333	0.311	0.332
I	2.663	2.654	2.502	2.373	2.387	2.057
J58T60	1.319	1.539	1.388	1.171	1.069	1.132
J61	1.521	1.951	1.840	1.693	1.489	1.422
J62_63	0.865	1.335	1.330	1.421	1.612	1.993
K	4.822	5.410	5.388	5.011	5.188	5.345
L	6.706	6.726	6.882	6.467	6.174	6.426
M	3.912	4.406	4.498	4.305	4.477	4.708
N	2.291	2.683	2.655	2.487	2.565	2.659
O	5.500	5.284	5.344	5.378	4.888	5.206
P	3.020	3.047	3.023	3.025	2.915	3.023
Q	4.086	4.064	4.291	4.297	4.202	4.461
R	0.868	0.842	0.861	0.819	0.762	0.618
S	1.504	1.449	1.318	1.215	1.163	1.114
T	0.172	0.155	0.160	0.177	0.153	0.135

there is no drastic change in most industries. As a result, it might be challenging to determine the benchmark year. However, for consistency, we will also chose the world industrial structures in 2000 and 2015 for the analysis of coefficients.

(2) Factors for Labor exploitation

To explore the factors that influence the varying trends in labor exploitation, it would be helpful to depict the three aspects. Fig. 2.9 illustrates the temporal changes in the three aspects by using the world's sectoral labor coefficients and industrial structure of year 2000 for these representative regions. China and India experienced a sharp decline in their $l(S^{2000})$

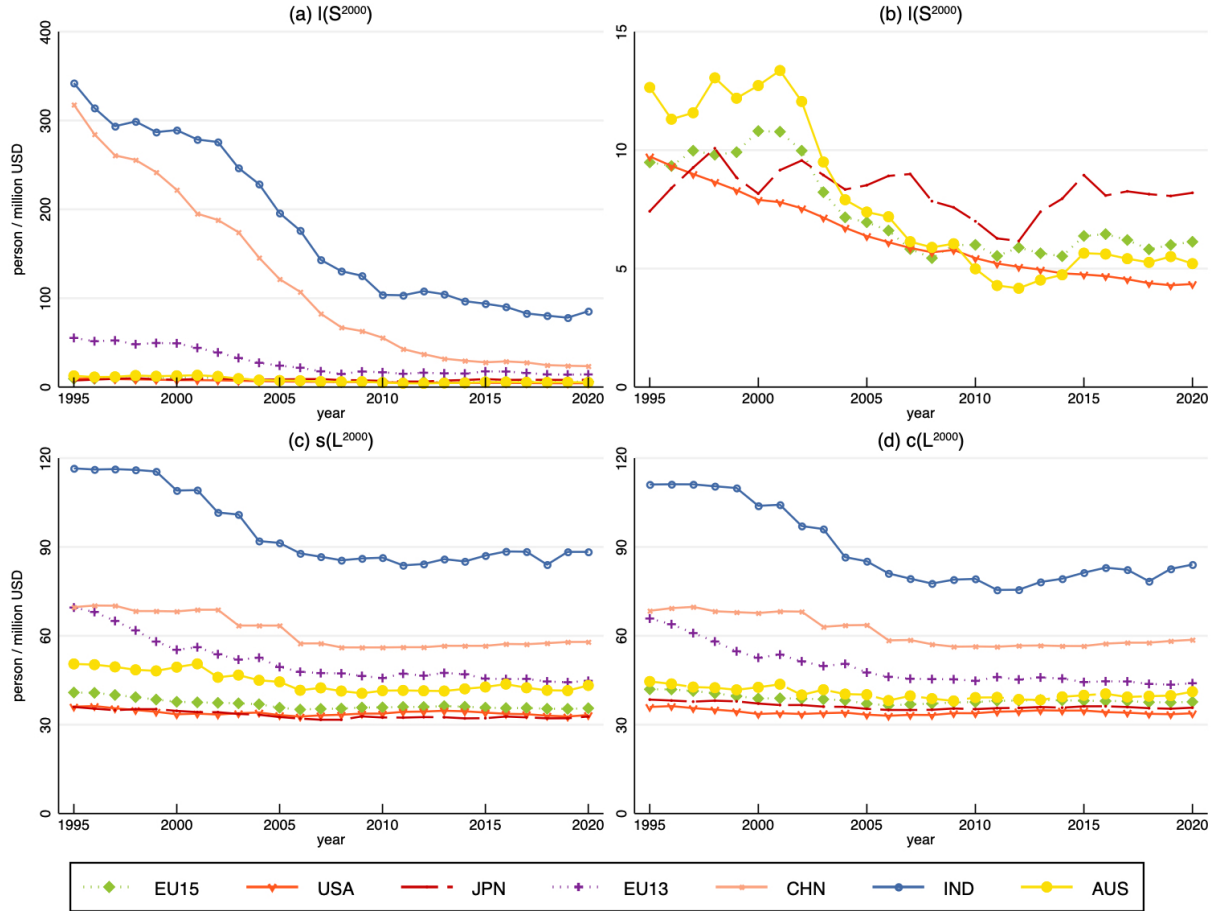


Figure 2.9 $l(S^{2000})$, $s(L^{2000})$, and $c(L^{2000})$ for typical regions from 1995 to 2020

values, reflecting a substantial increase in labor productivity. However, in the past decade, this improvement appears to have stagnated. EU13's $l(S^{2000})$ also decreased from 1995 to 2008, but remained stable at around 16 p/\$mln thereafter. The lines representing the EU15, the United States, Japan, and Australia are clustered together, making them difficult to distinguish; therefore, we provided a zoomed-in view in panel (b). The value of $l(S^{2000})$ for Japan have fluctuated in the past 26 years, but there has been little change between 1995 and 2020. America's $l(S^{2000})$ continued to decrease, with the value in 2020 falling to 4.35, less than half of its 1995 level. Both EU15 and Australia showed enhancement in labor productivity since 2001, although there has been little progress over the past ten years.

Compared to other regions, India's production structure displayed a strong bias toward labor-intensive direction. Between 2000 to 2005, there was a decline in $s(L^{2000})$ for India, China,

and EU13. However, the structural adjustment with regard to labor intensity nearly halted in subsequent years. Labor-exploiting economies, such as EU15, the United States, Japan, and Australia, have smaller values both in $l(S^{2000})$ and $s(L^{2000})$ compared to regions exploited with respect to labor. This indicates that developed nations tend to have lower labor coefficients and industrial structures biased toward non-labor-intensive direction, which explains their role as labor-exploiting economies. However, the source industry consumption structure biased toward labor-intensive direction does not necessarily lead to a country becoming a labor exploiter. As illustrated in panel (d), the values of $c(L^{2000})$ for India, China, and EU13 were actually higher than those of Australia, EU15, Japan, and the United States.

The calculation results based on the world average sectoral labor coefficients and industrial structure of year 2015 are shown in Fig. 2.10. The values of $l(S^{2015})$ for the seven typical

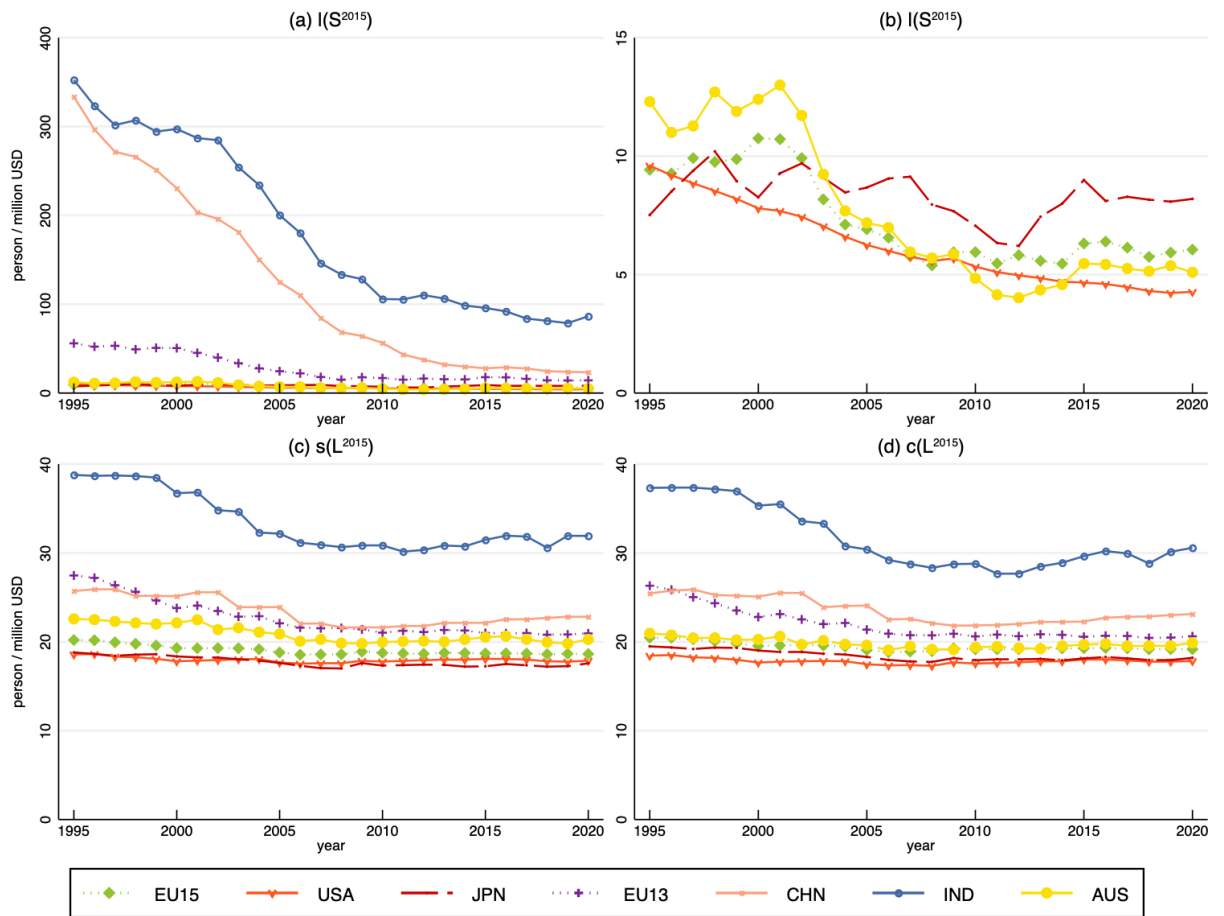


Figure 2.10 $l(S^{2015})$, $s(L^{2015})$, and $c(L^{2015})$ for typical regions from 1995 to 2020

regions closely resemble those of $l(S^{2000})$, due to the stability of the global industrial structure. In contrast, the magnitudes of $s(L^{2015})$ and $c(L^{2015})$ has decreased significantly when compared to those using L^{2000} . Importantly, the overall trends of the three indices and the relative rankings among regions remain largely consistent between Figs. 2.9 and 2.10. However, while the results in the two figures may help explain a country's position in labor exploitation, they fail to illuminate the changing trend except in the cases of Japan and Australia. While other

regions either saw an improvement in labor coefficients or industrial structure or source industry consumption structure, Japan was plainly stagnant, which led to the relative inferiority. For Australia, the decline in labor coefficients from 2000 to 2012 and the subsequent rise roughly conform to the variation of its labor exploitation during the whole period. Conversely, it is hard to interpret the decrease in China's labor exploitation ratio between 2001 and 2007, due to improvement in $l(S^{2000})$ and $s(L^{2000})$. A similar difficulty arises in explaining the decline in America's labor exploitation ratio between 2001 and 2007, due to improvement in $l(S^{2000})$ and $s(L^{2000})$. Moreover, it is also puzzling for India's stable labor exploitation ratio, given the progress seen in its labor productivity and labor-light industrial transformation.

To better investigate this problem, it may be useful to focus on foreign source of consumption and foreign absorption of output. Fig. 2.11(a) display the external labor ratio. The external

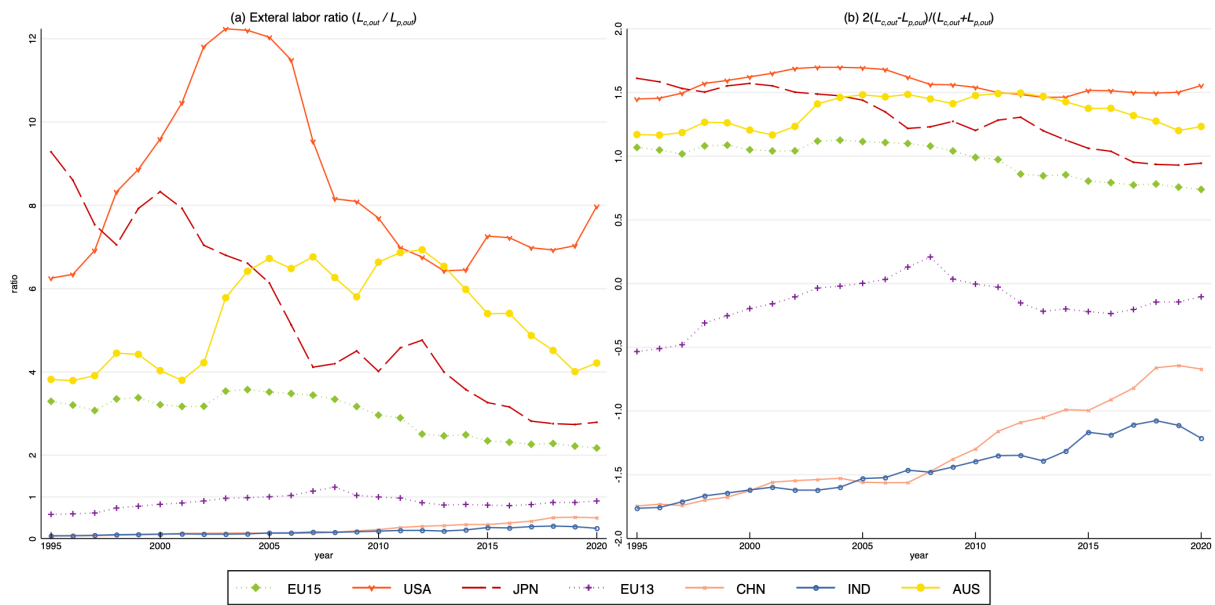


Figure 2.11 External labor ratio for typical regions from 1995 to 2020; also calculated in $2(L_{c,out} - L_{p,out}) / (L_{c,out} + L_{p,out})$.

labor ratio reveals much sharper disparities compared to the labor exploitation index. Between 2003 and 2006, the United States exhibited external labor exploitation levels nearly four times higher than those of the EU15. In Fig. 2.7, we observed that the labor exploitation for Australia consistently exceeded that of the United States from 2005 to 2018. However, in terms of external labor ratio, the United States surpassed Australia throughout the period, except in 2011 and 2012. This difference can be attributed to the higher employment embodied in domestically produced and consumed output in the United States compared to Australia. In fact, when measured by external labor ratio, the degrees of exploitation for both exploiting and exploited countries has intensified. For example, the value of external labor ratio for China slumped to 0.131 in 2003, while the value in labor exploitation was 0.851. For the United States, the corresponding results changed from 1.759 to 12.24. Although both countries experienced an eightfold variation, the scale of 1 to 10 is distinct from that of 1 to 0.1 in y-axis. It is difficult

to see the change in $L_{c,out}/L_{p,out}$ when the values are below one for exploited countries. Index $2(L_{c,out} - L_{p,out})/(L_{c,out} + L_{p,out})$ can express the degree of exploitation at the same scale for both exploiting and exploited countries, which is shown in Fig. 2.11(b). There was a steady increase in China's $(L_{c,out} - L_{p,out})/(L_{c,out} + L_{p,out})$ from 1995 to 2020, which seems as if the mirror image of China and America in Fig. 2.7 disappeared.

Let L_d represent domestic employment that is finally absorbed by domestic consumption, then

$$\frac{L_{c,out}}{L_{p,out}} = \frac{L_c - L_d}{L_p - L_d} = \frac{L_c/L_p - L_d/L_p}{1 - L_d/L_p}. \quad (2.11)$$

$\frac{L_{c,out}}{L_{p,out}}$ can increase even when $\frac{L_c}{L_p}$ decreases, depending on the change in $\frac{L_d}{L_p}$. When $\frac{L_c}{L_p} < 1$, which implies being exploited, decrease in $\frac{L_d}{L_p}$ can increase $\frac{L_{c,out}}{L_{p,out}}$, and as far as $\Delta(\frac{L_d}{L_p}) < \frac{L_p - L_d}{L_p - L_c} \Delta(\frac{L_c}{L_p})$, $\frac{L_{c,out}}{L_{p,out}}$ will increase even when $\frac{L_c}{L_p}$ decreases. $\Delta(\frac{L_d}{L_p}) < 0$ means that the ratio of domestically absorbed labor to total labor exercised decreases, or the ratio of labor absorbed abroad increases. Since China's $\frac{L_c}{L_p}$ decreased from 2001 to 2007, the rise in $\frac{L_{c,out}}{L_{p,out}}$ during the same period must have been accompanied by the increase in the ratio of labor absorbed in foreign countries. Decrease in $\frac{L_c}{L_p}$, which can be expressed also by the decrease in $L_c - L_p$, implies decrease in $L_{c,out} - L_{p,out}$. This means both $\frac{L_c}{L_p}$ and $L_{c,out} - L_{p,out}$ indicate the same exploitation status. Therefore, the rising trend in $\frac{L_{c,out}}{L_{p,out}}$ of China does not indicate an alleviation of exploitation. The degree of being exploited was actually deepened in this period, because $\frac{L_c}{L_p}$ decreased as illustrated in Fig. 2.7, which undoubtedly implies $L_{c,out} - L_{p,out}$ also decreased.

Fig. 2.12 presents the changes in $s_{out}(L)$, $c_{out}(L)$, and $\eta_{out}(L)$. The values of $\eta_{out}(L^{2000})$ and $\eta_{out}(L^{2015})$ for China also increased steadily in the past 26 years. Nevertheless, for India, the United States, EU13, it is still challenging to elucidate their variation by the three aspects. Apart from that, $s(L^{2000})$ and $s(L^{2015})$ confirm that economies with less labor-intensive biases are more likely to act as exploiters more prominently. But an exception is observed, Australia, whose values are higher than those of China and EU13, ranking second only to India. This change may be due to the large share of the agriculture, hunting, forestry sector and mining as well as the quarrying, non-energy producing products sector in Australia's output that meets foreign final demand. $c_{out}(L^{2000})$ and $c_{out}(L^{2015})$ may also provide stronger evidence for aspect 3—namely, that a country's likelihood of becoming an exploiter increases when the source structure of consumption is biased toward labor-intensive direction. As shown in Fig. 2.12(b) and (e), EU15 and Japan are positioned at the top. The large values of $c_{out}(L^{2000})$ and $c_{out}(L^{2015})$ for Japan and EU15 is attributed to their substantial imports from the agriculture, hunting, forestry sector.

The remaining index is the source country consumption structure evaluated by labor intensity. It is hard to show this sectoral index for every country, so we select the United States as a representing demonstration. To keep simplicity, Table 2.3 directly presents $\lambda_{i,out}^r$ for 17 manufacturing sectors in the United States from 1995 to 2020. All ratios exceed one, strongly supporting aspect 3. Most importantly, across all 13 industries, a shared rise-and-fall trend that resembles the change in labor exploitation can be observed, although the peaks occur in different years. In

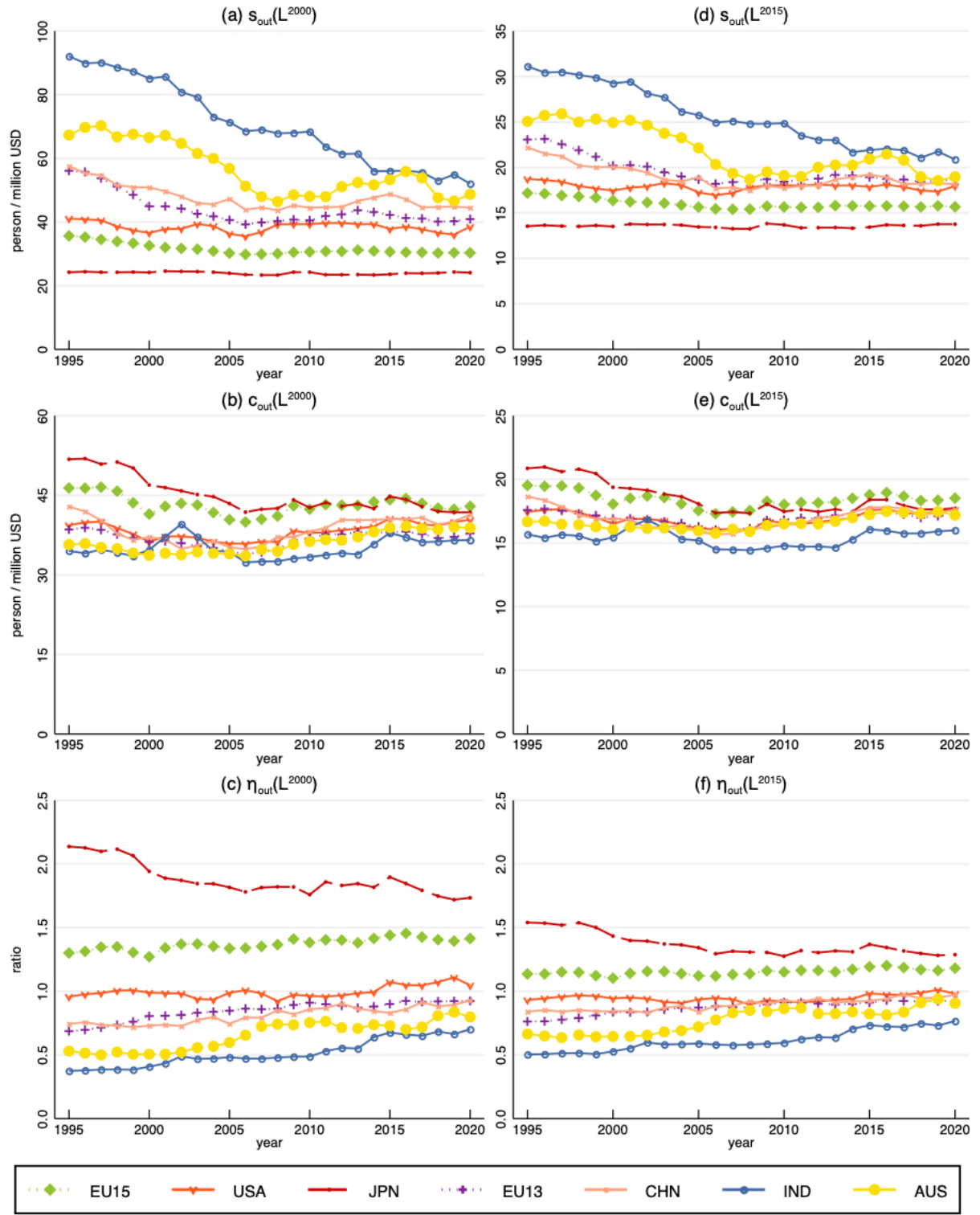


Figure 2.12 $s_{out}(L^{2000})$, $c_{out}(L^{2000})$, $\eta_{out}(L^{2000})$, $s_{out}(L^{2015})$, $c_{out}(L^{2015})$, and $\eta_{out}(L^{2015})$ for typical regions from 1995 to 2020

the case of the United States, $\lambda_{i,out}^r$ appears to play a crucial role in explaining the shape of exploitation changes.

Table 2.3 The ratio of labor intensity of foreign countries' manufacturing industry to America's own industry

	C10T12	C13T15	C16	C17_18	C19	C20	C21	C22	C23	C24	C25	C26	C27	C28	C29	C30	C31T33
1995	5.61	8.75	8.62	3.02	14.52	5.61	3.70	4.71	5.58	3.46	3.66	2.53	3.11	2.18	1.69	2.65	13.78
1996	5.59	9.37	7.88	2.81	16.98	5.15	5.19	4.47	5.58	3.17	3.74	2.82	3.39	2.14	1.66	2.37	15.10
1997	6.31	11.46	7.94	2.82	15.74	5.11	3.56	4.76	5.94	3.18	4.06	3.22	3.66	2.34	1.78	2.40	16.28
1998	7.06	11.45	9.68	3.64	12.30	7.16	7.70	6.42	6.56	3.72	4.17	3.83	4.31	2.41	2.05	3.73	16.47
1999	7.23	11.41	9.80	4.00	15.36	8.27	7.85	6.87	6.62	3.95	4.20	3.57	4.28	2.40	2.05	3.45	15.30
2000	8.04	11.12	10.02	4.35	22.22	9.36	8.48	7.59	5.83	3.57	3.91	3.42	4.01	2.36	1.98	3.96	14.38
2001	7.76	11.83	9.70	3.92	19.75	7.30	7.42	6.20	6.83	3.65	4.38	3.29	4.05	2.64	2.05	3.10	16.29
2002	7.36	12.38	10.55	3.88	14.55	7.09	6.93	5.79	8.14	4.33	4.93	3.26	4.28	2.91	2.10	2.87	19.40
2003	7.28	11.86	10.82	3.82	17.14	7.19	6.51	5.42	9.27	3.88	4.80	3.81	4.50	2.87	2.11	3.61	19.19
2004	7.02	11.54	10.27	3.88	26.25	7.73	5.78	5.47	8.31	3.86	4.49	3.94	4.34	2.66	2.04	3.23	17.59
2005	6.95	11.70	9.80	4.07	32.60	8.21	5.53	5.38	7.99	3.81	4.42	3.79	4.21	2.64	2.00	3.44	16.31
2006	6.70	10.77	10.38	3.98	24.29	7.70	4.96	4.96	8.14	3.63	4.26	3.82	3.99	2.67	1.90	2.91	15.02
2007	6.06	8.17	9.21	3.75	25.79	7.71	4.37	4.63	6.29	3.36	4.05	3.88	3.80	2.59	1.87	2.80	12.84
2008	5.81	7.16	8.37	3.58	29.61	6.73	4.10	4.35	5.35	3.25	4.04	3.51	3.49	2.50	1.62	2.59	11.67
2009	5.89	7.14	9.37	3.72	21.14	5.74	3.97	4.17	5.04	3.21	3.80	3.09	2.87	3.09	1.95	2.57	13.60
2010	5.67	7.06	8.91	3.51	22.96	6.27	3.76	4.10	4.87	3.57	3.62	2.99	2.86	3.17	1.93	2.49	12.29
2011	5.19	6.90	8.38	3.32	24.19	5.62	3.16	3.81	4.28	3.17	3.16	2.72	2.68	2.79	1.94	2.20	11.02
2012	5.47	5.53	6.19	3.43	21.19	5.95	3.26	3.79	4.39	2.92	3.06	2.71	3.21	2.70	1.80	2.31	10.17
2013	5.21	5.46	7.61	3.32	21.32	5.79	3.62	3.74	4.29	3.07	2.96	2.78	3.12	2.74	1.97	2.40	10.13
2014	5.06	5.32	6.41	3.25	19.29	5.29	3.47	3.66	4.14	3.08	2.92	2.65	3.07	2.75	2.08	2.45	8.93
2015	4.93	4.93	6.40	3.31	14.33	4.87	3.49	3.69	4.27	2.95	3.09	2.70	3.07	2.65	2.31	2.65	8.42
2016	4.82	5.24	6.95	3.30	12.79	5.00	3.67	3.65	4.41	2.89	3.05	2.61	3.12	2.74	2.35	2.54	8.09
2017	4.46	4.77	6.54	3.14	13.53	4.70	3.14	3.52	4.24	2.81	2.85	2.71	2.94	2.75	2.23	2.74	7.90
2018	4.19	4.62	5.86	2.97	17.46	4.39	2.65	3.39	3.63	2.75	2.95	2.64	2.82	2.54	2.30	2.48	7.30
2019	4.14	4.80	5.69	3.04	12.14	4.13	2.19	3.33	3.85	2.53	3.07	2.62	2.73	2.51	2.35	2.24	7.74
2020	4.25	5.27	6.61	3.24	6.80	4.01	2.35	3.36	4.21	2.40	3.15	2.79	2.77	2.57	2.52	1.94	8.27

(3) Factors for GHG emission exploitation

To investigate factors that increase the likelihood of a country's exploitation regarding GHG emissions, Fig. 2.13 illustrates the time-varying trends of the three aspects, using the years 2000 and 2015 as the benchmarks. For $g(S^{2000})$ and $g(S^{2015})$, we observe a noticeable drop in China, EU13, India, Australia and the United States. In 2020, the values of $g(S^{2000})$ and $g(S^{2015})$ were overlapping for EU13, China, the United States, and Australia. There is a moderate decrease in EU15 and a minimal variation in Japan. Even without significant improvement, the values for EU15 and Japan kept at the lowest during the whole period. Unlike $l(S^{2000})$, of which the division between exploiting and exploited economies is prominent, the distance in $g(S^{2000})$ is smaller, and there is no difference between the USA and China after 2015. But this factor is still strong in explaining the situation of India, EU15, and Japan with respect to the position in GHG emission exploitation.

The industrial structure from the standpoint of GHG emissions is stable for most economies from 1995 to 2020. Only India, EU13, and China saw a decline in $s(G^{2000})$ and $s(G^{2015})$. The similar pattern applies to $c(G^{2000})$ and $c(G^{2015})$. It seems that for the last 26 years, there is no significant adjustment in industrial compositions for high-income nations. The distances in $s(G^{2000})$ and $c(G^{2000})$ between developed and developing regions are wider than that in $g(S^{2000})$, which is very different from in the case of the three factors concerning labor.

In recent five years, the similar values of $g(S^{2000})$ for China, Australia, and EU13 possibly relates to the closeness of their GHG emission exploitation levels. The fact that Japan's decline in $g(S^{2000})$ and $g(S^{2015})$ is the most moderate conforms to its weakened GHG emission exploitation

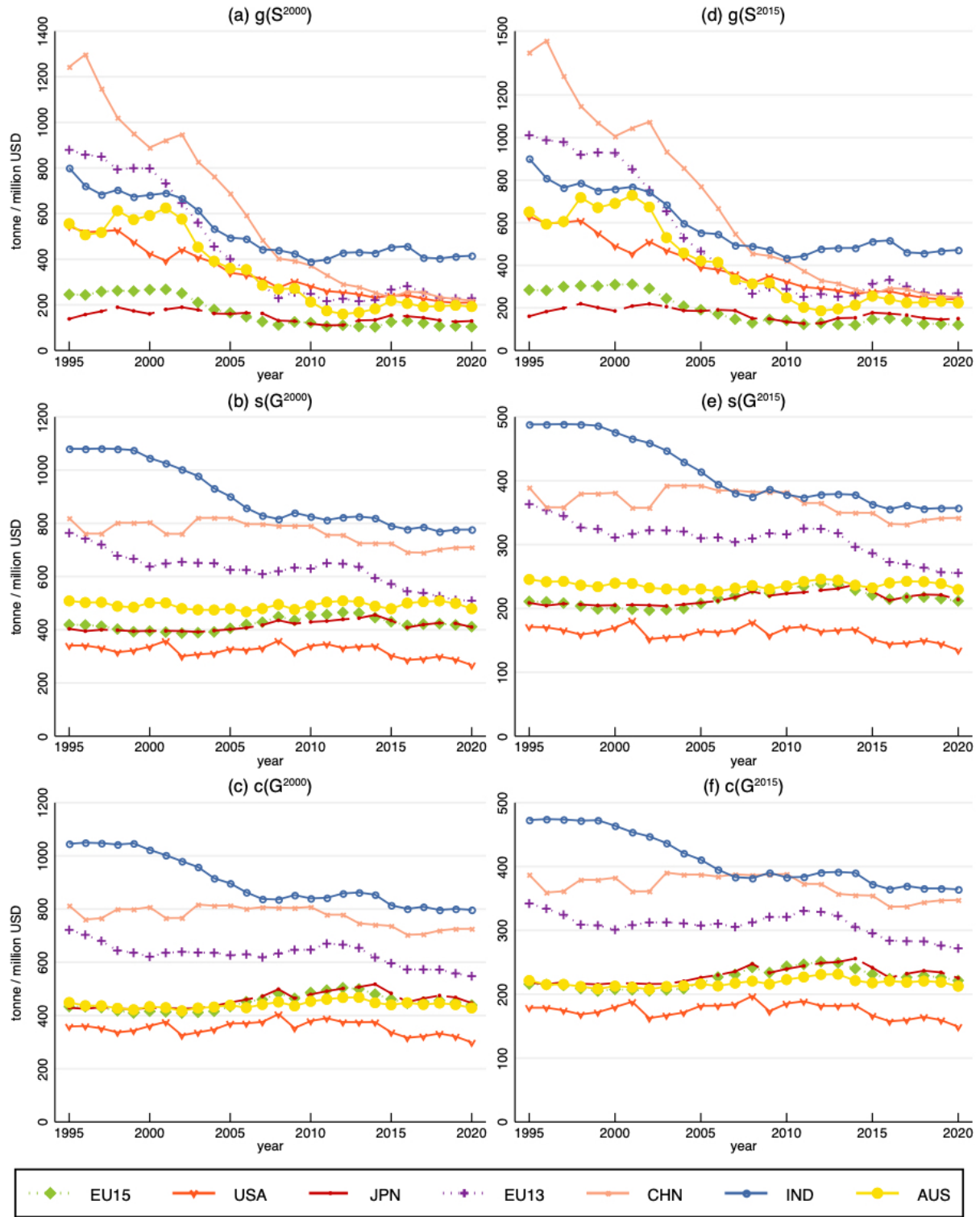


Figure 2.13 $g(S^{2000})$, $s(G^{2000})$, $c(G^{2000})$, $g(S^{2015})$, $s(G^{2015})$, and $c(G^{2015})$ for typical regions from 1995 to 2020

during the whole observation period. However, we did not find any other supporting evidence in the indices of $s(G^{2000})$, $c(G^{2000})$, $s(G^{2015})$, and $c(G^{2015})$. Additionally, those indices also fail to explain the rise in America's GHG emission exploitation from 1995 to 2005 and the exacerbation

of China's exploited situation between 2002 and 2006. $g(S^{2000})$ and $g(S^{2015})$ decreased more rapidly for China than the USA, whereas $s(G^{2000})$ and $c(G^{2000})$ seem rather stable for both China and the USA.

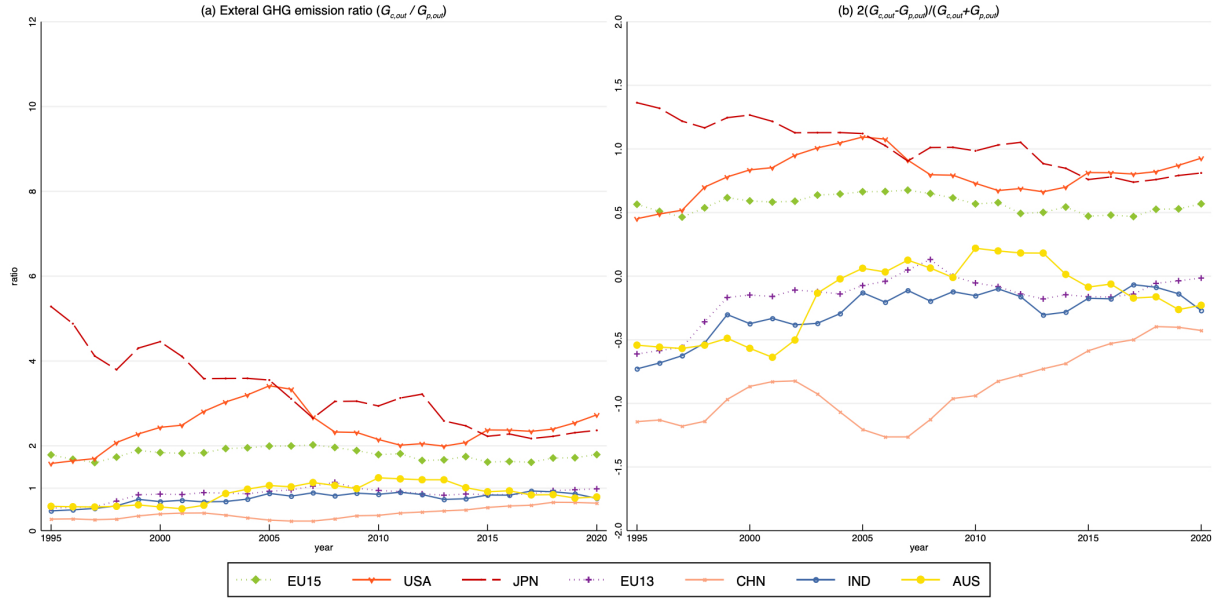


Figure 2.14 External GHG emission ratio for typical regions from 1995 to 2020; also calculated in $2(G_{c,out} - G_{p,out}) / (G_{c,out} + G_{p,out})$.

In external GHG emission ratio (panels (a) and (b) in Fig. 2.14), different from external labor ratio, most varying trends in GHG emission exploitation are inherited. But the USA and EU15 switched positions. Fig. 2.15 illustrates the indices of $s_{out}(G^{2000})$, $c_{out}(G^{2000})$, $\eta_{out}(G^{2000})$, $s_{out}(G^{2015})$, $c_{out}(G^{2015})$, and $\eta_{out}(G^{2015})$ from 1995 to 2020. $s_{out}(G^{2000})$ and $s_{out}(G^{2015})$ for China and India are consistently higher than those of the USA, Japan, and EU15. For China, there was an increase from 2002 to 2005, and followed by a decrease thereafter. Moreover, Australia's values of $s_{out}(G^{2000})$ were incredibly stable throughout the study period, which may be due to its concentration on mining-related exports. This also explains why Australia is at the bottom in $c_{out}(G^{2000})$, as the imports lean toward non-GHG emission-intensive direction. Nearly no evidence can be found in $c_{out}(G^{2000})$ or $c_{out}(G^{2015})$ to explain the characteristic movements in external GHG emission ratio. However, $\eta_{out}(G^{2000})$ and $\eta_{out}(G^{2015})$ provide constructive information in explaining the shape of certain regions' fluctuation. Specifically, the values of $\eta_{out}(G^{2000})$ for the USA soared between 2001 and 2006, while China's $\eta_{out}(G^{2000})$ declined from 2002 to 2006 before steadily increasing thereafter. These facts imply that the movements in external GHG emission ratio for China and the USA around 2002 to 2006 may result from the structural changes.

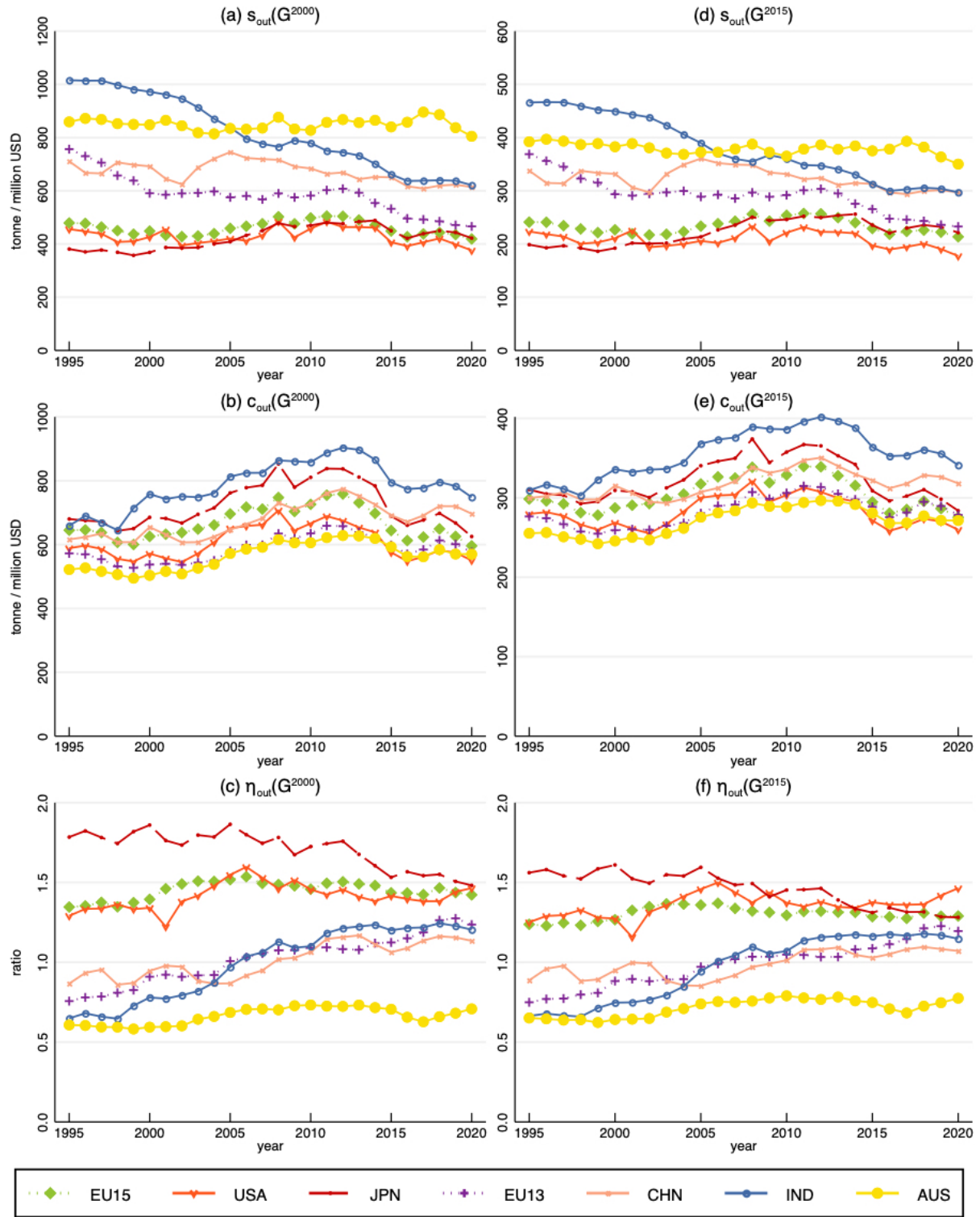


Figure 2.15 $s_{out}(G^{2000})$, $c_{out}(G^{2000})$, $\eta_{out}(G^{2000})$, $s_{out}(G^{2015})$, $c_{out}(G^{2015})$, and $\eta_{out}(G^{2015})$ for typical regions from 1995 to 2020

2.4 Concluding remarks

This chapter explored the factors influencing the values and variations of a country's labor and GHG emission exploitation. The analysis can be divided into three aspects: coefficients,

industrial structure, and source consumption structure. The former two belong to the domain of production, while the third one falls into the domain of consumption. Obviously, when a country's sectoral labor coefficients are lower than those of the corresponding sectors in other countries, the likelihood of a country exploits other countries would increase. The same applies to GHG emission exploitation. Regarding production and source consumption structure, we evaluate a country's industrial structure and source consumption structure from the viewpoint of bias in respect to labor intensity and GHG emission intensity, respectively.

In order to extract the aspect of coefficients, the world average industrial structure is utilized as a weight. Similarly, to extract the aspect of industrial structure, the world average sectoral coefficients are applied. However, as shown by the case of Laos in 2020, the use of world average sectoral coefficients does lead to incorrect measure of a country's industrial structure. This is mainly due to the inherent limitation in the ICIO tables, of which the number of industry is only 45. Taking the electricity, gas, steam and air conditioning supply as an example, electricity can be generated through various sources, including hydropower, thermal power, nuclear power, and others. The associated CO₂ emissions vary significantly depending on the energy source. As a result, in certain circumstances, a high value of $s(L)$ or $s(G)$ of a country does not necessarily imply this country's industrial structure is biased toward labor- or GHG emission- intensive direction.

The indices for source consumption structure consider source industry structure and source country structure. Whether the source industry consumption structure of a country is biased toward labor- or GHG emission- intensive direction is also assessed using corresponding world sectoral coefficients, which would induce the same difficulty mentioned in industrial structure. Moreover, given the high self-sufficiency rates in most countries and the increased share of "tertiary sector" consumption in high-income nations, the calculation results of this index are usually opposite to what was expected. To solve this problem, we developed indices including the external ratio and the industrial structure of output meeting foreign final demand, the source consumption structure of output source abroad, and their ratio.

The empirical results did confirm the explaining powers of the three factors in determining a country's role in exploitation and its relative position. Nonetheless, there are some varying trends that have not been explained by the three aspects. The index of source country consumption structure for the United States strongly supports to explain the variation in its labor exploitation. However, it has not yet investigated whether the power of this index applies to all 77 regions.

3

Trade in Value Added and Global Footprint: A Unified Output Accounting Framework

3.1 Introduction

The development of international production networks and the construction of global multi-regional input-output tables have produced two areas of study. The literature on trade in value added has concerned the divergence between traditional trade statistics and value-added accounts. The rise in intermediate goods trade has impaired the capability of official trade data to accurately reflect the true inter-country demand and supply linkages. These studies aim at identifying what is value added and what is double counted in gross trade so as to provide a better understanding of production sharing in so-called global value chains. (Borin and Mancini, 2023; Koopman et al., 2014; Los and Timmer, 2018; Miroudot and Ye, 2021). The global footprint literature has shown an increased interest in the impact of trade on environmental issues (Wiedmann and Lenzen, 2018). A hot discussion centered around the measurement of embodied CO₂ emissions in gross exports or imports (Peters, 2008; Peters and Hertwich, 2006). Another focus is the disparity between a country's production-based and consumption-based emissions and other factor contents, such as employment and resources (Aichele and Felbermayr, 2012; Dorninger et al., 2021; Wang et al., 2024).

Although there appears to be a relation between trade in value added and global footprint (Tukker and Dietzenbacher, 2013), little attention has been paid to link them. Meng et al. (2018) is one of the few exceptions, but it does not seem to have succeeded. One reason for the disconnection lies in the property of the total value added multiplier (global Leontief inverse evaluated by direct value-added coefficients) of which all elements are unity. This convenient trait cannot be relied upon for attributes other than value added, such as carbon dioxide, employment, land use, and biodiversity. To connect the two areas, it is necessary to be free from the unity property.

In this chapter, we propose a new framework, not using the special property of the total value added multiplier, and discuss all relations in terms of output. In this framework, any attributes could be combined, only by multiplying their coefficients to output. We express the breakdown of gross exports by global matrices, simplifying the formula and enabling calculation easier. We provide answers to several questions in trade in value added study, such as what is the distinction between foreign value added (FVA) and double counting. Based on the new framework, we decompose global footprint measurements according to final destination and complexity of trade.

Combining the two research fields would have some political implications as well. For example, in carbon border adjustment mechanism (CBAM), tariffs will be imposed based on the estimation of CO₂ emissions. It will matter whether the emissions are defined as emissions embodied in gross imports or direct emissions by importers; whether the emissions embodied in certain quantity of products are well identified or not.

3.2 Literature review

Koopman et al. (2014, henceforth KWW)'s seminal work is at the center of the study on trade in value added, which firstly proposed an accounting framework to decompose gross exports into various value-added and double-counted terms. The basic decomposition scheme of KWW is widely adopted. Typically, gross exports are first decomposed by country of origin into domestic content (DC) and foreign content (FC). Then DC and FC are further divided into value-added components (domestic value added DVA, and FVA) and double-counted items (domestic double counted DDC and foreign double counted FDC). Around KWW, there have been many studies pointing out its limitations, such as not being available at bilateral and sectoral levels (Borin and Mancini, 2015; Los and Timmer, 2018; Wang et al., 2013), underestimating domestic indirect value added (Nagengast and Stehrer, 2016) and FVA (Borin and Mancini, 2023).

The fact that KWW holds only for a country's total exports (reasons in Appendix A.2.1) restricts analyses of bilateral and sectoral trade relations which matter in a range of empirical questions (Borin and Mancini, 2019). Wang et al. (2013, henceforth WWZ) extended KWW's accounting framework to bilateral and sectoral dimensions. However, KWW and WWZ used distinct decomposition approaches¹, leading to different DDC terms (details in Appendix A.2.3). At aggregate level, value-added exports are a component of total exports, nonetheless, the relation between bilateral gross and value-added exports was poorly clarified. Nagengast and Stehrer (2016) distinguished two methods for assigning value-added exports to gross trade flows at the bilateral level, either taking the perspective of the country of origin or the country of final absorption, termed the source-based and sink-based approach. Nevertheless, since the aim of Nagengast and Stehrer (2016) was to identify value-added components accounting for the difference between bilateral gross and value-added trade balance, they did not provide a

¹However, WWZ's derivation idea is applicable to KWW as illustrated in Appendix A.2.2

complete breakdown. To achieve this, Borin and Mancini (2015, 2017) derived a revised sink-based approach for decomposing a country's exports, recording value-added for the last time it leaves the exporter's border. The choice between the source-based and sink-based approaches in decomposition arises when the "perspective" is more aggregate than the considered trade flows (Borin and Mancini, 2023). The perspective specifically delimits the perimeter used to identify double counting—the value added that crosses this perimeter more than once.

Koopman et al. (2014); Nagengast and Stehrer (2016); Wang et al. (2013) define double counting with the entire array of collective international borders being the perimeter, a criterion later termed "world perspective" by Borin and Mancini (2017). Different empirical questions call for distinct perspectives, for example, measuring the foreign gross domestic product (GDP) embedded in a country's exports can be addressed by an "exporting country perspective", which sets the national border as the perimeter. Borin and Mancini (2023) argue that every decomposition of trade flows should adhere to a single perspective for internal consistency, and thus criticize KWW and WWZ for using an exporting country perspective in singling out DVA, while using a world perspective to isolate FVA. However, what they fail to accurately acknowledge is that when the aim is to isolate a country's GDP from its total exports, both the world perspective and the exporting country perspective yield the identical DVA (Miroudot and Ye, 2021). In other words, it is equally valid to assert that KWW and WWZ consistently follow a world perspective in identifying DVA and FVA in aggregate exports. What is more, Miroudot and Ye (2021) also pointed out that there is no source-based or sink-based approach when isolating DVA in gross exports with the world perspective.

Nevertheless, adopting a world perspective versus an exporting country perspective inevitably results in different FVA when decomposing gross exports. Under the world perspective, FVA is by definition double-counted since it is DVA in other countries' exports (Miroudot and Ye, 2021). In their framework, FVA in the world perspective is equal to zero to be consistent with country and bilateral perspectives in defining double counting. In KWW's decomposition, part of the foreign content of exports is regarded as FVA if it passes through the exporting country and is absorbed by the direct importer as either final or intermediate goods. Similar to Miroudot and Ye (2021), Borin and Mancini (2023) also use perspectives to define double counting, but they give a non-zero FVA under the world perspective. They define FVA using both source-based and sink-based approaches. In the former approach, a portion of gross exports is considered FVA if it crosses a border other than that of the original country for the first time, and in the latter approach, if it crosses a border other than that of the original country for the last time. Borin and Mancini (2023)'s FVA is larger than KWW's.

For the exporting country perspective, it considers foreign items that cross the exporter's border once as FVA. This measurement is non-additive—the summation does not represent the world FVA since some portion of value added might be counted multiple times when the exporter varies. The divergent views about FVA underline the complexity of defining double counting. In the OECD TiVA Indicators, double-counted terms are not defined, as gross trade flows were

treated as final demand (Guilhoto et al., 2022). Some work measures value-added trade derived from final demand or production (Johnson and Noguera, 2012; Wang et al., 2017a,b, 2022), removing the occurrence of double counting.

Understanding double counting is not only important for value-added decomposition of gross exports but also for other embodied domestic and foreign net components in trade (Miroudot and Ye, 2021). Early methods like the emissions embodied in bilateral trade (EEBT) proposed by Peters (2008) used local Leontief inverse and bilateral trade statistics to compute domestic emissions for producing exports, avoiding double counting. Meng et al. (2018) adopted WWZ's decomposition of bilateral exports, just deleting WWZ's double-counted components and substituting value-added coefficients with CO₂ emission coefficients. The authors left unanswered the issue of whether WWZ's separation of FVA and FDC is correct or not, and simply applied their result to another area than value added.

In addition to embodied contents in gross exports, concerning the interactions between trade and the environment, significant attention has been given to a region's production-based and consumption-based carbon emissions as well as the difference resulting from international trade. In consumption-based accounting, there is no double-counted part since it is derived from final demand. At first, consumption-based accounting was utilized to analyze carbon leakage and climate policy (Peters and Hertwich, 2008; Peters et al., 2011). However, with the growing importance of global value chains (GVCs), researchers start to examine the GVC characteristics of production-based and consumption-based attributes. Xiao et al. (2020) distinguished a country's consumption-based carbon emissions and value-added by considering the heterogeneity of demand and trade routes, thereby constructing a diversified carbon intensity. Wang et al. (2022)'s framework, although focusing on GDP, is primarily an output breakdown to measure different types of GVC activities. This decomposition is based on forward and backward industrial linkages, pertaining to only production side². Neither Wang et al. (2022) nor Xiao et al. (2020) provide a unified decomposition of production-based and consumption-based factor contents, nor do they directly deal with gross exports³.

Very little literature has analyzed the environmental and social footprints in the context of GVCs from the perspectives of production, consumption, and trade. To link trade in value added and global footprint, several steps are necessary. First, by using basic relations about output, we rephrase what was framed by value added in terms of output. Discussion about what is value added and what is double counted must be replaced by discussion about what is "true output" and what is "double-counted output". This procedure is equivalent to separating

²In Peters (2008), a country's carbon emissions based on backward industrial linkage—emissions from producing final goods for domestic and foreign consumption—are regarded as the MRIO consumption-based national emissions inventories (NEI). However, we argue that a country's consumption-based NEI should be defined as—the emissions from all the production stages to meet this country's final goods consumption.

³Both Wang et al. (2022) and Xiao et al. (2020) categorize split terms into pure domestic, traditional trade, simple GVC, and complex GVC, albeit with different criteria. The classification of pure domestic, traditional trade, simple GVC, and complex GVC are not standardized. Even the same authors employ different categorizations in distinct papers, see Wang et al. (2017a, 2013)

value-added coefficients from value-added amounts (value-added coefficients multiplied by the Leontief inverse and gross exports). The residual would be “output”. This decoupling makes operations in global matrix expressions easier. Second, under this framework, we address the issue of FVA and FDC and revive the concept of FVA in the world perspective by abandoning the perimeter criterion. A part of exports is defined as FVA when it can find its counterpart in DVA. The counterpart relation between DVA and FVA allows us to have non-zero FVA in the world perspective, however, when we count FVA as a component of global GDP, we must discard its counterpart in DVA as part of world GDP. Third, we decompose bilateral output according to trade complexity and final destination.

3.3 A unified output accounting framework: from trade in value added to global footprint

3.3.1 Definitions

Without loss of generality, we consider an ICIO⁴ table with G countries and N sectors:

Table 3.1 Inter-Country Input-Output Table

		Intermediates				Final demand				Total Output
		1	2	...	G	1	2	...	G	
Intermediates	1	Z^{11}	Z^{12}	...	Z^{1G}	y^{11}	y^{12}	...	y^{1G}	x^1
	2	Z^{21}	Z^{22}	...	Z^{2G}	y^{21}	y^{22}	...	y^{2G}	x^2
	$\vdots$	$\vdots$	$\vdots$	$\ddots$	$\vdots$	$\vdots$	$\vdots$	$\ddots$	$\vdots$	$\vdots$
	G	Z^{G1}	Z^{G2}	...	Z^{GG}	y^{G1}	y^{G2}	...	y^{GG}	x^G
Value added		w^1	w^2	...	w^G					
Total input		$(x^1)'$	$(x^2)'$	...	$(x^G)'$					

In Table 3.1, superscripts indicate countries. Z^{rs} is an $N \times N$ representation of intermediate flows from country r to country s . Specifically, the element in the i -th row and j -th column of this matrix, denoted as z_{ij}^{rs} , signifies the intermediate inputs from sector i in country r to sector j in country s . y^{rs} is an $N \times 1$ vector of final products provided by country r to country s . The i -th element y_i^{rs} gives the final products from sector i in country r to country s (Table 1 is a simplified ICIO table, the final demand not being divided into subcategories). x^s is an $N \times 1$ vector and its i -th element x_i^s gives the output of sector i in country s . w^r is a $1 \times N$ row vector and the j -th element w_j^r represents value added of sector j of country r . The input-output coefficient matrix is defined as: $A^{rs} = Z^{rs} \widehat{x^s}^{-1}$, where $\widehat{\cdot}$ denotes diagonalization. The element a_{ij}^{sr} is the technical coefficient describing units of intermediate goods in sector i of country r needed for one unit output production of sector j in country s ; $v^r = w^r \widehat{x^r}^{-1}$ is the direct value-added

⁴GRMIO and ICIO in this study are interchangeable.

coefficient row vector. Similarly, carbon emission or employment coefficients can be calculated if the corresponding country-sector carbon emissions and employment data are available. Bold letters without superscripts denote global matrices.

The renowned global Leontief inverse matrix is defined as $\mathbf{B} = (\mathbf{I} - \mathbf{A})^{-1}$, which takes into account all upstream production linkages: $\mathbf{B} = \mathbf{I} + \mathbf{A} + \mathbf{A}^2 + \mathbf{A}^3 + \dots$ and thus gives the direct and indirect inputs needed for one unit of final goods production. From $\mathbf{A}\mathbf{x} + \mathbf{y} = \mathbf{x}$, we obtain $\mathbf{x} = \mathbf{B}\mathbf{y}$.

We express the global Leontief inverse matrix in the block matrix representation and define $\mathbf{B}^r$ ($r = 1, 2, \dots, G$) as:

$$\mathbf{B} = \begin{bmatrix} \mathbf{B}^{11} & \mathbf{B}^{12} & \dots & \mathbf{B}^{1G} \\ \mathbf{B}^{21} & \mathbf{B}^{22} & \dots & \mathbf{B}^{2G} \\ \vdots & \vdots & \ddots & \vdots \\ \mathbf{B}^{G1} & \mathbf{B}^{G2} & \dots & \mathbf{B}^{GG} \end{bmatrix} = [\mathbf{B}^1 \quad \mathbf{B}^2 \quad \dots \quad \mathbf{B}^G].$$

We decompose $\mathbf{A}$ into $\mathbf{A} = \mathbf{A}^D + \mathbf{A}^F$, where $\mathbf{A}^D$ is a $GN \times GN$ semi-diagonal block matrix with domestic input coefficients, i.e.

$$\mathbf{A}^D = \begin{bmatrix} \mathbf{A}^{11} & \mathbf{O} & \dots & \mathbf{O} \\ \mathbf{O} & \mathbf{A}^{22} & \dots & \mathbf{O} \\ \vdots & \vdots & \ddots & \vdots \\ \mathbf{O} & \mathbf{O} & \dots & \mathbf{A}^{GG} \end{bmatrix}, \quad \mathbf{A}^F = \begin{bmatrix} \mathbf{O} & \mathbf{A}^{12} & \dots & \mathbf{A}^{1G} \\ \mathbf{A}^{21} & \mathbf{O} & \dots & \mathbf{A}^{2G} \\ \vdots & \vdots & \ddots & \vdots \\ \mathbf{A}^{G1} & \mathbf{A}^{G2} & \dots & \mathbf{O} \end{bmatrix}.$$

We can further define $\mathbf{L} = (\mathbf{I} - \mathbf{A}^D)^{-1}$ as the local Leontief inverse matrix, which can be written as:

$$\mathbf{L} = \begin{bmatrix} \mathbf{L}^{11} & \mathbf{O} & \dots & \mathbf{O} \\ \mathbf{O} & \mathbf{L}^{22} & \dots & \mathbf{O} \\ \vdots & \vdots & \ddots & \vdots \\ \mathbf{O} & \mathbf{O} & \dots & \mathbf{L}^{GG} \end{bmatrix}.$$

We define $\mathbf{Y}$, $\mathbf{Y}^D$ and $\mathbf{Y}^F$ as

$$\mathbf{Y} = \begin{bmatrix} \mathbf{y}^{11} & \dots & \mathbf{y}^{1G} \\ \vdots & \ddots & \vdots \\ \mathbf{y}^{G1} & \dots & \mathbf{y}^{GG} \end{bmatrix}, \quad \mathbf{Y}^D = \begin{bmatrix} \mathbf{y}^{11} & \mathbf{0} & \dots & \mathbf{0} \\ \mathbf{0} & \mathbf{y}^{22} & \dots & \mathbf{0} \\ \vdots & \vdots & \ddots & \vdots \\ \mathbf{0} & \mathbf{0} & \dots & \mathbf{y}^{GG} \end{bmatrix}, \quad \mathbf{Y}^F = \begin{bmatrix} \mathbf{0} & \mathbf{y}^{12} & \dots & \mathbf{y}^{1G} \\ \mathbf{y}^{21} & \mathbf{0} & \dots & \mathbf{y}^{2G} \\ \vdots & \vdots & \ddots & \vdots \\ \mathbf{y}^{G1} & \mathbf{y}^{G2} & \dots & \mathbf{0} \end{bmatrix},$$

and define $\mathbf{y}^D = \mathbf{Y}^D \mathbf{d}$, $\mathbf{y}^F = \mathbf{Y}^F \mathbf{d}$, $\mathbf{y} = \mathbf{Y} \mathbf{d}$, and $\mathbf{y} = \mathbf{y}^D + \mathbf{y}^F$, where $\mathbf{d}$ is a $G \times 1$ vector, all the elements of which are unity (we call it “ones vector”).

If we define X as $X = BY$, then an element x^{rs} of

$$X = \begin{bmatrix} x^{11} & \dots & x^{1G} \\ \vdots & \ddots & \vdots \\ x^{G1} & \dots & x^{GG} \end{bmatrix},$$

represents a portion of country r 's output x^r that is finally absorbed by country s . We label X as “bilateral absorbed output”. x can be connected to X as $x = Xd$.

We define

$$X^D = \begin{bmatrix} x^{11} & 0 & \dots & 0 \\ 0 & x^{22} & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & x^{GG} \end{bmatrix}, \quad X^F = \begin{bmatrix} 0 & x^{12} & \dots & x^{1G} \\ x^{21} & 0 & \dots & x^{2G} \\ \vdots & \vdots & \ddots & \vdots \\ x^{G1} & x^{G2} & \dots & 0 \end{bmatrix}$$

and define $x^D = X^D d$, $x^F = X^F d$; then $x = x^D + x^F$.

Finally, we define e_i^{rs} as representing exports of commodity i from country r to country s and define

$$e^{rs} = \begin{bmatrix} e_1^{rs} \\ e_2^{rs} \\ \vdots \\ e_N^{rs} \end{bmatrix}, \quad e^r = \sum_{s \neq r} e^{rs}, \quad \text{and} \quad e = \begin{bmatrix} e^1 \\ e^2 \\ \vdots \\ e^G \end{bmatrix};$$

then

$$e = A^F x + y^F.$$

The operation of creating a semi-diagonal matrix from a vector is expressed by using an over-parenthesis, such as

$$\widehat{x} = \begin{bmatrix} x^1 & 0 & \dots & 0 \\ 0 & x^2 & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & x^G \end{bmatrix}.$$

3.3.2 Basic relations

The above formula for e is used frequently later on, so it should be listed here again.

$$e = y^F + A^F x. \tag{3.1}$$

The relation $x = Ax + y = A^D x + A^F x + y^D + y^F = A^D x + y^D + e$ yields

$$x = Ly + LA^F x = Ly^D + Le. \tag{3.2}$$

The equation $B(I - A) = B(I - A^D - A^F) = I = (I - A)B = (I - A^D - A^F)B$ gives

$$B = L + LA^F B = L + BA^F L. \quad (3.3)$$

The decomposition of X or x with respect to final destination

$$X = X^D + X^F \text{ or} \quad (3.4)$$

$$x = x^D + x^F \quad (3.5)$$

is fundamental, and is used frequently below.

3.3.3 Total Value Added Multiplier

The reason why the trade in value added study is so special lies in the unique feature of total value added coefficient matrix:

$$vB = v(I - A)^{-1} = u(I - A)(I - A)^{-1} = u, \quad (3.6)$$

where u is a $1 \times GN$ ones vector. The fact $v = u(I - A)$ has produced this outcome, which is equivalent to $u = uA + v$. This means that the price of all output is assumed to be unity.

Equation (3.6) implies $ue = vBe$ or $u\hat{e} = vB\hat{e}$, which has been utilized in the value-added decomposition of gross exports by KWW and subsequent work. KWW's object to decompose was te^s (t is a $1 \times N$ ones vector), and they decomposed it based on $vB^s e^s = te^s$.

This attractive property is not the case for other attributes. For example, if f represents a CO₂ emission coefficient vector, fB is not the ones row vector in general. So, if we pursue to bridge the trade in value added and the footprint fields, we must be free from this trait. A straightforward way of doing so is to separate v from B , and to talk about $B\hat{e}$ or $B^s e^s$. When we base our discussion on $B\hat{e}$ or $B^s e^s$, multiplying any coefficient vector to it from the left allows us to apply the appropriate relations set up for $B\hat{e}$ to relations involving attributes other than value added.

We will show this can be done for KWW's decomposition first.

3.3.4 KWW by global matrix and FVA in the world perspective

As mentioned above, KWW's object for decomposition is $te^s = vB^s e^s$. We have proposed to change the object to $B^s e^s$. This is nothing but the s -th column of $B\hat{e}$. Therefore, we can talk about the decomposition of $B\hat{e}$. Meanwhile, we will show how the basic relations can be applied in the derivation.

From equation (3.3), we have

$$B\hat{e} = (L + BA^F L)\hat{e} = L\hat{e} + BA^F L\hat{e}.$$

From equation (3.1), $\widehat{e} = \widehat{y^F} + \widehat{A^F x}$, then

$$B\widehat{e} = \widehat{Ly^F} + \widehat{LA^F x} + BA^F L\widehat{e}. \quad (3.7)$$

From equation (3.2), we get

$$\widehat{x} = \widehat{LA^F x} + \widehat{Ly}.$$

Since the off-diagonal blocks in L are zero matrices and $y = y^D + y^F$,

$$\widehat{x} = \widehat{LA^F x} + L\widehat{y} = \widehat{LA^F x} + \widehat{Ly^D} + \widehat{Ly^F}.$$

Therefore, using equation (3.5),

$$\widehat{Ly^F} + \widehat{LA^F x} = \widehat{x} - \widehat{Ly^D} = \widehat{x^F} + \widehat{x^D} - \widehat{Ly^D}.$$

Substituting it into equation (3.7) yields

$$B\widehat{e} = \underbrace{\widehat{x^F}}_{(i)} + \underbrace{\widehat{x^D} - \widehat{Ly^D}}_{(ii)} + \underbrace{BA^F L\widehat{e}}_{(iii)}. \quad (3.8)$$

Term (i) multiplied by v from the left is called “value-added exports” by Johnson and Noguera (2012) and is included in KWW’s accounting equations. Let us call this output $\widehat{x^F}$ “true exports”. Term (ii) represents output for domestic demands excluding non-trade parts. When multiplied by v , it represents the domestic value added that returned home (RDV). Term (iii) is considered double-counted output, as (i) and (ii) encompass all true output related to international trade; adding $\widehat{Ly^D}$ to (i) and (ii) undoubtedly results in the total true output.

Term (iii) is further divided into $[BA^F L\widehat{e}]^D + [BA^F L\widehat{e}]^F$; $[BA^F L\widehat{e}]^D$ is the semi-diagonal block matrix of $BA^F L\widehat{e}$ and represents domestic double-counted output, and $[BA^F L\widehat{e}]^F$ is the off-diagonal block matrix and represents double-counted foreign output. The relation $B = L + BA^F L$ implies that $B^F = [BA^F L]^F$ for the off-diagonal blocks of L is zero. Taking $[B\widehat{e}]^F = B^F \widehat{e}$ and $[BA^F L\widehat{e}]^F = [BA^F L]^F \widehat{e}$ into account,

$$[BA^F L\widehat{e}]^F = [BA^F L]^F \widehat{e} = B^F \widehat{e} = [B\widehat{e}]^F.$$

Applying $e = y^F + A^F x = y^F + A^F Ly^D + A^F Le$,

$$[B\widehat{e}]^F = [By^F]^F + [\widehat{BA^F Ly^D}]^F + [\widehat{BA^F Le}]^F.$$

The three terms of the right-hand side correspond to the seventh, eighth and ninth terms of KWW’s equation (36).

As a result,

$$B\hat{e} = \underbrace{\widehat{x^F}}_{(i)} + \underbrace{\widehat{x^D - Ly^D}}_{(ii)} + \underbrace{[BA^F L\hat{e}]^D}_{(iii)} + \underbrace{[By^F]^F}_{(iv)} + \underbrace{[BA^F Ly^D]^F}_{(v)} + \underbrace{[BA^F Le]^F}_{(vi)} \quad (3.9)$$

is a complete expression of KWW's decomposition of gross exports in terms of output rather than value added. In this formula, the exports of all countries are decomposed in accordance with KWW's classification.

Equal to $\widehat{x^F} + \widehat{x^D} - \widehat{Ly^D}$, $L\hat{e}$ is the trade-related true output as well, therefore $BA^F L\hat{e}$ as a whole or $[BA^F L\hat{e}]^D + [BA^F L\hat{e}]^F$ is in a sense double counted. However, KWW named $[BA^F L\hat{e}]^D$ and $[BA^F Le]^F$ as “pure double-counted” (PDC) and distinguished them from $[By^F]^F$ and $[BA^F Ly^D]^F$, which represent FVA when multiplied by v .

The key difference between $[By^F]^F + [BA^F Ly^D]^F$ and $[BA^F Le]^F$ is that in the former when the exporting country in question imports intermediates to produce its exports, it must be the final exporter. Yet, it remains unclear why this difference leads to the distinction between FVA and PDC.

Borin and Mancini (2023) defines FVA in the world perspective as well. Stating by our output-based global matrix expression, what they did is to add a term:

$$H = \begin{bmatrix} 0 & B^{12} A^{21} L^{11} \sum_{r \neq 1} (y^{1r} + A^{1r} L^{rr} y^{rr}) & \dots & B^{1G} A^{G1} L^{11} \sum_{r \neq 1} (y^{1r} + A^{1r} L^{rr} y^{rr}) \\ B^{21} A^{12} L^{22} \sum_{r \neq 2} (y^{2r} + A^{2r} L^{rr} y^{rr}) & 0 & \dots & B^{2G} A^{G2} L^{22} \sum_{r \neq 2} (y^{2r} + A^{2r} L^{rr} y^{rr}) \\ \vdots & \vdots & \ddots & \vdots \\ B^{G1} A^{1G} L^{GG} \sum_{r \neq G} (y^{Gr} + A^{Gr} L^{rr} y^{rr}) & B^{G2} A^{2G} L^{GG} \sum_{r \neq G} (y^{Gr} + A^{Gr} L^{rr} y^{rr}) & \dots & 0 \end{bmatrix}$$

to KWW's $[By^F]^F + [BA^F Ly^D]^F$. Each column of H indicates the exporting country of $\hat{e}$, and each row indicates the original producing country.

To better understand what H means, it is convenient to decompose KWW's pure double-counted part $[BA^F Le]^F$ further into

$$\begin{aligned} [BA^F Le]^F &= [BA^F Ly^F]^F + [BA^F LA^F x]^F \\ &= [BA^F Ly^F]^F + [BA^F LA^F Ly^D]^F + [BA^F LA^F Le]^F \\ &= [BA^F L(y^F + A^F Ly^D)]^F + [BA^F LA^F Le]^F. \end{aligned}$$

H is a portion of $[BA^F L(y^F + A^F Ly^D)]^F$ where the last exporter is the country of origin of production. The common feature among the three terms $[By^F]^F$, $[BA^F Ly^D]^F$ and H is that the exporting country in question is the last exporter except for the country of origin.

The above idea to extract FVA is called a sink-based approach by Borin and Mancini (2023). They also define FVA by a source-based approach—a certain imported item is identified as FVA when it crosses a foreign border for the first time, which is equivalent to $LA^F L\hat{e}$. The

aggregation of the source-based and sink-based FVA over all importing country results in the same measures.

However, the two criteria do not conform to Borin and Mancini (2023)'s standpoint—the identification of double counting depends on the perspective adopted, which defines a particular perimeter to discern whether a trade flow is considered double counted based on crossing that specific perimeter more than once. For the world perspective, the perimeter should be all borders. Regarding the second border crossing as not double counted when it is over the origin country would contradict the world perspective (Feás, 2023). In this sense, KWW's identification of FVA was also inconsistent with the world perspective.

On the contrary, Miroudot and Ye (2021) strictly follow the concept of perspective and argue that in the world perspective, FVA should be zero since the corresponding value added has crossed the international borders more than once. Certainly, FVA should be regarded as double counted under the world perspective as long as the criterion is based on whether a particular item crosses the relevant perimeter more than once or not. But we go one step further to revive the concept of FVA for the world perspective.

We propose an alternative criterion for FVA in the world perspective based on whether it can find its counterpart in DVA instead of the perimeter criterion.

3.3.5 Counterpart criterion in the world perspective

The counterpart idea is inspired by KWW's two-country case, in which they found the equality between FVA and RDV. In general settings with more than two countries, WWZ found that FVA is equal to RDV plus DVA_INT_{rex} . Here DVA_INT_{rex} represents DVA in intermediate exports utilized by the direct importer to produce final goods exports destined for a third country. Nonetheless, KWW's FVA may not cover all possible counterparts. By using the basic relations (3.1)-(3.3), we can easily find a complete portion in the foreign output that has its counterpart in the domestic one. Our decomposition object is $B\hat{e}$. Applying equation (3.3), we have

$$B\hat{e} = L\hat{e} + BA^F L\hat{e},$$

$L\hat{e}$ is the true domestic output and by using equations (3.1) and (3.2),

$$L\hat{e} = \widehat{Ly^F} + \widehat{LA^F Ly^D} + \widehat{LA^F Le}.$$

The second term $BA^F L\hat{e}$ represents foreign output, which by using equation (3.3) is further divided into

$$BA^F L\hat{e} = LA^F L\hat{e} + BA^F LA^F L\hat{e}.$$

As a result,

$$B\hat{e} = \underbrace{Ly^F + LA^F Ly^D}_{(i)} + \underbrace{LA^F Le}_{(ii)} + \underbrace{LA^F L\hat{e}}_{(iii)} + \underbrace{BA^F LA^F L\hat{e}}_{(iv)}. \quad (3.10)$$

(i) and (ii) represent the domestic true output (DTO). (iii) and (iv) are foreign output. The global aggregation of (iii) is

$$LA^F L\hat{e}d = LA^F Le,$$

which is equal to the global aggregation of (ii), $\widehat{LA^F Le}d$. Therefore, (ii) is a counterpart of (iii). This suggests that the output in (ii) appears again as other countries' exports, and it finds the complete counterpart in the foreign account (iii). In contrast, there cannot be any other counterpart in (i) that has corresponding part in (iv), because the output in (i) crosses the border only once, impossible to appear in other countries' exports again.

The two items in (i) involve one single border crossing (SBC). (ii) is the multiple border crossing (MBC) output⁵. (iii) represents foreign output imported to the exporter and then re-exported from it. Since it finds its counterpart in DTO, let us call it foreign true output (FTO). Depending on different empirical issues, whether to call term (ii) as true output and term (iii) as double counted, or conversely, to call term (iii) as true output and term (ii) as double counted, is contingent. In the latter scenario, we count existing output in foreign territories and consider the corresponding output in home territories as double counted. Term (iv) is pure double-counted output including domestic and foreign parts.

$LA^F L\hat{e}$ multiplied by v is Borin and Mancini (2023)'s source-based FVA, which are mathematically equal to their sink-based FVA after global aggregation. This equality is expressed in terms of output as⁶

$$LA^F Le = [By^F]^F d + [BA^F Ly^D]^F d + Hd. \quad (3.11)$$

This relation reveals that KWW's FVA (corresponding to $[By^F]^F + [BA^F Ly^D]^F$) does not cover all the possible counterpart.

Borin and Mancini (2023) argue that FVA in the world perspective can be used to address the question: "what part of a country's GDP enters other countries' exports?", while the FVA in the exporting country perspective can answer "which part of a country's exports can be traced back to another country's GDP". They, however, found that the above question, which can be addressed by the world perspective FVA, can be answered by the exporting country perspective DVA subtracted by the part directly absorbed by the importing country. Based on this fact, they are sceptical about the FVA in the world perspective, claiming it does not provide meaningful

⁵Similar to Wang et al. (2022), the number of international border crossing is used to judge the complexity of trade activities. The international border here is not the boundary for identifying double-counted items.

⁶Detailed proof is reported in Appendix.A.3

insights. This suggests the possible overlook of the counterpart relation and the significance of FVA in the global context.

Miroudot and Ye (2017) came to identify the same FVA in the world perspective. They decompose the exports from country j to country i as $E_{ji} = A_{ji}(I - A_{ii})^{-1}E_i + A_{ji}(I - A_{ii})^{-1}Y_{ii} + Y_{ji} = \tilde{A}_{ji}E_i + \tilde{A}_{ji}Y_{ii} + Y_{ji}$. They described the first term multiplied by $V_j(I - A_{jj})^{-1}$ as “country j ’s value added (or GDP) in country i ’s exports”, and argued “if we sum up the value added from all foreign countries in country i ’s exports, we obtain the foreign value added in country i ’s exports, expressed as $\sum_{j \neq i}^G V_j(I - A_{jj})^{-1} \tilde{A}_{ji}E_i$ ”. However, the authors did not give any explanation about why this can be regarded as FVA.

By expressing what Miroudot and Ye (2017) stated using global matrices, we could capture the essential reason for the equality of term (ii) and term (iii) in equation (3.10) after aggregation. With the bilateral exports matrix:

$$\mathbf{E} = \begin{bmatrix} \mathbf{0} & \mathbf{e}^{12} & \dots & \mathbf{e}^{1G} \\ \mathbf{e}^{21} & \mathbf{0} & \dots & \mathbf{e}^{2G} \\ \vdots & \vdots & \ddots & \vdots \\ \mathbf{e}^{G1} & \mathbf{e}^{G2} & \dots & \mathbf{0} \end{bmatrix},$$

their decomposition of E_{ji} can be expressed in more general forms as:

$$\mathbf{E} = \mathbf{A}^F \hat{\mathbf{x}} + \mathbf{Y}^F.$$

From this we have

$$\begin{aligned} \mathbf{LE} &= \mathbf{LA}^F \hat{\mathbf{x}} + \mathbf{LY}^F \\ &= \mathbf{LA}^F (\mathbf{L}\hat{\mathbf{e}} + \widehat{\mathbf{Ly}^D}) + \mathbf{LY}^F \\ &= \mathbf{LA}^F \mathbf{L}\hat{\mathbf{e}} + \mathbf{LA}^F \widehat{\mathbf{Ly}^D} + \mathbf{LY}^F. \end{aligned} \quad (3.12)$$

Miroudot and Ye (2017)’s argument is tantamount to that the FVA in each country’s exports is represented by $\mathbf{vLA}^F \mathbf{L}\hat{\mathbf{e}}$ ($=\tilde{\mathbf{v}}\tilde{\mathbf{A}}\hat{\mathbf{e}}$, where $\tilde{\mathbf{A}} = \mathbf{A}^F \mathbf{L}$ and $\tilde{\mathbf{v}} = \mathbf{vL}$).

$\mathbf{LE}$ covers the whole part of trade-related output, so does the right-hand side of equation (3.12), which represents at the bilateral level the division of an exporting country’s true output into the re-export, the inputs for importers’ domestic final goods production for their own consumption, and the direct final goods consumption of the importing countries. Viewing equation (3.12) horizontally enables us to catch a division of a country’s trade-related output for all the other countries, and its summation is $\mathbf{LEd} = \mathbf{Le} = \mathbf{LA}^F \mathbf{Le} + \mathbf{LA}^F \mathbf{Ly}^D + \mathbf{Ly}^F$, of which the semi-diagonal arrangement produces $\widehat{\mathbf{LEd}} = \mathbf{L}\hat{\mathbf{e}} = \widehat{\mathbf{Ly}^F} + \widehat{\mathbf{LA}^F \mathbf{Ly}^D} + \widehat{\mathbf{LA}^F \mathbf{Le}}$. This is exactly the (i) and (ii) in equation (3.10), the decomposition of domestic true output.

Viewing equation (3.12) vertically shows us from the importing countries’ perspective what amounts of various countries’ output enter a certain country’s imports, and the right-hand side

gives the division into the importing country's re-export, the importing country's final goods production for its own demand, and the direct final consumption of the importing country. The first term of equation (3.12) represents foreign output for importing countries' re-export. This is the only real foreign output for each importing country's re-export, because the other two terms never indicate re-export.

In equation (3.10), we identified the term (ii) as the domestic MBC output, and the term (iii) as the FTO, but in equation (3.12), these two things are just the horizontal and vertical views of the first term, $LA^F L\hat{e}$. This is precisely the fact that lies at the basis of the equivalence between the domestic MBC output and FTO. In fact, the term (iii) in equation (3.10) is identical with the first term in equation (3.12).

3.3.6 An output accounting of bilateral exports with the world perspective

Equations (3.10) and (3.11) are applicable solely to a country's total exports to the world. Wang et al. (2013) devised an alternative decomposition framework for bilateral exports. Without loss of generality, let us consider the gross exports from country 1 to country 2. Then WWZ's object of decomposition is $[(vB^1)^T \# e^{12}]^T$, which is equivalent to $vB^1 \widehat{e^{12}}$. Accordingly, we could separate v from B^1 and change the object to $B^1 e^{12}$. Since we can interchange e^{12} and $\widehat{e^{12}}$ easily through the relation $e^{12} = \widehat{e^{12}} t'$, let us regard $B^1 e^{12}$ as the decomposition object to simplify matrix expressions.

In this sub-section, we do not replicate WWZ's decomposition but directly propose a new output accounting framework of bilateral exports from the world perspective. Our method differs from WWZ in two key aspects: i) we use $L^{11} e^{12}$ to separate out DTO, unlike WWZ, to include $v^1 B^{11} y^{12}$, it capriciously adjusted DVA; and ii) we apply the counterpart idea to identify FTO, whereas WWZ followed KWW's definition of FVA. Although the global matrix expression streamlines and enhances the breakdown process of total exports, attempts to adapt it to bilateral exports were ultimately unsuccessful⁷.

Consequently, we express the decomposition by regional matrices. Applying equation (3.3), we have

$$B^1 e^{12} = \begin{bmatrix} B^{11} \\ B^{21} \\ \vdots \\ B^{G1} \end{bmatrix} e^{12} = \begin{bmatrix} L^{11} + \sum_{r \neq 1} B^{1r} A^{r1} L^{11} \\ \sum_{r \neq 1} B^{2r} A^{r1} L^{11} \\ \vdots \\ \sum_{r \neq 1} B^{Gr} A^{r1} L^{11} \end{bmatrix} e^{12}.$$

We then decompose domestic and foreign contents separately. For domestic contents $L^{11} e^{12} + \sum_{r \neq 1} B^{1r} A^{r1} L^{11} e^{12}$:

⁷To decompose all bilateral exports simultaneously, we have to deal with E , which is an off semi-diagonal matrix. When E is multiplied with B from the left, one row of the Leontief inverse will be multiplied by one column of bilateral exports, resulting a summation. To preserve individual bilateral exports and obtain the column summation of B , we could vertically sum B first and then semi-diagonalize it before the multiplication. However, the summed Leontief inverse has no economic meaning.

i) $L^{11}e^{12}$ is DTO. Using equations (3.1) and (3.2),

$$L^{11}e^{12} = L^{11}(y^{12} + A^{12}x^2) = L^{11}y^{12} + L^{11}A^{12}L^{22}y^{22} + L^{11}A^{12}L^{22}e^2.$$

(a) $L^{11}y^{12}$ and $L^{11}A^{12}L^{22}y^{22}$ are SBC output,

(b) $L^{11}A^{12}L^{22}e^2$ is MBC output, which could be further broken down according to final destination by equations (3.1) and (3.5):

$$\begin{aligned} L^{11}A^{12}L^{22}e^2 &= L^{11}A^{12}L^{22} \sum_{t \neq 2} (y^{2t} + A^{2t}x^t) \\ &= L^{11}A^{12}L^{22} \left(y^{21} + \sum_{t \neq 2} A^{2t}x^{t1} \right) + L^{11}A^{12}L^{22} \left(\sum_{t \neq 1,2} y^{2t} + \sum_{t \neq 2} A^{2t} \sum_{u \neq 1} x^{tu} \right). \end{aligned}$$

ii) $\sum_{r \neq 1} B^{1r}A^{r1}L^{11}e^{12}$ is considered as domestic double counted.

For foreign contents:

$$\begin{aligned} \sum_{r \neq 1} B^{tr}A^{r1}L^{11}e^{12} &= B^{tt}A^{t1}L^{11}e^{12} + \sum_{r \neq t,1} B^{tr}A^{r1}L^{11}e^{12} \\ &= L^{tt}A^{t1}L^{11}e^{12} + \sum_{g \neq t} B^{tg}A^{gt}L^{tt}A^{t1}L^{11}e^{12} + \sum_{r \neq t,1} B^{tr}A^{r1}L^{11}e^{12} \quad (t = 2, \dots, G), \end{aligned}$$

i) $\sum_{t \neq 1} L^{tt}A^{t1}L^{11}e^{12}$ is FTO.

ii) $\sum_{g \neq t} B^{tg}A^{gt}L^{tt}A^{t1}L^{11}e^{12} + \sum_{r \neq t,1} B^{tr}A^{r1}L^{11}e^{12}$ are foreign double counted.

Above is an output accounting framework of bilateral exports, from the left of which one can multiply any coefficient row vector with the dimension of $1 \times GN$. To directly compare with Meng et al. (2018), we multiply carbon emission coefficient vector $f = [f^1 \ f^2 \ \dots \ f^G]$ from the left. Below is the breakdown of the global carbon emissions induced by the bilateral exports e^{12} :

$$\begin{aligned} fB^1e^{12} &= f^1L^{11}y^{12} + f^1L^{11}A^{12}L^{22}y^{22} + f^1L^{11}A^{12}L^{22} \left(y^{21} + \sum_{t \neq 2} A^{2t}x^{t1} \right) \\ &\quad + f^1L^{11}A^{12}L^{22} \left(\sum_{t \neq 1,2} y^{2t} + \sum_{t \neq 2} A^{2t} \sum_{u \neq 1} x^{tu} \right) + f^1 \sum_{r \neq 1} B^{1r}A^{r1}L^{11}e^{12} \\ &\quad + \sum_{t \neq 1} f^tL^{tt}A^{t1}L^{11}e^{12} + \sum_{t \neq 1} \sum_{g \neq t} f^tB^{tg}A^{gt}L^{tt}A^{t1}L^{11}e^{12} + \sum_{t \neq 1} \sum_{r \neq t,1} f^tB^{tr}A^{r1}L^{11}e^{12}. \end{aligned} \tag{3.13}$$

Equation (29) in Meng et al. (2018) is somewhat misleading, not only because it merely applied WWZ's value-added decomposition method to carbon emissions, but also because it considered both domestic induced emissions and foreign induced emissions as true emissions. From a world perspective, only one of the two could be regarded as true, depending on the specific question

under investigation. Additionally, given the decomposition object is $\mathbf{f}B^1e^{12}$, it is imperative to retain the double-counted terms, even if they do not reflect actual emissions.

3.3.7 Decomposition of bilateral absorbed output

KWW's decomposition succeeded to identify the DVA in trade. It further divided the trade-related DVA into the value-added exports (VAX) and RDV. In our output framework, it corresponds to the decomposition of $L\hat{e}$ into $\widehat{x^F}$ and $\widehat{x^D} - L\widehat{y^D}$. This decomposition is based on the relation (3.5), of which the bilateral expression is (3.4). Relation (3.4) represents the division of the bilateral absorbed output ($\mathbf{X}$) according to whether the final destination is home or abroad. Each component of the matrix $\mathbf{X}$, which is defined by $\mathbf{B}\mathbf{Y}$, indicates the original producing country and the final consuming country. Viewing $\mathbf{X}$ horizontally, each row captures the destinations where a country's sectoral output is absorbed. In this sense, $\mathbf{X}$ shows the decomposition of the true output with respect to final absorption. Conversely, when viewed vertically, each column represents the output from various countries and sectors that are ultimately consumed by the country corresponding to that column. In this sense, the matrix $\mathbf{X}$ is the basis of the calculation of consumption-based entity, such as CO₂ emissions, labor, value added.

Meng et al. (2018) has provided an indirect method for estimating consumption-based carbon emissions. This approach first calculates the total emissions generated by final goods production of commodity i in country s . Subsequently, these emissions are allocated to another country, such as r , based on the proportion of country r 's final demand for commodity i relative to the total output of commodity i in country s . However, by examining the r -th column of matrix $\mathbf{X}$ and multiplying it by the coefficient vector $\mathbf{f}$, we can easily obtain the consumption-based CO₂ emissions for country r . Indeed, the carbon emissions induced by final goods production are irrelevant for determining consumption-based emissions.

In our reproduction of KWW's decomposition, we first divide $B\hat{e}$ into $L\hat{e}$ and $BA^FL\hat{e}$ by using equation (3.3). Similarly, we use this relation repeatedly to decompose $\mathbf{X}$,

$$\begin{aligned}\mathbf{X} &= \mathbf{B}\mathbf{Y} = \mathbf{L}\mathbf{Y} + \mathbf{L}\mathbf{A}^F\mathbf{B}\mathbf{Y} \\ &= \mathbf{L}\mathbf{Y} + \mathbf{L}\mathbf{A}^F\mathbf{L}\mathbf{Y} + \mathbf{L}\mathbf{A}^F\mathbf{L}\mathbf{A}^F\mathbf{B}\mathbf{Y},\end{aligned}$$

and by $\mathbf{Y} = \mathbf{Y}^D + \mathbf{Y}^F$, we have

$$\mathbf{X} = \underbrace{\mathbf{L}\mathbf{Y}^D}_{(i)} + \underbrace{\mathbf{L}\mathbf{Y}^F}_{(ii)} + \underbrace{\mathbf{L}\mathbf{A}^F\mathbf{L}\mathbf{Y}^D}_{(iii)} + \underbrace{\mathbf{L}\mathbf{A}^F\mathbf{L}\mathbf{Y}^F + \mathbf{L}\mathbf{A}^F\mathbf{L}\mathbf{A}^F\mathbf{B}\mathbf{Y}}_{(iv)}. \quad (3.14)$$

Equation (3.14) is a decomposition of bilateral absorbed output with respect to the complexity of international trade. For each term in the right-hand side, the r -th row block represents the output of country r and the s -th column indicates the output ultimately consumed by country

s. (i) represents output to produce final goods that are consumed domestically without being involved in international trade. (ii) represents output to produce final goods exports, involved in ‘traditional trade’ with SBC. (iii) represents output to produce the intermediate goods imported by the direct trading partner to produce final products consumed in that country. Although term (iii) crosses international border only once, it indicates intermediate goods trade and its value added can thus be considered as one measurement of simple GVCs. (iv) represents intermediates trade that crosses multiple international borders before final absorption and its value added can be a measurement of complex GVCs.

To further decompose equation (3.14) based on whether the final destination is domestic or foreign, it is necessary to subdivide terms (iii) and (iv) into semi-diagonal and non-semi-diagonal components. In contrast to terms (i) and (ii), where the superscripts on Y convey the needed information, the trade complexity of terms (iii) and (iv) increases with the number of production stages, which renders Y^D and Y^F insufficient for providing the required details. Consequently, we reformulate equation (3.14) as:

$$\begin{aligned} X = BY = & \underbrace{LY^D + [LA^F LY^F]^D + [LA^F LA^F BY]^D}_{(D)} \\ & + \underbrace{LY^F + LA^F LY^D + [LA^F LY^F]^F + [LA^F LA^F BY]^F}_{(F)}, \end{aligned} \quad (3.15)$$

Term (D) denotes the gross output ultimately absorbed by the originating country, while term (F) represents gross output whose final destination is abroad. Specifically, (D) corresponds precisely to X^D , and (F) aligns exactly with X^F . The equation $X = X^D + X^F$ provides a sufficient and more straightforward framework for decomposing with respect to final destination.

The equation $X = BY$ gives a division of X according to its final destination. An alternative division of output is $LE + LY^D$ based on its direct trade destination. Let this be labelled as “bilateral direct output” and denoted by X' , where $X' = LE + LY^D$. X' is not equal to X . From equation (3.12),

$$\begin{aligned} X' &= LA^F L\hat{e} + LA^F \widehat{Ly^D} + LY^F + LY^D \\ &= LA^F L\hat{e} + LA^F \widehat{Ly^D} + LY, \end{aligned}$$

whereas

$$X = BY = LA^F BY + LY.$$

Therefore,

$$\begin{aligned} X - X' &= LA^F BY - (LA^F L\hat{e} + LA^F \widehat{Ly^D}) \\ &= LA^F BY - LA^F L(\hat{e} + \widehat{y^D}) \end{aligned}$$

$$\begin{aligned}
&= \mathbf{L} \mathbf{A}^F \mathbf{X} - \mathbf{L} \mathbf{A}^F \hat{\mathbf{x}} \\
&= \mathbf{L} \mathbf{A}^F (\mathbf{X} - \hat{\mathbf{x}})
\end{aligned} \tag{3.16}$$

Equation (3.16) is useful to catch the difference between gross trade and the trade with respect to absorption, the latter having close relation to concepts such as “value-added exports” and “emission exports”. Furthermore, equation (3.16) formulates the difference between the MRIO and EEBT method, which lies in the treatment regarding intermediate production of imported products (Peters, 2008), in mathematical terms. This goes beyond Peters (2007)’s empirical calculations and concretizes Meng et al. (2018)’s critique of EEBT when used to estimate consumption-based carbon emissions. Specifically, the off-diagonal blocks of

$$\mathbf{L} \mathbf{A}^F \hat{\mathbf{x}} = \begin{bmatrix} \mathbf{0} & \mathbf{L}^{11} \mathbf{A}^{12} \mathbf{x}^2 & \dots & \mathbf{L}^{11} \mathbf{A}^{1G} \mathbf{x}^G \\ \mathbf{L}^{22} \mathbf{A}^{21} \mathbf{x}^1 & \mathbf{0} & \dots & \mathbf{L}^{22} \mathbf{A}^{2G} \mathbf{x}^G \\ \vdots & \vdots & \ddots & \vdots \\ \mathbf{L}^{GG} \mathbf{A}^{G1} \mathbf{x}^1 & \mathbf{L}^{GG} \mathbf{A}^{G2} \mathbf{x}^2 & \dots & \mathbf{0} \end{bmatrix}$$

give the output of each sector in a country that is induced by its intermediate good exports to another country, while the diagonal blocks are zero vectors. On the other hand,

$$\mathbf{L} \mathbf{A}^F \mathbf{X} = \begin{bmatrix} \mathbf{L}^{11} \sum_{r \neq 1} \mathbf{A}^{1r} \mathbf{x}^{r1} & \mathbf{L}^{11} \sum_{r \neq 1} \mathbf{A}^{1r} \mathbf{x}^{r2} & \dots & \mathbf{L}^{11} \sum_{r \neq 1} \mathbf{A}^{1r} \mathbf{x}^{rG} \\ \mathbf{L}^{22} \sum_{r \neq 2} \mathbf{A}^{2r} \mathbf{x}^{r1} & \mathbf{L}^{22} \sum_{r \neq 2} \mathbf{A}^{2r} \mathbf{x}^{r2} & \dots & \mathbf{L}^{22} \sum_{r \neq 2} \mathbf{A}^{2r} \mathbf{x}^{rG} \\ \vdots & \vdots & \ddots & \vdots \\ \mathbf{L}^{GG} \sum_{r \neq G} \mathbf{A}^{Gr} \mathbf{x}^{r1} & \mathbf{L}^{GG} \sum_{r \neq G} \mathbf{A}^{Gr} \mathbf{x}^{r2} & \dots & \mathbf{L}^{GG} \sum_{r \neq G} \mathbf{A}^{Gr} \mathbf{x}^{rG} \end{bmatrix}$$

gives the output of an industry in a country that is induced by its intermediate goods exports that are finally absorbed by a particular country. The diagonal blocks of $\mathbf{L} \mathbf{A}^F \mathbf{X}$ are normally non-zero vectors.

3.4 Empirical examples

In this section, we first provide some comparisons that illustrate the numerical difference between our accounting framework and previous methods. We also show the decomposition results of a country’s final consumption concerning trade complexity. The calculation is based on the OECD ICIO Tables (2021 edition) for 67 regions and for the year 2018 (OECD, 2021a). The CO₂ emission coefficients are taken from the OECD’s Trade in embodied CO₂ (TECO2) database (OECD, 2021b).

In Tables 3.2, we show the results of gross exports, foreign content, and FVA defined by three methods under the world perspective. We find that the share of foreign content or FVA to gross exports is comparatively small despite the diffusion of GVCs. With respect to FVA, although both source-based and sink-based FVA follow the counterpart idea, they are generally unequal at

the country level. The difference might be useful in analyzing a country's position in the GVCs. The last two columns demonstrate that, for every country, its sink-based FVA exceeds KWW's FVA, which validates our critique regarding KWW's underestimation of FVA.

In the second example, we trace the CO₂ emissions induced by bilateral exports of China with all partners. We further assess the empirical difference between Meng et al. (2018)'s and our decomposition. Given that the European Union (EU) operates as a customs union, we aggregate the EU member countries. However, considering the substantial distinction between the EU15 and EU13 regions, we display them separately. The third column of Table 3.3 reports the amounts of CO₂ emissions induced within domestic territories, of which emissions related to MBC is reported in column 4. The MBC domestic emissions are comparable to the foreign-induced emissions in column 5, as they are counterparts, but the former is much larger (except for China-the United States and China-Saudi Arabia). This implies that China is involved in more emitting activities in complex GVCs. Comparing column 3 with column 6, we can find that Meng et al. (2018)'s method gives larger domestic emissions in three quarters of the partner regions. For the 10 countries with higher domestic emissions using our approach, there is substantial heterogeneity, as the exceeding amount is much bigger for Korea (1465 kt) and Taiwan (1147 kt). The difference in domestic emissions from the two methods disappears after aggregating the trading partners, but our method still get larger foreign emissions. This highlights the importance of a solid and correct baseline accounting framework. In Table 3.3, we confirm that the incomplete identification of FVA is inherited by carbon emissions.

In the third example, we examine a country's final consumption structure with respect to the complexity of trade. By multiplying value-added coefficients to equation (3.15), we obtain the decomposition of value added induced by a country's final demand. A country can meet its final demand in four ways: with purely domestically produced goods, with imported final products via traditional trade, and with products made through simple or complex GVCs. For final consumption met by production within complex GVCs, we further differentiate their origin (home or abroad). Table 3.4 presents their percentage of the total final consumption respectively. Among the 67 countries, only four (Ireland, Luxembourg, Malta, and Singapore) have a self-sufficiency rate below 50%. For most developed countries, the self-sufficiency rates are very high, such as the United States (87.77%) and Japan (84.74%). Columns 4-7 highlight that the share of traditional trade is generally larger than that of simple GVCs and complex GVCs (summation of columns 4 and 7). But the gap narrows and even reverses when summing the two types GVC trade. This phenomenon reflects the growing importance of GVCs in international supply and demand linkages.

Table 3.2 Different measurements of FVA in the world perspective for 2018

Country	Gross exports (million USD)	Foreign content	World perspective		
			source-based FVA	sink-based FVA	KWW FVA
AUS	305304	32563	24257	24822	24417
AUT	230643	71497	53298	53073	51529
BEL	315968	114233	88538	83978	82427
CAN	519950	129372	106024	113662	109791
CHL	84862	11993	9885	9152	8990
COL	52309	6414	5130	5331	5252
CRI	19692	3741	3053	3370	3339
CZE	170689	71961	51496	53396	51945
DNK	158625	50229	39038	39138	38705
EST	18989	6713	5064	5276	5220
FIN	98293	28263	22050	20885	20594
FRA	801664	195204	149967	151740	149782
DEU	1548423	354564	264892	265519	262839
GRC	72491	22240	18271	17567	17304
HUN	124510	57635	41212	43581	42539
ISL	11407	3398	2520	2582	2551
IRL	419727	167155	138603	138470	137093
ISR	102222	19949	16529	16636	16497
ITA	639543	148048	112009	115857	114483
JPN	905281	155778	125739	119235	117649
KOR	716685	229344	190366	174642	170683
LVA	15041	3542	2585	2781	2751
LTU	29885	9197	7431	6979	6913
LUX	130321	86531	73418	64408	63410
MEX	479856	155361	122355	140874	137978
NLD	519236	171268	137324	129142	127480
NZL	54233	8191	6601	7169	7115
NOR	157780	24778	18566	17743	17478
POL	293304	91021	68201	67651	66329
PRT	99595	30512	23250	24773	24294
SVK	84622	40629	28320	30002	29389
SVN	35860	13198	9482	9836	9638
ESP	467540	111333	86208	87888	86801
SWE	221569	57358	43933	44524	43976
CHE	361694	86637	65430	71179	70216
TUR	212850	44476	33617	35960	35567
GBR	721874	128709	102397	100407	99367
USA	2258156	214891	173758	166814	163838
ARG	75108	7923	6405	6822	6751
BRA	271367	35394	28113	28538	28207
BRN	6831	671	456	395	384
BGR	39437	14511	11666	11051	10943
KHM	15166	4403	3332	3876	3841
CHN	2429056	400111	318588	321512	318659
HRV	24317	5752	4310	4920	4871
CYP	12840	4368	3577	3484	3447
IND	538248	106826	91496	87568	86615
IDN	219797	31630	23279	24532	24148
HKG	176684	45884	34586	36230	35781
KAZ	68814	6703	5594	4577	4484
LAO	5943	1119	670	830	749
MYS	218434	75994	56125	58425	57343
MLT	18614	10090	8063	8702	8636
MAR	42962	13367	9850	11060	10894
MMR	21906	3776	2379	3009	2952
PER	53401	7165	6017	5363	5279
PHL	101995	24204	18155	18693	18372
ROU	86076	21010	15263	15993	15702
RUS	512041	43843	33861	32663	32240
SAU	303361	11242	8986	8902	8793
SGP	438524	207375	171022	162250	160412
ZAF	104571	22694	17983	17948	17634
TWN	374523	149211	118402	110117	106916
THA	327997	113429	88193	94327	93208
TUN	17762	6544	4956	5247	5142
VNM	246825	126118	94322	104586	102596
ROW	1518430	154646	122837	121646	120607
Aggregate	21731717	4813932	3779302	3779302	3721778

Table 3.3 Decomposition of global carbon emissions induced by Chinese bilateral exports for 2018

Bilateral relationship	Gross exports (million USD)	This study			Meng et al. (2018)	
		Total domestic emissions (kt)	MBC domestic emissions (kt)	Foreign emissions (kt)	Domestic emissions (kt)	Foreign emissions (kt)
CHN_EU15	352515	231874	62083	19751	232521	18696
CHN_EU13	54627	37045	14258	3281	37134	2586
CHN_AUS	60415	39830	4138	3691	39938	4183
CHN_CAN	60005	42294	9826	3498	42391	3544
CHN_CHL	17544	12976	1816	1039	12976	1151
CHN_COL	11295	8154	799	684	8196	804
CHN_CRI	2102	1602	313	125	1610	132
CHN_ISL	689	455	137	41	456	37
CHN_ISR	8551	6239	1133	494	6253	519
CHN_JPN	190972	128049	23265	10883	128062	11531
CHN_KOR	123138	91242	34567	7185	89777	5617
CHN_MEX	80467	53200	20977	5085	53346	3837
CHN_NZL	7999	5476	729	467	5497	520
CHN_NOR	9195	5927	987	515	5951	557
CHN_CHE	13483	7803	2809	745	7811	614
CHN_TUR	20658	15757	2863	1304	15823	1366
CHN_USA	490471	311210	22515	28281	312890	33528
CHN_ARG	14035	9401	901	851	9456	991
CHN_BRA	37069	27625	4031	2259	27688	2480
CHN_BRN	1620	1814	155	107	1817	119
CHN_KHM	6375	4481	1235	338	4483	286
CHN_IND	104915	83769	9205	6844	84129	7670
CHN_IDN	48645	39996	5475	3080	40025	3278
CHN_HKG	95640	65614	15561	6010	65806	6048
CHN_KAZ	5321	4443	740	304	4446	323
CHN_LAO	1412	1448	235	94	1446	100
CHN_MYS	32285	24017	10710	1987	23695	1334
CHN_MAR	4721	3297	801	270	3308	256
CHN_MMR	5527	4676	743	335	4670	348
CHN_PER	10547	8917	942	642	8940	718
CHN_PHL	24360	20492	3794	1678	20438	1664
CHN_RUS	56450	38193	5371	3330	38328	3693
CHN_SAU	26298	21110	1146	1579	21230	1905
CHN_SGP	40550	35688	24555	2346	35223	1046
CHN_ZAF	18155	12817	2857	1127	12823	1135
CHN_TWN	52263	39646	20167	3252	38499	1955
CHN_THA	51780	41830	18946	3247	41600	2294
CHN_TUN	1756	1259	437	106	1263	88
CHN_VNM	65570	56770	33021	4455	56015	2194
CHN_ROW	219637	175411	19690	13378	175887	14985
Aggregate	2429056	1721846	383933	144688	1721846	144134

Table 3.4 Decomposition of final consumption (%) for 2018

Country	Final consumption (million USD)	VA originated home		VA originated abroad		
		Pure domestic	Complex GVCs	Traditional trade	Simple GVCs	Complex GVCs
AUS	1343577	79.99	0.14	9.52	5.74	4.61
AUT	419038	64.90	0.22	16.62	9.99	8.26
BEL	537974	58.89	0.31	18.40	12.98	9.41
CAN	1683274	74.60	0.22	11.62	9.28	4.28
CHL	281935	74.11	0.04	12.90	7.97	4.99
COL	334359	81.23	0.02	8.55	6.61	3.60
CRI	58551	71.09	0.00	15.43	8.01	5.47
CZE	215276	61.35	0.19	15.63	13.29	9.55
DNK	316746	68.24	0.11	13.87	10.65	7.12
EST	28707	57.08	0.07	20.59	12.26	10.00
FIN	262902	70.88	0.09	11.13	11.39	6.50
FRA	2671199	75.49	0.36	10.10	8.67	5.38
DEU	3547676	72.87	0.87	12.16	8.08	6.02
GRC	204563	72.78	0.04	12.64	8.33	6.21
HUN	138370	56.08	0.13	18.29	14.07	11.44
ISL	24580	67.38	0.01	14.88	10.40	7.33
IRL	263671	44.69	0.23	32.00	12.84	10.24
ISR	351653	75.61	0.03	10.31	9.20	4.86
ITA	1924061	76.65	0.24	9.13	8.44	5.54
JPN	4830967	84.53	0.21	5.19	7.14	2.93
KOR	1580392	74.34	0.23	8.11	12.86	4.46
LVA	33191	62.52	0.11	18.73	8.72	9.92
LTU	51762	56.51	0.11	21.35	12.32	9.71
LUX	59924	42.19	0.11	20.30	26.34	11.07
MEX	1189183	71.41	0.22	14.38	8.72	5.28
NLD	795292	65.60	0.32	14.85	12.18	7.05
NZL	199297	75.66	0.02	11.17	7.97	5.18
NOR	393884	70.06	0.24	12.88	9.75	7.07
POL	534220	65.28	0.24	14.26	12.02	8.20
PRT	225792	68.42	0.09	14.26	9.98	7.25
SVK	99325	57.25	0.14	20.42	11.19	11.00
SVN	47433	58.68	0.08	19.30	11.29	10.66
ESP	1312444	75.44	0.24	10.35	8.45	5.52
SWE	515834	69.32	0.19	14.78	8.48	7.22
CHE	629403	67.87	0.15	15.40	9.41	7.18
TUR	745755	75.94	0.08	8.61	9.57	5.80
GBR	2767054	75.89	0.34	10.57	8.01	5.18
USA	20830799	87.12	0.65	5.28	4.50	2.45
ARG	483263	83.53	0.03	7.77	5.65	3.01
BRA	1730745	86.54	0.06	5.23	5.55	2.62
BRN	12717	59.00	0.03	20.53	10.44	10.00
BGR	60495	58.49	0.04	18.38	13.66	9.42
KHM	24639	52.78	0.01	25.10	10.38	11.73
CHN	13394501	85.66	0.42	3.93	7.43	2.56
HRV	57327	64.74	0.05	13.97	11.98	9.26
CYP	24305	56.92	0.02	23.15	9.96	9.95
IND	2826808	79.61	0.10	7.32	9.01	3.96
IDN	1033060	80.38	0.16	6.57	7.79	5.10
HKG	415022	54.33	0.10	25.46	8.93	11.18
KAZ	147574	73.68	0.05	11.74	9.80	4.73
LAO	19663	63.57	0.05	15.25	8.95	12.19
MYS	335877	63.81	0.15	13.82	13.73	8.49
MLT	12412	44.43	0.01	26.04	17.25	12.27
MAR	121488	63.87	0.03	16.82	10.25	9.04
MMR	72223	74.21	0.02	8.90	8.55	8.32
PER	210034	78.17	0.02	10.25	7.60	3.95
PHL	363410	66.11	0.06	14.98	10.59	8.26
ROU	237266	69.17	0.09	12.09	10.85	7.80
RUS	1429354	78.68	0.24	9.59	7.01	4.49
SAU	693308	70.19	0.15	17.16	6.54	5.96
SGP	292058	46.91	0.23	26.20	17.17	9.49
ZAF	347949	76.61	0.03	8.75	9.54	5.07
TWN	524739	67.94	0.15	12.37	13.28	6.26
THA	438220	62.32	0.14	14.17	15.63	7.74
TUN	42126	60.92	0.02	18.09	11.56	9.42
VNM	227761	50.95	0.14	12.49	24.34	12.07
ROW	5933344	75.82	0.66	11.12	7.58	4.81

3.5 Concluding remarks

This chapter has provided an output accounting framework to connect the fields of trade in value added and global footprint. After getting rid of the unity property of the total value added multiplier, previous decomposition methods in trade in value added could be solidly applied to other variables, which enables deeper analyses of environmental and social footprints in the rise of GVCs. We have demonstrated this by rephrasing KWW's decomposition in terms of output rather than value added as an example.

Although any attributes could be combined by multiplying their coefficients, we slightly leaned to environmental impacts, guaranteeing the global additivity feature in this framework. To achieve it, we adopted the world perspective, which is marginalized in the trade in value added study, and investigated the concept of FVA under the world perspective in the decomposition of gross exports. Neither Koopman et al. (2014) nor Borin and Mancini (2023)'s definition of FVA in the world perspective is consistent with the perimeter criterion. As a result, we proposed to identify FVA by the counterpart criterion—whether it can find its counterpart in DVA. Combining the counterpart idea, we provide a general output accounting scheme for breaking down aggregate, bilateral, and sectoral export flows according to source country and complexity of trade. This framework could be further decomposed to include destination country; the extension is contingent on specific empirical issues.

In addition, we defined bilateral absorbed output that gives a division of gross output according to final destination. The horizontal view of the bilateral absorbed output matrix reflects a country's bilateral production-based output, while the vertical view gives a country's consumption-based output. This allows us to simultaneously decompose production-based and consumption-based entities and reveal their GVC characteristics. The bilateral absorbed output is closely related to the MRIO method of consumption-based accounting, while the bilateral direct output is associated with the EEBT method. Unlike existing literature, which empirically compares the two methods, we formulated the difference between the MRIO and EEBT methods in mathematical terms.

Empirically, we found the underestimation of FVA is inherited by carbon emissions when using Meng et al. (2018)'s accounting framework, highlighting the caveat of cross-domain adoption without scrutiny. The consumption structure regarding trade complexity shows that the domestic sustainability of most countries is greater than 50%. Among the final demand supported by international trade, the role of GVCs is non-negligible, as the share of GVC trade has, on average, surpassed that of traditional trade.

Finally, it is worth pointing out that although in this chapter we mainly focus on output accounting in the world perspective, our framework could be incorporated into other perspectives, such as the exporting country perspective.

Conclusions

Through the concept of “embodied in trade”, this study focused on the global footprint in international trade. The decomposition of carbon productivity revealed its real improvement only comes from true carbon productivity, not the part with zero-sum nature. By analyzing 66 countries/regions and the rest of the world in 2018, we found that by excluding the exploitation part, the differences in carbon productivity among countries – particularly between developed and developing countries – shrink. Analysis of selected economies (EU15, EU13, the United States, Japan, China, and India) from 1995 to 2018 revealed the structure of exploitation has been maintained throughout the entire period. For China, USA, and EU15, international exploitation of labor and carbon emissions deepened from 1995 to 2006 and weakened from 2006 to 2018. The consumption-based labor productivity and population-sustaining power of CO₂ effects are the principal driving factors of change in carbon productivity. The growth in true carbon productivity increased moderately in the last half of the period.

The calculation of 77 regions in 2020 revealed that low coefficients are the strongest power to turn a country into an exploiter. Compared to GHG emission coefficients, small labor coefficients are more connected with advanced economic status. Although not as significant as coefficients, exploited countries tend to have an industrial structure less biased toward labor- and GHG emission-intensive directions. In contrast, the source industry consumption structure appears to fail in explaining the exploitation situation, as exploited countries’ source industry structure is more biased to labor- and GHG emission-intensive direction. When using external labor and GHG emission ratios to reflect the degrees of exploitation, the values for both exploiting and exploited countries are intensified. Analysis of typical regions (EU15, EU13, the United States, Japan, China, India, and Australia) from 1995 to 2020 showed that a country’s role in exploitation and its relative position can be largely explained by the three factors, however, some varying trends that have not been explained yet. We also found that variation in external labor ratios is different from that in labor exploitation index for China, which is due to the fact that external ratios can increase even when exploitation ratios decrease.

The reason for the disconnection between the field of trade in value-added and the field of global footprint was identified as the unity property of the total value added multiplier. By getting rid of this trait, the existing decomposition methods can be used for other embodied factors. However, we focused on the world perspective to ensure the global additivity of CO₂ emissions

and propose a counterpart criterion to identify FTO. Empirical calculations compared the different measures of FVA and found Meng et al. (2018)'s accounting method also underestimated foreign carbon emissions in bilateral trade flows for it used the same identification as WWZ. The decomposition of final consumption for 67 regions in 2018 revealed that, on average, 30% of the value added in final demand originates from abroad. Moreover, the role of GVC trade has become increasingly significant, with its share surpassing that of traditional trade.

A.1 OECD ICIO table information

Compared to OECD ICIO 2021 edition, which includes 66 regions and the rest of the world, the 2023 edition has added 10 more countries. Table A.1 is a complete list of these 76 countries and the rest of the world and their ISO codes. Both the 2021 and 2023 editions use the same sectoral classification, as shown in Table A.2.

A.2 KWW and WWZ: similarities and differences

A.2.1 Why is KWW only valid for aggregate exports?

When using regional matrix, the breakdown targets of KWW and WWZ are surprisingly similar:

$$\begin{aligned} KWW &: v^s B^{ss} e^{s*} \\ WWZ &: v^s B^{ss} \widehat{e^{sr}} \end{aligned} \tag{a1}$$

Since WWZ also applies to a country's total gross exports, we could have:

$$\begin{aligned} KWW &: v^s B^{ss} e^{s*} \\ WWZ &: v^s B^{ss} \widehat{e^{s*}}. \end{aligned} \tag{a2}$$

First, we investigate why KWW's cannot be applied to bilateral trade flows. The key reason roots in $L\widehat{e} = \widehat{x^F} + \widehat{x^D} - L\widehat{y^D}$. For better explanation, we rewrite this relation by using regional matrices:

$$L^{ss} e^{s*} = x^s - L^{ss} y^{ss} \tag{a3}$$

For bilateral trade $L^{ss}e^{sr} = L^{ss}A^{sr}x^r + L^{ss}y^{sr}$, even if we define a corresponding output for bilateral trade induced production, it is impossible to simply split it into output for domestic final demand and output for foreign final demand like equation (3.5). Therefore, this technique is not available for bilateral trade decomposition.

As for not being available at sectoral level, the reason is:

$$\widehat{L^{ss}e^{s*}} \neq L^{ss}\widehat{e^{s*}}. \quad (\text{a4})$$

Matrix form will be clearer (subscript suggests sector):

$$\widehat{L^{ss}e^{s*}} = \begin{bmatrix} L_{ii}e_i + L_{ij}e_j & 0 \\ 0 & L_{ji}e_i + L_{jj}e_j \end{bmatrix},$$

$$L^{ss}\widehat{e^{s*}} = \begin{bmatrix} L_{ii}e_i & L_{ij}e_j \\ L_{ji}e_i & L_{jj}e_j \end{bmatrix}. \quad (\text{a5})$$

Consequently, WWZ needs to find its own path to directly decompose intermediate trade flows.

A.2.2 Apply WWZ's derivation idea to get KWW

Although KWW's derivation idea is not applicable for WWZ, WWZ's derivation idea could obtain KWW. Wang et al. (2013) has proven the aggregation property in their appendix—after summing up over sectors and trade partners, WWZ becomes KWW. As a supplement, we show how to get KWW by applying WWZ's idea as follows, taking country 1 as an example:

$$\begin{bmatrix} B^{11} \\ B^{21} \\ \vdots \\ B^{G1} \end{bmatrix} \left(\sum_{r \neq 1} A^{1r} x^r + \sum_{r \neq 1} y^{1r} \right). \quad (\text{a6})$$

What KWW states in value-added terms could also be found in the output decomposition.

i) $B^{11} \sum_{r \neq 1} y^{1r}$ is the **first term** in KWW.

ii) $B^{11} \sum_{r \neq 1} A^{1r} x^r$

$$= L^{11} \sum_{r \neq 1} A^{1r} x^r + L^{11} \sum_{g \neq 1} A^{1g} B^{g1} \sum_{r \neq 1} A^{1r} x^r$$

(a) $L^{11} \sum_{r \neq 1} A^{1r} x^r$

$$= L^{11} \sum_{r \neq 1} A^{1r} \sum_g B^{rg} y^{g1} + L^{11} \sum_{r \neq 1} A^{1r} \sum_{t \neq 1} x^{rt}$$

$$\text{i. } L^{11} \sum_{r \neq 1} A^{1r} \sum_g B^{rg} y^{g1}$$

$$\begin{aligned} &= L^{11} \sum_{r \neq 1} A^{1r} B^{r1} y^{11} + L^{11} \sum_{r \neq 1} A^{1r} \sum_{g \neq 1} B^{rg} y^{g1} \\ &= \sum_{r \neq 1} B^{1r} A^{r1} L^{11} y^{11} + \sum_{g \neq 1} B^{1g} y^{g1}, \end{aligned}$$

which represent the **fifth term and fourth term** in KWW.

$$\text{ii. } L^{11} \sum_{r \neq 1} A^{1r} \sum_{t \neq 1} x^{rt}$$

$$\begin{aligned} &= L^{11} \sum_{r \neq 1} A^{1r} \sum_{t \neq 1} \sum_g B^{rg} y^{gt} = L^{11} \sum_{r \neq 1} A^{1r} \sum_g B^{rg} \sum_{t \neq 1} y^{gt} \\ &= L^{11} \sum_{r \neq 1} A^{1r} B^{r1} \sum_{t \neq 1} y^{1t} + L^{11} \sum_{r \neq 1} A^{1r} \sum_{g \neq 1} B^{rg} \sum_{t \neq 1} y^{gt}. \end{aligned}$$

The first term belongs to the double-counted part, while the second term can be converted into $\sum_{g \neq 1} B^{1g} \sum_{t \neq 1} y^{gt}$ corresponding to the **second term and third term** in KWW.

$$\begin{aligned} \text{(b) } &L^{11} \sum_{r \neq 1} A^{1r} B^{r1} \sum_{t \neq 1} y^{1t} + L^{11} \sum_{g \neq 1} A^{1g} B^{g1} \sum_{r \neq 1} A^{1r} x^r \\ &= L^{11} \sum_{g \neq 1} A^{1g} B^{g1} \left(\sum_{r \neq 1} A^{1r} x^r + \sum_{r \neq 1} y^{1r} \right) = \sum_{g \neq 1} B^{1g} A^{g1} L^{11} e^{1*}, \end{aligned}$$

This term with no doubt is the **sixth term** in KWW and why it is double counted term is perfectly self-explained.

iii) $\sum_{r \neq 1} B^{r1} \sum_{t \neq 1} y^{1t}$ is the **seventh term** in KWW.

$$\text{iv) } \sum_{r \neq 1} B^{r1} \sum_{t \neq 1} A^{1t} x^t$$

$$= \sum_{r \neq 1} B^{r1} \sum_{t \neq 1} A^{1t} L^{tt} y^{tt} + \sum_{r \neq 1} B^{r1} \sum_{t \neq 1} A^{1t} L^{tt} e^{t*}$$

Which represent the **eighth term and ninth term** separately.

In fact, by using the expression of

$$\begin{bmatrix} B^{11} \\ B^{21} \\ \vdots \\ B^{G1} \end{bmatrix} \left(\widehat{A^{1r} x^r} + \widehat{y^{1r}} \right),$$

we can derive both KWW and WWZ in a consistent way.

A.2.3 Different approaches to single out DDC

Another difference between KWW and WWZ is their identification of pure domestic double counted. In other words, the identification of GDP embedded in trade by KWW differs from that in WWZ.

WWZ identifies the value-added exports, along with RDV (trade-related GDP) in the gross bilateral exports from country 1 to country 2 as:

$$v^1 B^{11} y^{12} + v^1 L^{11} A^{12} \sum_{s \neq 1} \sum_{r \neq 1} B^{2r} y^{rs} + v^1 L^{11} A^{12} \sum_{r=1}^G B^{2r} y^{r1}. \quad (\text{a7})$$

The first two terms represent value-added exports and the third term is the value-added returning home. By output expression, equation (a7) is equivalent to

$$B^{11} y^{12} + L^{11} A^{12} \sum_{s \neq 1} \sum_{r \neq 1} B^{2r} y^{rs} + L^{11} A^{12} \sum_{r=1}^G B^{2r} y^{r1}. \quad (\text{a8})$$

With some calculation, we can rewrite equation (a8) as

$$\begin{aligned} & B^{11} y^{12} + L^{11} A^{12} \sum_{s \neq 1} \sum_{r \neq 1} B^{2r} y^{rs} + L^{11} A^{12} \sum_{r=1}^G B^{2r} y^{r1} \\ &= L^{11} y^{12} + L^{11} \sum_{r \neq 1} A^{1r} B^{r1} y^{12} + L^{11} A^{12} \sum_{s \neq 1} \sum_{r \neq 1} B^{2r} y^{rs} + L^{11} A^{12} \sum_{r=1}^G B^{2r} y^{r1} \\ &= L^{11} y^{12} + L^{11} \sum_{r \neq 1} A^{1r} B^{r1} y^{12} + L^{11} A^{12} \sum_{s=1}^G \sum_{r \neq 1} B^{2r} y^{rs} + L^{11} A^{12} B^{21} y^{11} \\ &= L^{11} y^{12} + L^{11} \sum_{r \neq 1} A^{1r} B^{r1} y^{12} + L^{11} A^{12} \sum_{s=1}^G \sum_{r=1}^G B^{2r} y^{rs} - L^{11} A^{12} \sum_{s=1}^G B^{21} y^{1s} + L^{11} A^{12} B^{21} y^{11} \\ &= L^{11} y^{12} + L^{11} A^{12} \sum_{s=1}^G \sum_{r=1}^G B^{2r} y^{rs} + L^{11} \sum_{r \neq 1} A^{1r} B^{r1} y^{12} - L^{11} A^{12} \sum_{s \neq 1} B^{21} y^{1s} \\ &= L^{11} y^{12} + L^{11} A^{12} x^2 + L^{11} \sum_{r \neq 1} A^{1r} B^{r1} y^{12} - L^{11} A^{12} \sum_{s \neq 1} B^{21} y^{1s} \\ &= L^{11} e^{12} + L^{11} \sum_{r \neq 1} A^{1r} B^{r1} y^{12} - L^{11} A^{12} \sum_{s \neq 1} B^{21} y^{1s}. \end{aligned} \quad (\text{a9})$$

From equation (a9), we find that WWZ's trade-related true output is different from $L^{11} e^{12}$ by the amount $L^{11} \sum_{r \neq 1} A^{1r} B^{r1} y^{12} - L^{11} A^{12} \sum_{s \neq 1} B^{21} y^{1s}$. However, the difference disappears when aggregating over all the partner countries;

$$L^{11} \sum_{s \neq 1} \sum_{r \neq 1} A^{1r} B^{r1} y^{1s} - L^{11} \sum_{r \neq 1} A^{1r} B^{r1} \sum_{s \neq 1} y^{1s} = 0. \quad (\text{a10})$$

Simply speaking, $L^{11}e^{12}$ is obtained by subtracting (ii) and (iv) from the right-hand side of

$$\begin{aligned} B^{11}e^{12} &= (L^{11} + L^{11} \sum_{r \neq 1} A^{1r} B^{r1})(y^{12} + A^{12}x^2) \\ &= \underbrace{L^{11}y^{12}}_{(i)} + \underbrace{L^{11} \sum_{r \neq 1} A^{1r} B^{r1} y^{12}}_{(ii)} + \underbrace{L^{11} A^{12} x^2}_{(iii)} + \underbrace{L^{11} \sum_{r \neq 1} A^{1r} B^{r1} A^{12} x^2}_{(iv)}, \end{aligned} \quad (a11)$$

and WWZ's true output is obtained by subtracting (iv) and $L^{11} A^{12} B^{21} \sum_{r \neq 1} y^{1r}$; the latter is included in (iii).

A.3 The proof of equation (3.11)

From basic relations, $B\hat{e}$ is decomposed as:

$$\begin{aligned} B\hat{e} &= [B\hat{e}]^D + [B\hat{e}]^F \\ &= [L\hat{e}]^D + [BA^F L\hat{e}]^D + [L\hat{e}]^F + [BA^F L\hat{e}]^F \\ &= L\hat{e} + [BA^F L\hat{e}]^D + O + [BA^F L\hat{e}]^F \\ &= \widehat{Ly^F} + \widehat{LA^F x} + [BA^F L\hat{e}]^D + [BA^F L\hat{e}]^F \\ &= \widehat{Ly^F} + \widehat{LA^F Ly^D} + \widehat{LA^F Le} + [BA^F L\hat{e}]^D + [LA^F L\hat{e}]^F + [BA^F LA^F L\hat{e}]^F \\ &= \widehat{Ly^F} + \widehat{LA^F Ly^D} + \widehat{LA^F Le} + [LA^F L\hat{e}]^F + BA^F LA^F L\hat{e}, \end{aligned}$$

where

$$[B\hat{e}]^D = \widehat{Ly^F} + \widehat{LA^F Ly^D} + \widehat{LA^F Le} + [BA^F L\hat{e}]^D. \quad (b1)$$

$$[B\hat{e}]^F = [LA^F L\hat{e}]^F + [BA^F LA^F L\hat{e}]^F. \quad (b2)$$

Equality between the third term of the right-hand side of (b1) and the first term of the right-hand side of (b2) in aggregate is established by

$$\widehat{LA^F Led} = [LA^F L\hat{e}]^F d = LA^F L\hat{e}d = LA^F Le. \quad (b3)$$

Another decomposition of $[B\hat{e}]^F$ is

$$[B\hat{e}]^F = [\widehat{By^F}]^F + [\widehat{BA^F Ly^D}]^F + [\widehat{BA^F Ly^F}]^F + [\widehat{BA^F LA^F Ly^D}]^F + [\widehat{BA^F LA^F Le}]^F.$$

or

$$[B\hat{e}]^F = [\widehat{By^F}]^F + [\widehat{BA^F Ly^D}]^F + [BA^F L(y^F + A^F Ly^D)]^F + [\widehat{BA^F LA^F Le}]^F.$$

Let us define:

$$G = \begin{bmatrix} O & B^{12} A^{21} L^{11} & B^{13} A^{31} L^{11} & \dots & B^{1G} A^{G1} L^{11} \\ B^{21} A^{12} L^{22} & O & B^{23} A^{32} L^{22} & \dots & B^{2G} A^{G2} L^{22} \\ B^{31} A^{13} L^{33} & B^{32} A^{23} L^{33} & O & \dots & B^{3G} A^{G3} L^{33} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ B^{G1} A^{1G} L^{GG} & B^{G2} A^{2G} L^{GG} & B^{G3} A^{3G} L^{GG} & \dots & O \end{bmatrix}$$

Borin and Mancini (2023)'s sink-based world perspective decomposition of $[B\hat{e}]^F$ into foreign true output and double-counted is

$$[B\hat{e}]^F = \underbrace{[B\hat{y}^F]^F + [\widehat{BA^F L y^D}]^F + H}_{\text{FTOsink}} + \underbrace{[\widehat{BA^F L (y^F + A^F L y^D)}]^F - H + [\widehat{BA^F L A^F L e}]^F}_{\text{FDCsink}}.$$

$$Hd = \widehat{Gu}(y^F + A^F L y^D) = \begin{bmatrix} \sum_{s \neq 1} B^{1s} A^{s1} L^{11} (\sum_{r \neq 1} y^{1r} + \sum_{r \neq 1} A^{1r} L^{rr} y^{rr}) \\ \sum_{s \neq 2} B^{2s} A^{s2} L^{22} (\sum_{r \neq 2} y^{2r} + \sum_{r \neq 2} A^{2r} L^{rr} y^{rr}) \\ \vdots \\ \sum_{s \neq G} B^{Gs} A^{sG} L^{GG} (\sum_{r \neq G} y^{Gr} + \sum_{r \neq G} A^{Gr} L^{rr} y^{rr}) \end{bmatrix}.$$

Since $\widehat{Gu} = [BA^F L]^D$, using the relation $y^F + A^F L y^D = e - A^F L e$,

$$\begin{aligned} Hd &= [BA^F L]^D (y^F + A^F L y^D) \\ &= (B^D - L)(y^F + A^F L y^D) \\ &= (B^D - L)(e - A^F L e) \\ &= B^D e - L e - B^D A^F L e + L A^F L e. \end{aligned} \tag{b4}$$

On the other hand, using the relation $\hat{y}^F + \widehat{A^F L y^D} = \hat{e} - \widehat{A^F L e}$, Borin and Mancini (2023)'s sink-based FTO is

$$\begin{aligned} [B\hat{y}^F]^F + [\widehat{BA^F L y^D}]^F + H &= [B(\hat{y}^F + \widehat{A^F L y^D})]^F + H \\ &= [B(\hat{y}^F + \widehat{A^F L y^D})]^F + H \\ &= [B\hat{e} - \widehat{BA^F L e}]^F + H \\ &= [B\hat{e}]^F - [\widehat{BA^F L e}]^F + H. \end{aligned}$$

Since $[\widehat{B\hat{e}}]^F d = B^F e$ and $[\widehat{BA^F Le}]^F d = B^F A^F Le$, taking (b4) into consideration,

$$\begin{aligned}
[\widehat{By^F}]^F d + [\widehat{BA^F Ly^D}]^F d + Hd &= [\widehat{B\hat{e}}]^F d - [\widehat{BA^F Le}]^F d + Hd \\
&= B^F e + B^F A^F Le + B^D e - Le - B^D A^F Le + LA^F Le \\
&= Be - BA^F Le - Le + LA^F Le \\
&= LA^F Le.
\end{aligned}$$

Taking (b3) into consideration, it shows that $[\widehat{By^F}]^F + [\widehat{BA^F Ly^D}]^F + H$ is equal to $[LA^F L\hat{e}]^F$ in aggregate.

This result is not surprising; the third term $\widehat{LA^F Le}$ in (b1) is true output produced in the original country that is exported from the origin and will be exported again by the other countries not less than once. It crosses the border again at least once from some of the other countries. The term $[LA^F L\hat{e}]^F$ in (b2) captures those crossings only once at the first re-export from the other countries than the origin. Therefore, the magnitude must be equal to the one measured at the export from the original countries. The criterion of sink-based approach is another way of capturing the re-export only once from the other countries than the origin, i.e. at the last time. So the magnitude should be equal to the one captured by the other rule that also counts border crossing only once.

Table A.1 OECD ICIO table reference area

OECD countries	ISO code	Non-OECD economies	ISO code
Australia	AUS	Argentina	ARG
Austria	AUT	Bangladesh	BGD
Belgium	BEL	Belarus	BLR
Canada	CAN	Brazil	BRA
Chile	CHL	Brunei Darussalam	BRN
Colombia	COL	Bulgaria	BGR
Costa Rica	CRI	Cameroon	CMR
Czechia	CZE	Cambodia	KHM
Denmark	DNK	China (People's Republic of)	CHN
Estonia	EST	Côte d'Ivoire	CIV
Finland	FIN	Croatia	HRV
France	FRA	Cyprus	CYP
Germany	DEU	Egypt	EGY
Greece	GRC	Hong Kong, China	HKG
Hungary	HUN	India	IND
Iceland	ISL	Indonesia	IDN
Ireland	IRL	Jordan	JOR
Israel	ISR	Kazakhstan	KAZ
Italy	ITA	Lao People's Democratic Republic	LAO
Japan	JPN	Malaysia	MYS
Korea	KOR	Malta	MLT
Latvia	LVA	Morocco	MAR
Lithuania	LTU	Myanmar	MMR
Luxembourg	LUX	Nigeria	NGA
Mexico	MEX	Pakistan	PAK
Netherlands	NLD	Peru	PER
New Zealand	NZL	Philippines	PHL
Norway	NOR	Romania	ROU
Poland	POL	Russian Federation	RUS
Portugal	PRT	Saudi Arabia	SAU
Slovak Republic	SVK	Senegal	SEN
Slovenia	SVN	Singapore	SGP
Spain	ESP	South Africa	ZAF
Sweden	SWE	Chinese Taipei	TWN
Switzerland	CHE	Thailand	THA
Türkiye	TUR	Tunisia	TUN
United Kingdom	GBR	Ukraine	UKR
United States	USA	Viet Nam	VNM
		Rest of the World	ROW

Table A.2 OECD ICIO table activities

sector code	industry
A01_02	Agriculture, hunting, forestry
A03	Fishing and aquaculture
B05_06	Mining and quarrying, energy producing products
B07_08	Mining and quarrying, non-energy producing products
B09	Mining support service activities
C10T12	Food products, beverages and tobacco
C13T15	Textiles, textile products, leather and footwear
C16	Wood and products of wood and cork
C17_18	Paper products and printing
C19	Coke and refined petroleum products
C20	Chemical and chemical products
C21	Pharmaceuticals, medicinal chemical and botanical products
C22	Rubber and plastics products
C23	Other non-metallic mineral products
C24	Basic metals
C25	Fabricated metal products
C26	Computer, electronic and optical equipment
C27	Electrical equipment
C28	Machinery and equipment, nec
C29	Motor vehicles, trailers and semi-trailers
C30	Other transport equipment
C31T33	Manufacturing nec; repair and installation of machinery and equipment
D	Electricity, gas, steam and air conditioning supply
E	Water supply; sewerage, waste management and remediation activities
F	Construction
G	Wholesale and retail trade; repair of motor vehicles
H49	Land transport and transport via pipelines
H50	Water transport
H51	Air transport
H52	Warehousing and support activities for transportation
H53	Postal and courier activities
I	Accommodation and food service activities
J58T60	Publishing, audiovisual and broadcasting activities
J61	Telecommunications
J62_63	IT and other information services
K	Financial and insurance activities
L	Real estate activities
M	Professional, scientific and technical activities
N	Administrative and support services
O	Public administration and defence; compulsory social security
P	Education
Q	Human health and social work activities
R	Arts, entertainment and recreation
S	Other service activities
T	Activities of households as employers; undifferentiated goods- and services-producing activities of households for own use

References

- Aichele, R. and Felbermayr, G. (2012). Kyoto and the carbon footprint of nations. *Journal of Environmental Economics and Management*, 63(3):336–354.
- Ang, B. W. (2005). The LMDI approach to decomposition analysis: a practical guide. *Energy policy*, 33(7):867–871.
- Ang, B. W. and Liu, F. L. (2001). A new energy decomposition method: perfect in decomposition and consistent in aggregation. *Energy*, 26(6):537–548.
- Arto, I. and Dietzenbacher, E. (2014). Drivers of the growth in global greenhouse gas emissions. *Environmental science & technology*, 48(10):5388–5394.
- Baldwin, R. E. (1971). Determinants of the commodity structure of us trade. *The American Economic Review*, 61(1):126–146.
- Borin, A. and Mancini, M. (2015). Follow the value added: bilateral gross export accounting. *Bank of Italy Temi Di Discussione (Working Paper) No.*, 1026.
- Borin, A. and Mancini, M. (2017). Follow the value added: Tracking bilateral relations in global value chains.
- Borin, A. and Mancini, M. (2019). Measuring what matters in global value chains and value-added trade. *World Bank policy research working paper*, (8804).
- Borin, A. and Mancini, M. (2023). Measuring what matters in value-added trade. *Economic Systems Research*, pages 1–28.
- Chinn, M. D. (2019). Purchasing power parity and real exchange rates.
- De Freitas, L. C. and Kaneko, S. (2011). Decomposing the decoupling of CO₂ emissions and economic growth in brazil. *Ecological Economics*, 70(8):1459–1469.
- Dietzenbacher, E. and Los, B. (1998). Structural decomposition techniques: sense and sensitivity. *Economic Systems Research*, 10(4):307–324.
- Dietzenbacher, E. and Mukhopadhyay, K. (2007). An empirical examination of the pollution haven hypothesis for india: towards a green leontief paradox? *Environmental and Resource Economics*, 36:427–449.
- Dorning, C., Hornborg, A., Abson, D. J., Von Wehrden, H., Schaffartzik, A., Giljum, S., Engler, J.-O., Feller, R. L., Hubacek, K., and Wieland, H. (2021). Global patterns of ecologically unequal exchange: Implications for sustainability in the 21st century. *Ecological Economics*, 179:106824.

- Feás, E. (2023). Decomposition of value added in gross exports: a critical review. *Applied Economic Analysis*, (ahead-of-print).
- Guilhoto, J. M., Webb, C., and Yamano, N. (2022). Guide to OECD TiVA Indicators, 2021 edition.
- Hagiwara, T. (2017). Labor value and exploitation in the global economy. In *Return of Marxian Macro-Dynamics in East Asia (Research in Political Economy, Volume 32)*, pages 15–37. Emerald Publishing Limited.
- Horvát, P., Webb, C., and Yamano, N. (2020). Measuring employment in global value chains. *OECD Science, Technology and Industry Working Papers*, No. 2020/01.
- ILO (2020). ILO modelled estimates database, ILOSTAT [database]. <https://ilostat.ilo.org/data/>. Accessed on 2022-9-6.
- International Labour Organization (2022). *ILO modelled estimates Methodological overview*. Department of Statistics.
- International Labour Organization (2023). ILO modelled estimates database. <https://ilostat.ilo.org/data/>. Accessed on 28-07-2024.
- IPCC (2023). Sections. in: Climate change 2023: Synthesis report. contribution of working groups i, ii and iii to the sixth assessment report of the intergovernmental panel on climate change [Core Writing Team, H. Lee and J. Romero (eds.)]. IPCC, Geneva, Switzerland, pp. 35-115. doi:10.59327/IPCC/AR6-9789291691647.
- Johnson, R. C. and Noguera, G. (2012). Accounting for intermediates: Production sharing and trade in value added. *Journal of international Economics*, 86(2):224–236.
- Kaya, Y., Yokobori, K., et al. (1997). *Environment, energy, and economy: strategies for sustainability*. United Nations University Press Tokyo.
- Keynes, J. M. (1936). The general theory of employment. *The quarterly journal of economics*, 51(2):209–223.
- Koopman, R., Wang, Z., and Wei, S.-J. (2014). Tracing value-added and double counting in gross exports. *American economic review*, 104(2):459–494.
- Kyophilavong, P., Souphonphacdy, D., Komany, S., and Tounalom, K. (2021). *Decarbonization in Lao PDR: the options and challenges*. ClimateWorks Australia.
- Lan, J., Malik, A., Lenzen, M., McBain, D., and Kanemoto, K. (2016). A structural decomposition analysis of global energy footprints. *Applied Energy*, 163:436–451.
- Leontief, W. (1953). Domestic production and foreign trade; the american capital position re-examined. *Proceedings of the American philosophical Society*, 97(4):332–349.
- Los, B. and Timmer, M. P. (2018). Measuring bilateral exports of value added: a unified framework. Technical report, National Bureau of Economic Research.
- Malik, A., Lan, J., and Lenzen, M. (2016). Trends in global greenhouse gas emissions from 1990 to 2010. *Environmental science & technology*, 50(9):4722–4730.
- Marx, K. (1867). 1976. capital, vol. 1. New York: Modern Library.

- Meng, B., Peters, G. P., Wang, Z., and Li, M. (2018). Tracing CO₂ emissions in global value chains. *Energy Economics*, 73:24–42.
- Meng, M. and Niu, D. (2012). Three-dimensional decomposition models for carbon productivity. *Energy*, 46(1):179–187.
- Mir, G.-U.-R. and Storm, S. (2016). Carbon emissions and economic growth: production-based versus consumption-based evidence on decoupling. *Institute for new Economic Thinking working paper series*, (41).
- Miroudot, S. and Ye, M. (2017). Decomposition of value-added in gross exports: Unresolved issues and possible solutions.
- Miroudot, S. and Ye, M. (2021). Decomposing value added in gross exports. *Economic Systems Research*, 33(1):67–87.
- Morishima, M. (1973). *Marx's economics: A dual theory of value and growth*. Cambridge University Press.
- Moutinho, V., Moreira, A. C., and Silva, P. M. (2015). The driving forces of change in energy-related CO₂ emissions in eastern, western, northern and southern europe: The LMDI approach to decomposition analysis. *Renewable and Sustainable Energy Reviews*, 50:1485–1499.
- Murshed, M., Apergis, N., Alam, M. S., Khan, U., and Mahmud, S. (2022). The impacts of renewable energy, financial inclusivity, globalization, economic growth, and urbanization on carbon productivity: Evidence from net moderation and mediation effects of energy efficiency gains. *Renewable Energy*, 196:824–838.
- Nagengast, A. J. and Stehrer, R. (2016). Accounting for the differences between gross and value added trade balances. *The World Economy*, 39(9):1276–1306.
- OECD (2012). *Eurostat-OECD methodological manual on purchasing power parities*. Statistical Office of the European Communities.
- OECD (2017). *Green Growth Indicators 2017*. OECD Publishing, Paris.
- OECD (2021a). OECD Inter-Country Input-Output Database. <http://oe.cd/icio>.
- OECD (2021b). Trade in Embodied CO₂ Database (TECO2). https://stats.oecd.org/OECDStat_Metadata/ShowMetadata.ashx?Dataset=IO_GHG_2021&ShowOnWeb=true&Lang=en.
- OECD (2021c). Trade in Employment Database (TiM). https://stats.oecd.org/OECDStat_Metadata/ShowMetadata.ashx?Dataset=TIM_2021&ShowOnWeb=true&Lang=en.
- OECD (2024a). Greenhouse gas footprint indicators. <https://www.oecd.org/en/data/datasets/greenhouse-gas-footprint-indicators.html>.
- OECD (2024b). OECD Inter-Country Input-Output Database. <http://oe.cd/icio>.
- OECD (2024c). Trade in Employment Database (TiM). <https://www.oecd.org/en/data/datasets/trade-in-employment.html>.
- Okishio, N. (1954). Value and price—labor value theory and equilibrium price theory. *Annals of Economic Review (Kobe University) No.1 (in Japanese, included in Okishio 1977 as Chapter1)*.
- Okishio, N. (1977). *Marx's Economics: a theory of value and price*. Chikuma shobō (in Japanese).

- Paraskevopoulou, C., Tsaliki, P., and Tsoulfidis, L. (2016). Revisiting leontief's paradox. *International Review of Applied Economics*, 30(6):693–713.
- Pasinetti, L. L. (1981). Structural change and economic growth: a theoretical essay on the dynamics of the wealth of nations.
- Peters, G. P. (2007). Opportunities and challenges for environmental mrio modeling: illustrations with the gtap database. In *16th international input-output conference*, volume 30.
- Peters, G. P. (2008). From production-based to consumption-based national emission inventories. *Ecological economics*, 65(1):13–23.
- Peters, G. P. and Hertwich, E. G. (2006). The importance of imports for household environmental impacts. *Journal of Industrial Ecology*, 10(3):89–109.
- Peters, G. P. and Hertwich, E. G. (2008). CO₂ embodied in international trade with implications for global climate policy.
- Peters, G. P., Minx, J. C., Weber, C. L., and Edenhofer, O. (2011). Growth in emission transfers via international trade from 1990 to 2008. *Proceedings of the national academy of sciences*, 108(21):8903–8908.
- Reimer, J. J. (2011). The domestic content of imports and the foreign content of exports. *International Review of Economics & Finance*, 20(2):173–184.
- Simas, M., Wood, R., and Hertwich, E. (2015). Labor embodied in trade: The role of labor and energy productivity and implications for greenhouse gas emissions. *Journal of Industrial Ecology*, 19(3):343–356.
- Stern, R. M. and Maskus, K. E. (1981). Determinants of the structure of us foreign trade, 1958–1976. *Journal of International Economics*, 11(2):207–224.
- Tsaliki, P. V. (2008). Economic development, human capital and technical change: the question of machinery revisited. *International Review of Economics*, 55:363–371.
- Tukker, A. and Dietzenbacher, E. (2013). Global multiregional input–output frameworks: an introduction and outlook. *Economic Systems Research*, 25(1):1–19.
- UNFCCC (2004). *Guidelines for the preparation of national communications by Parties included in Annex I to the Convention, Part I: UNFCCC reporting guidelines on annual inventories (following incorporation of the provisions of decision 13/CP.9). FCCC/SBSTA/2004/8, United Nations Framework Convention on Climate Change.*
- United Nations (2008). *International Standard Industrial Classification of All Economic Activities (ISIC), Rev.4*. Statistical Papers (Ser. M), UN, New York.
- Wang, Z., Wei, S.-J., Yu, X., and Zhu, K. (2017a). Characterizing global value chains: production length and upstreamness. Technical report, National Bureau of Economic Research.
- Wang, Z., Wei, S.-J., Yu, X., and Zhu, K. (2017b). Characterizing global value chains: production length and upstreamness. Technical report, National Bureau of Economic Research.
- Wang, Z., Wei, S.-J., Yu, X., and Zhu, K. (2022). Global value chains over business cycles. *Journal of International Money and Finance*, 126:102643.
- Wang, Z., Wei, S.-J., and Zhu, K. (2013). Quantifying international production sharing at the bilateral and sector levels. Technical report, National Bureau of Economic Research.

- Wang, Z., Yan, H., Gao, X., Liang, Q., Mi, Z., and Liu, L. (2024). Have consumption-based CO₂ emissions in developed countries peaked? *Energy Policy*, 184:113894.
- Wiedmann, T. and Lenzen, M. (2018). Environmental and social footprints of international trade. *Nature Geoscience*, 11(5):314–321.
- Wiedmann, T. O., Schandl, H., Lenzen, M., Moran, D., Suh, S., West, J., and Kanemoto, K. (2015). The material footprint of nations. *Proceedings of the national academy of sciences*, 112(20):6271–6276.
- Wood, R. (2009). Structural decomposition analysis of australia’s greenhouse gas emissions. *Energy Policy*, 37(11):4943–4948.
- World Bank (2019). World bank country and lending groups. <https://datahelpdesk.worldbank.org/knowledgebase/articles/906519-world-bank-country-and-lending-groups>.
- World Bank (2021). World bank country and lending groups. <https://datahelpdesk.worldbank.org/knowledgebase/articles/906519-world-bank-country-and-lending-groups>.
- World Bank (2022). World development indicators database. <https://databank.worldbank.org>. Accessed on 2022-4-27, 2022-7-20 and 2022-9-15.
- World Bank (2024). World development indicators database. <https://databank.worldbank.org>. Accessed on 2024-8-5.
- Xiao, H., Sun, K., Tu, X., Bi, H., and Wen, M. (2020). Diversified carbon intensity under global value chains: A measurement and decomposition analysis. *Journal of Environmental Management*, 272:111076.
- Xu, X. and Ang, B. W. (2013). Index decomposition analysis applied to CO₂ emission studies. *Ecological Economics*, 93:313–329.
- Yamano, N. and Guilhoto, J. (2020). CO₂ emissions embodied in international trade and domestic final demand. *OECD Science, Technology and Industry Working Papers*, No. 2020/11.
- Zhang, Y.-J. and Da, Y.-B. (2015). The decomposition of energy-related carbon emission and its decoupling with economic growth in china. *Renewable and Sustainable Energy Reviews*, 41:1255–1266.

