Journal of Cleaner Production 170 (2018) 34–41

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

CO_2 metabolic flow analysis in global trade based on ecological network analysis

Yan Zhang*, Yaoguang Li, Gengyuan Liu, Yan Hao

State Key Joint Laboratory of Environment Simulation and Pollution Control, School of Environment, Beijing Normal University, Xinjiekouwai Street No. 19, Beijing 100875, China

ARTICLE INFO

Article history:
Received 4 January 2017
Received in revised form
20 August 2017
Accepted 29 August 2017
Available online 8 September 2017

Handling Editor: Yutao Wang

Keywords:
Global trade
Ecological network analysis
Metabolic flow
Direct and indirect effects
Important path

ABSTRACT

CO_2 emission induced by international trade brings a plenty of pressure on global warming. Hence, it is important to understand multi-regional CO_2 flows that result from global trade and flow variation of different paths. After transforming capital flows into CO_2 carbon flows, we built an ecological network model of the global trade system's carbon metabolism. Through ecological network analysis, we identified the direct and indirect effects of temporal CO_2 flows in the network. We found that the total integral flow through the network experienced a remarkable increase during the study period. In addition, total import and export flows of four countries, including US, China, Germany and Russia, turned out to be rather big. Direct flow share was usually beyond 50% between two geographical adjacent countries, while that share was below 50% when two countries are far away. This research reveals the importance role of indirect flows and can therefore provide an empirical basis for adjusting and optimizing global trade network.

1. Introduction

With the spread of global trade activities, carbon transfer accompanying with trading goods and service speeds up in recent years (Bu et al., 2016). Present research data indicated that CO_2 transfer induced by global trade rose from 4.5 to 7.8 Gt during 1990 and 2008, and its share in global total CO_2 emission also roared from 20% to 26% (Peters et al., 2011), while the total monetary volume of global trade increased from 32.2 to 164 billion dollars at the same time (WTO, 2012). This shows the significance of global carbon trade transfer. Although present literatures have focused on the CO_2 flow along supply chain through structural path analysis, this flow perspective is still unidirectional and do not form a circuit network. Based on this, we try to trace the CO_2 flow from a holistic metabolic perspective in this article.

Baccini raised "carbon metabolism" in 1996 for the first time when investigating carbon flow in Swiss lowland area (Baccini, 1996). Such concept makes a metaphor of carbon transfer in social economic system to material flow in natural ecological system (Churkina, 2008; Krausmann et al., 2008). Former studies have investigated direct carbon metabolic flow in multiple scale, and they also cover different carbon types, including carbon emission from raw material to products and wastes during industrial metabolism (Wu et al., 2016), carbon extraction, exchange and emission in urban community and between its natural environment (Lu et al., 2015a), carbon flows between urban and rural system and within different sub-systems (Zhao et al., 2014), carbon element, CO_2 and CH_4 flow in five subsystem of Siena province (Marchi et al., 2012), and sectoral carbon flow of China from 2008 to 2012 (Li et al., 2015). Some other scholars took both direct and indirect carbon flow into consideration. For example, Lu et al. (2015b) analyzed the carbon fluxes of Eco-industrial Parks. Zhang et al. (2015) resolved both carbon emission and sequestration of different urban land use types. Laying a good research foundation of carbon metabolism, those researches have not yet expanded the scale to multi-nation or worldwide.

On the other hand, a great number of researches have investigated national embodied CO_2 flow accounting in trade activity. IPCC (1995) firstly defined carbon emission embodied in trade (EET) as "carbon emission during the production, transportation and consumption of trade good and service". Early scholars analyzed the direct EET based on multi-regional input-output table (Tolmasquim

* Corresponding author. State Key Joint Laboratory of Environmental Simulation and Pollution Control, School of Environment, Beijing Normal University, Xinjiekouwai Street No. 19, Beijing 100875, China.
E-mail address: zhangyanyxy@126.com (Y. Zhang).

http://dx.doi.org/10.1016/j.jclepro.2017.08.244
0959-6526/

and Machado, 2003). Later people realized the limitation of direct EET, then it was extended to integral EET whose most popular calculation method is input-output analysis (Leontief, 1970, 1974). Except for the convenience of EET calculation (Peters and Hertwich, 2006), the biggest merits of this method is that it can derive integral EET from direct carbon emission to uncover the indirect effect (Wiedmann et al., 2007). Among main flows of multiple countries, study scales can be subdivided into national flows within the same continent (Steen-Olsen et al., 2012), flows between country group (Chen and Chen, 2011), flows between developing and developed country groups (Peters et al., 2011) and multinational flows around the world (Davis and Caldeira, 2010, 2011). Besides, the net CO_2 flow of one single country (Liu et al., 2017) and bilateral countries are also taken into consideration (Wiebe et al., 2012).

Based on IO analysis, structural path analysis decomposes individual supply chain to find big flow paths and focused on the flow distribution in different production level. In global scale, Skelton et al. (2011) extracted global industrial supply chain to calculate the CO_2 path flow. Kanemoto et al. (2014) analyzed the 200 largest national sectorial supply chains of CO_2 flow. Scholars also focused on the structural paths of global scarce water (Lenzen et al., 2013). Except for global scale, CO_2 (Peters and Hertwich, 2006; Yang et al., 2015), NO_x (Alcantra et al., 2017), $PM_{2.5}$ (Meng et al., 2015), mercury (Liang et al., 2014) are investigated in country scale. However, such path flows trace the supply chain conversely of terminal consumers but could not analyze the network morphology which constitute by interlaced supply chain.

This makes it possible to construct multinational trade-induced carbon metabolism network by introducing a new method, ecological network analysis (ENA). This will broaden the research view of national trade carbon transfer because it can visualize the import and export CO_2 flow of each based on graph theory (Zhang et al., 2014b, 2015). Former researchers have utilized ENA to study carbon metabolic flow mainly in urban scale. Chen and Chen (2012) built carbon metabolic network model including agriculture, construction and other six industries of Vienna, and identified key nodes which had large flow after analyzing the carbon integral flow. Zhang et al. (2015) set up a spatially urban carbon metabolic model to analysis the metabolic process both horizontally and vertically. Besides, some scholars built carbon metabolic process model of Beijing (Zhang et al., 2014a) and Jing-jin-ji agglomeration (Zheng et al., 2016) to make a comparison between direct and indirect flow. Nowadays this method has not been applied to study carbon metabolism in global scale, which was only used in global virtual water metabolism and not involved in water flow analysis (Yang et al., 2012).

Above all, present research on direct and indirect flow of global carbon transfer did not make it clear their share in integral flow. Based on this, we selected ecological network flow analysis to answer the following questions: 1. what is the direct and indirect structure overall trend of global and continental carbon transfer? 2. What are the direct and indirect shares of the import and export flow of global countries? 3. What are the geographical characteristics of indirect share among different countries? Targeting on unspecific analysis of global trade-induced carbon transfer and direct and indirect flow, this article built global trade carbon metabolic ecological network model to identify and dig into the flow variation of vital countries' import and export flow. In addition, flows of key paths which had a great impact on countries were also targeted. The aim is to clarify the characteristics and changing law of node and path in the network.

2. Method

In order to build the network model, input-output table released by WIOD was utilized which includes 40 regions and one country union. Each element K_{ij} in the matrix means total capital flow of intermediate production and final consumption from country i to country j. Then we got the direct CO_2 flow f_{ij} based on the total emission of country i and capital share from i to j.

On the basis of direct flow, the direct flow intensity matrix G' can be calculated by the share of f_{ij} to total through flow of each node. We then got the integral flow matrix of CO_2 transfer through ecological network flow analysis in equation (1):

$$\mathbf{N}' = (n') = (\mathbf{G}')^{\mathbf{0}} + (\mathbf{G}')^{\mathbf{1}} + (\mathbf{G}')^{\mathbf{2}} + (\mathbf{G}')^{\mathbf{3}} + \dots(\mathbf{G}')^{\mathbf{m}} + \dots = (\mathbf{I} - \mathbf{G}')^{-1} \quad (1)$$

$$g'_{ij} = f_{ij} \big/ T_j \quad (2)$$

$$T_i = \sum_{j=1}^{n} f_{ij} + z \quad (3)$$

$(G')^0$ represents self-feedback matrix, which refers to the feedback effect of flow through each node; $(G')^1$ refers to the direct flow intensity matrix, representing the direct material flux between each node. The high power of G refers to indirect flow intensity of different path length. For example, $(G')^2$ means such intensity of length 2, and $(G')^m$ $(m \geq 2)$ means length m. N' presents the integral flow intensity of each node. T_i means the total import floe of country i from other nodes within the network. In addition, Z_i represents import flow from environ outside the network.

By premultiplying the integral flow intensity matrix by the diagonal of the flow matrix, *diag(T)*, we obtain the matrix Y (40*40). The equation is as follows:

$$\mathbf{Y} = \text{diag}(\text{T})^{*}\text{N} \quad (4)$$

Matrix Y includes row vector $y_i = (y_{i1}, y_{i2}, \dots, y_{in})$, which represents the integral CO_2 flow of country i from other countries. Adding up all the elements in the matrix Y, we can get the total integral flow of the network. Furthermore, the indirect flow means the flow from country A to country B while at least passing another country. Its equation is shown in (5):

$$\textbf{Indirect} = \text{Y} - \text{diag}(\text{T}) - \text{F} \quad (5)$$

Here F means the matrix of direct CO_2 flow.

3. Results

3.1. General network flow characteristics

The total integral flow doubled during sixteen years, which increased from 3010 million tons (Mt) in 1996 to 6036 Mt in 2011. Among them, the increase of total indirect flow was more notable than direct flow. Their growth rate were 105% and 85%. Their shares in total flow were quite near during the study period and had little fluctuation year by year. From Fig. 1 we divided sixteen years into three periods. The indirect share rose from 52% to 54%. In the first period (1996–2002), total integral flow only had a big growth in the year of 1997 (19.86%) and that rate was the second largest among sixteen years. In this year, contribution from direct flow was larger as direct growth rate was 31.04% while the indirect growth rate was 9.61%. In subsequent five years the total flow fluctuated little. Indirect flow increased 20.48% while direct flow decreased 13.74% in 1998. The situation altered in the next year as indirect/direct flow fell/rose for −10.68% and 3.03%. After slight variation in