Environmental Science & Technology
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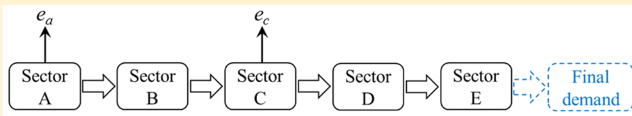
Betweenness-Based Method to Identify Critical Transmission Sectors for Supply Chain Environmental Pressure Mitigation

Sai Liang,[†] Shen Qu,[†] and Ming Xu*[,†,‡]

[†]School of Natural Resources and Environment, University of Michigan, Ann Arbor, Michigan 48109-1041, United States
[‡]Department of Civil and Environmental Engineering, University of Michigan, Ann Arbor, Michigan 48109-2125, United States

S Supporting Information

ABSTRACT: To develop industry-specific policies for mitigating environmental pressures, previous studies primarily focus on identifying sectors that directly generate large amounts of environmental pressures (a.k.a. production-based method) or indirectly drive large amounts of environmental pressures through supply chains (e.g., consumption-based method). In addition to those sectors as important environmental pressure producers or drivers, there exist sectors that are also important to environmental pressure mitigation as transmission centers. Economy-wide environmental pressure mitigation might be achieved by improving production efficiency of these key transmission sectors, that is, using less upstream inputs to produce unitary output. We develop a betweenness-based method to measure the importance of transmission sectors, borrowing the betweenness concept from network analysis. We quantify the betweenness of sectors by examining supply chain paths extracted from structural path analysis that pass through a particular sector. We take China as an example and find that those critical transmission sectors identified by betweenness-based method are not always identifiable by existing methods. This indicates that betweenness-based method can provide additional insights that cannot be obtained with existing methods on the roles individual sectors play in generating economy-wide environmental pressures. Betweenness-based method proposed here can therefore complement existing methods for guiding sector-level environmental pressure mitigation strategies.

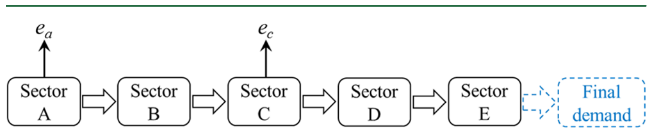


Methods	Sector A	Sector B	Sector C	Sector D	Sector E
Production-based	e_a	0	e_c	0	0
Consumption-based	0	0	0	0	e_a+e_c
Betweenness-based	0	e_a	e_a	e_a+e_c	0

■ INTRODUCTION

The industrial system contributes to the generation of environmental pressures (i.e., the usage of resources and energy and the generation of pollutants and wastes) in two ways: directly generating environmental pressures in industrial production, and indirectly driving environmental pressures through supply chains. To develop sector-specific policies for mitigating environmental pressures, previous studies primarily focus on identifying important sectors that either directly generate environmental pressures (a.k.a. production-based method[1,2]) or indirectly drive supply chain-wide environmental pressures (e.g., consumption-based method[1−3]). For approaches dealing with supply chain-wide environmental pressures, they essentially relate economic activities at the end (or beginning) of a supply chain path with environmental pressures occurring at the beginning (or end) of the supply chain path. For instance, consumption-based method examines environmental pressures generated in the upstream supply chain driven by the final demand of products.[1−3] Note that the concept of supply chain path is different from that of supply chain which is a generic term usually used to describe the product system. Supply chain path is instead strictly defined from structural path analysis (SPA) practice.[4−6] A supply chain path extracted by SPA shows the amount of environmental pressure generated by the starting sector that is step-by-step driven by the end sector producing final products for final uses (e.g., households, government, and capital formation). While supply chain is widely used conceptually, a supply chain path is defined as a linear chain of sectors in which upstream ones supply downstream ones sequentially and only the starting sector's emissions are counted, as described in the example of Figure 1.

Identifying critical sectors directly generating environmental pressures using production-based accounting (e.g., agricultural



Methods	Sector A	Sector B	Sector C	Sector D	Sector E
Production-based	e_a	0	e_c	0	0
Consumption-based	0	0	0	0	e_a+e_c
Betweenness-based	0	e_a	e_a	e_a+e_c	0

Figure 1. A five-sector example illustrating production-based, consumption-based, and betweenness-based methods.

Received: October 2, 2015
Revised: December 8, 2015
Accepted: January 4, 2016
Published: January 4, 2016

ACS Publications

DOI: 10.1021/acs.est.5b04855
Environ. Sci. Technol. 2016, 50, 1330−1337

sectors for water uses and electricity sector for air pollutant emissions) can guide production-side measures such as improving the efficiency of energy and water uses and implementing emission removal technologies in production processes.[2] Identifying critical sectors that drive upstream environmental pressures using consumption-based accounting (e.g., sectors producing household appliances and sectors providing residential services) can inform demand-side measures influencing the choice of final users, such as imposing consumption tax on products of critical sectors[2,7,8] and using eco-labeling to indicate the amount of environmental pressures caused by the production of finally used products.[8] While existing approaches are effective to identify key sectors as either direct sources or final producers (i.e., sectors producing products finally used by consumers) for supply chain-wide environmental pressures, there exist sectors that are also important to environmental pressure mitigation as transmission centers. Sectors as transmission centers exist between the two ends of supply chain paths.[9] Intermediate inputs to these sectors indirectly drive upstream environmental pressures. Measures on improving the efficiency of upstream input use (instead of only natural resources use) to these sectors, for example, reducing production tax or placing production subsidy to encourage efficiency improvements in these sectors, may also help reduce upstream environmental pressures.

Figure 1 shows an example of a supply chain containing five sectors. Sectors A and C generate emissions in the amounts of e_a and e_c, respectively, while sectors B, D, and E do not generate any emissions. This supply chain has two supply chain paths: path 1 as "A → B→C → D→E" (weight: e_a) and path 2 as "C → D→E" (weight: e_c)". Note that the weight of a supply chain path is the amount of emissions of its starting sector that is caused by the final demand of products from its end sector. Sectors A and C are important according to production-based method, while sector E is important according to consumption-based method. Sectors B and D will not be identified as important according to these existing methods. However, improving the production efficiency of sectors B and D (i.e., using less inputs of sectors A and C to produce unitary output, respectively) might help reduce economy-wide emissions (i.e., less requirements for outputs of sectors A and C leading to less emissions from sectors A and C). Therefore, a new method (betweenness-based method in Figure 1) is needed to identify such critical transmission sectors which can help mitigate environmental pressures through production efficiency improvement.

We define a transmission sector as a sector that exists between two ends of a particular supply chain path. Identifying important transmission sectors that transmit large amount of embodied environmental pressures through supply chains can help guide developing sector-specific policies to mitigate environmental pressures by improving production efficiency (i.e., using less intermediate inputs). Companies may be more likely to welcome policies encouraging the improvement of production efficiency which also bring the cobenefits of reducing production costs. Thus, such policy is potentially more effective than production-side (production-based accounting) and demand-side (consumption-based accounting) policies. We expect that a new method of identifying critical transmission sectors can complement existing methods for guiding sector-level environmental pressure mitigation strategies.

In this study we develop a betweenness-based method to measure the importance of transmission sectors. The betweenness of a sector is generally defined as the amount of environmental pressures generated by all supply chain paths passing through this sector, borrowing the concept from network analysis. We propose a structural path betweenness method based on supply chain paths extracted from structural path analysis (SPA) to measure the betweenness of sectors. We use a 135-sector Chinese input-output (IO) table in 2007 with a CO_2 satellite account to demonstrate the betweenness-based method by identifying critical transmission sectors for China's CO_2 emissions in 2007.

■ BETWEENNESS-BASED METHOD

Betweenness Metric. The concept of betweenness originates from network analysis.[10−13] A network consists of nodes (vertices) that are connected by links (edges).[14] The betweenness of a node is normally defined as the amount of information (which is simply proportional to the number of shortest paths[14]) passing through this node.[12−16] It measures the influence a node has over the spread of information (e.g., social messages and diseases) through the network.[16] A node with high betweenness may not necessarily be as important as an initial information sender or a final receiver, but has large control over information flowing between others.[16] Betweenness metrics have been widely used in studying social networks,[10,11] world trade networks,[17] urban transportation networks,[18,19] and scientific collaboration networks.[16] For example, the Anchorage International Airport in Alaska has limited direct connections with other airports around the world, but is one of the most central airports in the worldwide air transportation network, functioning as an important bridge connecting other airports.[18]

A transmission sector in an economy transmits embodied environmental pressures through supply chains. This role is similar to the role that nodes with high betweenness in a network have over the spread of information. If considering an economy characterized by an input-output (IO) model as a network (IO network) in which nodes are sectors and links are intermediate flows of goods and services between sectors, potentially we can use the concept of betweenness to measure the importance of sectors in an economy as transmission centers.

The betweenness of nodes in network analysis is mostly measured based on binary networks in which the links between nodes are often undirected and unweighted (i.e., link from A to B is the same as the link from B to A, links have no weight).[14] However, links in an IO network are directed and weighted (i.e., the link from A to B is different from the link from B to A; links also have different weights). Nodes in an IO network have strengths and mostly have self-flows. This requires significant modification of the betweenness metric commonly used in network analysis which is developed mostly for undirected and unweighted networks. The betweenness metric in IO networks should take into account both direction and weights of links, as well as both strengths and self-flows of nodes. Details are shown in the two following subsections.

In this study, we use structural path analysis (SPA) to extract individual supply chain paths taking into account both direction and weights of links as well as both strengths and self-flows of nodes in an IO network. Supply chain paths extracted from SPA are then used to measure the betweenness of sectors.

DOI: 10.1021/acs.est.5b04855
Environ. Sci. Technol. 2016, 50, 1330−1337

Structural Path Analysis. In IO models, environmental pressures driven by the consumption in an economy are expressed by eq 1:[20]

$$e = f(\mathrm{I} - \mathrm{A})^{-1}y \quad (1)$$

where the scalar e represents the quantity of environmental pressures in an economy; $1 \times n$ row vector f represents the intensity of environmental pressures for unitary output of each sector; n indicates the number of sectors in an IO network; $n \times n$ matrix I is the identity matrix; $n \times n$ matrix A is the technical coefficient matrix[20] the element of which a_{ij} represents the input from sector i directly required to produce unitary output of sector j; $n \times n$ matrix $L = (I{-}A)^{-1}$ is the *Leontief inverse*[20] the element of which l_{ij} represents total (direct and indirect) input from sector i required to produce unitary output of sector j; and $n \times 1$ column vector y represents the final demand of products from each sector.

One can extract individual supply chain paths by unraveling the *Leontief inverse* using its Taylor expansion as eq 2:[4−6,21−23]

$$e = f(\mathrm{I} + \mathrm{A} + \mathrm{A}^2 + \mathrm{A}^3 + ...)y = fy + f\mathrm{A}y + f\mathrm{A}^2y + ... \quad (2)$$

Each term in the right-hand side of eq 2 is defined as a production layer (PL).[5]

Let $w(s, t|k_1, k_2,..., k_r)$ indicate the weight of a supply chain path starting from sector s, passing through r sectors $(k_1, k_2,..., k_r)$, and ending at sector t. The number r changes with the number of PLs. The weight of this supply chain path is calculated as

$$w(s, t|k_1, k_2, ..., k_r) = f_s a_{sk_1} a_{k_1k_2} \cdots a_{k_rt} y_t \quad (3)$$

where the scalar f_s represents the intensity of environmental pressures for unitary output of sector s; y_t indicates the final demand of products from sector t; and a_{sk_1}, a_{k1k2}, ...,$_{krt}$ are technical coefficients from matrix A.

Structural Path Betweenness. We define the betweenness of sector i in an IO network as the amount of environmental pressure generated by all supply chain paths passing through sector i, using eq 4:

$$b_i = \sum_{s=1}^{n}\sum_{t=1}^{n}\sum_{r=1}^{\infty}(q_r \times w(s, t|k_1, k_2, ..., k_r))$$
$$\text{for all } w(s, t|k_1, k_2, ..., k_r) \text{ where } i \text{ is the element of} \{k_1, k_2, ..., k_r\} \quad (4)$$

where b_i is the betweenness of sector i; n indicates the number of sectors in an IO network; and q_r represents the time sector i appears between two ends of the supply chain path $w(s, t|k_1, k_2,..., k_r)$. In particular, when $r = 1$, $k_1 = i$. Higher betweenness means that a sector has larger influence in the transmission of environmental pressures directly generated in sectors or driven by the consumption of products in sectors.

Equations 3 and 4 show that the betweenness metric in IO networks can take into account both direction and weights of links as well as strengths of nodes. Moreover, self-flows of sectors are important components of IO networks, as they contribute to 15−30% of intersectoral flows.[24] The betweenness-based method in this study hence considers self-flows of sectors. In addition, a particular supply chain path can pass through a sector multiple times (q_r in eq 4). A sector appearing more times in a supply chain path has more opportunities to mitigate upstream environmental pressures than sectors appearing less times in this supply chain path. Thus, this sector has larger betweenness value than other sectors, indicating its importance as a transmission center.

Equation 4 can be written in matrix form. Define $b_i(l_1, l_2)$ as the total weight of supply chain paths that pass through sector i, with l_1 sectors to the upstream of sector i and l_2 sectors to the downstream of sector i; integers l_1, $l_2 \geq 1$; and J_i as a matrix with its (i,i)th element as 1 and other elements as zeros.

$$\begin{aligned} b_i(l_1, l_2) &= \sum_{1\le k_1,\cdots,k_{l_1}\le n}\ \sum_{1\le j_1,\cdots,j_{l_2}\le n}(f_{k_1}a_{k_1k_2}\cdots a_{k_{l_1}i}a_{ij_1}\cdots a_{j_{l_2-1}j_{l_2}}y_{j_{l_2}}) \\ &= \sum_{1\le k_1,\cdots,k_{l_1}\le n}(f_{k_1}a_{k_1k_2}\cdots a_{k_{l_1}i}\sum_{1\le j_1,\cdots,j_{l_2}\le n}(a_{ij_1}\cdots a_{j_{l_2-1}j_{l_2}}y_{j_{l_2}})) \\ &= (\sum_{1\le k_1,\cdots,k_{l_1}\le n}(f_{k_1}a_{k_1k_2}\cdots a_{k_{l_1}i}))(\sum_{1\le j_1,\cdots,j_{l_2}\le n}(a_{ij_1}\cdots a_{j_{l_2-1}j_{l_2}}y_{j_{l_2}})) \\ &= (fA^{l_1})_i(A^{l_2}y)_i = fA^{l_1}J_iA^{l_2}y \end{aligned} \quad (5)$$

Since our method considers self-flows of sectors, notations k_1, ..., k_{l_1}, j_1, ..., j_{l_2} can indicate any one of these n sectors. The notation $(f\,\mathrm{A}^{l_1})_i = \sum_{i\le k_1,..., k_{l_1}\le n}(f_{k_1}a_{k_1k_2}... a_{k_{l_1}i})$ represents the i^{th} element of the $1 \times n$ vector $f\mathrm{A}^{l_1}$, while $(\mathrm{A}^{l_2}\ y)_i = \sum_{i\le j_1,..., j_{l_2}\le n}(a_{ij_1}... a_{j_{l_2-1}j_{l_2}}y_{j_{l_2}})$ indicates the i^{th} element of the $n \times 1$ vector $\mathrm{A}^{l_2}\ y$.

The Taylor expansion of the *Leontief inverse* matrix L is shown in eq 6.

$$L = (I - A)^{-1} = I + A + A^2 + A^3 + ... \quad (6)$$

Defining $T = LA = AL = A + A^2 + A^3 + ...$, the betweenness of sector i can be written as

$$\begin{aligned} b_i &= \sum_{l_1=1}^{\infty}\sum_{l_2=1}^{\infty}b_i(l_1, l_2) = \sum_{l_1=1}^{\infty}\sum_{l_2=1}^{\infty}(f\,\mathrm{A}^{l_1}\mathrm{J}_i\mathrm{A}^{l_2}y) \\ &= \sum_{l_1=1}^{\infty}(f\,\mathrm{A}^{l_1}\mathrm{J}_i\sum_{l_2=1}^{\infty}(\mathrm{A}^{l_2}y)) = (\sum_{l_1=1}^{\infty}(f\,\mathrm{A}^{l_1}))J_i(\sum_{l_2=1}^{\infty}(\mathrm{A}^{l_2}y)) \\ &= f(\sum_{l_1=1}^{\infty}\mathrm{A}^{l_1})\mathrm{J}_i(\sum_{l_2=1}^{\infty}\mathrm{A}^{l_2})y = f\,\mathrm{T}\mathrm{J}_i\mathrm{T}y \end{aligned} \quad (7)$$

where the element t_{ij} in the $n \times n$ matrix $T = LA$ indicates the output of sector i both directly and indirectly caused by the production of direct upstream inputs used to produce unitary output of sector j; and the element t_{ij} in the $n \times n$ matrix T = AL indicates direct input from sector i to produce outputs of sectors that are both directly and indirectly caused by unitary output of sector j. Given that $T = L - I$, matrix T is in effect the indirect requirements for unitary output of each sector.

■ CASE STUDY

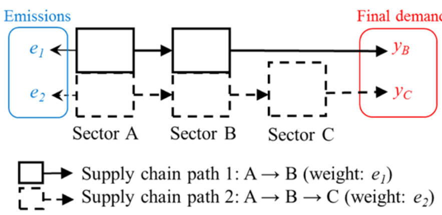
We use a 135-sector Chinese IO table in 2007 with a CO_2 satellite account to demonstrate the betweenness-based method. China's standard IO table in 2007 is in 135-sector format (SI Table S3), with endogenous imports.[25] We remove imports from the standard IO table[26] for simplicity and the purpose of demonstration. We also remove the "others" column, representing statistical errors,[27] from the final demand matrix. We then rebalance the IO table by adjusting total outputs accordingly. The 135-sector CO_2 satellite account is from our previous work,[28,29] covering sectoral CO_2 emissions from energy combustion and industrial processes in 2007.

DOI: 10.1021/acs.est.5b04855
Environ. Sci. Technol. 2016, 50, 1330−1337

Table 1. Kendall Correlation Coefficients between the Rankings of Sectors by Betweenness and by Two IO Metrics[a]

metrics		production-based CO_2 emissions	consumption-based CO_2 emissions
betweenness	correlation coefficients	0.51	0.26
	p-values	1.74×10^{-18}	6.78×10^{-06}

[a]Notes: Smaller *p*-value means that the correlation between two metrics is more significant. The correlation is usually regarded as significant if the *p*-value is smaller than 0.05, and highly significant if the *p*-value is smaller than 0.01. Full results are shown in Table S2 in the Supporting Information.



Metrics	Results for B
Emissions pure backward linkage	$e_1 + e_2$
Consumption-based	e_1
Betweenness-based	e_2

Figure 2. A three-sector example illustrating concepts of emissions pure backward linkage (EPBL), betweenness-based method, and consumption-based method.

Correlation with Other Metrics. Table 1 shows the Kendall correlation analysis between the rankings of sectors by the betweenness and two IO metrics (production-based and consumption-based CO_2 emissions). The correlations between the ranking by betweenness-based CO_2 emissions and the rankings by two IO metrics are low. SI Table S2 shows the Kendall correlation analysis between the rankings of sectors by the betweenness and more IO metrics (i.e., income-based CO_2 emissions[30−32] and linkage analysis metrics[5,33−35]). The ranking by betweenness-based CO_2 emissions has low correlations with the rankings by IO metrics, except for the Emissions Pure Backward Linkage (EPBL)[5] metric.

In particular, the EPBL of a sector measures upstream environmental pressure caused by intermediate purchases to produce the total output of this sector which can be used either by final users or as intermediate inputs for the production of other sectors.[5] Thus, EPBL describes the importance of a sector as both final producer at the end of supply chain paths (similar to consumption-based accounting) and transmission center between two ends of supply chain paths (similar to the betweenness-based method), as shown in Figure 2. In addition, the end of a supply chain path extracted by SPA in this study is not the final demand but sectors producing final products. The EPBL metric covers the scopes of consumption-based accounting and betweenness-based method. Therefore, the correlation between the ranking by betweenness-based CO_2 emissions and the ranking by EPBL is relatively high. However, EPBL mixes a sector's role as a transmission center and as a producer of final products, while the betweenness metric distinguishes the role of a sector as a transmission center from its role as a producer of final products. Thus, the betweenness metric can identify critical sectors which cannot be identified by the EPBL metric (details in the Supporting Information). These results indicate that the betweenness-based method can offer insights that cannot be obtained from existing methods on the importance of sectors in environmental pressure mitigation.

Betweenness-Based CO_2 Emissions of Chinese Sectors in 2007. Figure 3 shows betweenness-based CO_2 emissions of 135 sectors in 2007. The *steel-processing* sector has the largest

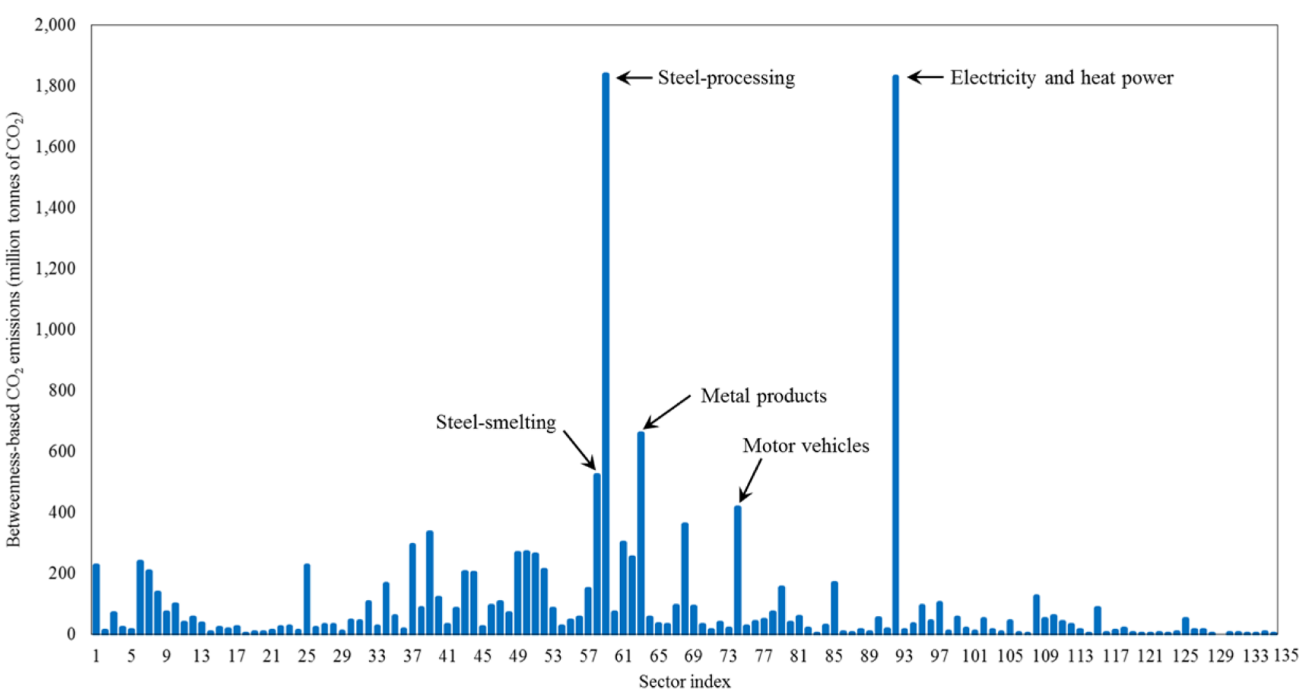


Figure 3. Betweenness-based CO_2 emissions of 135 Chinese sectors in 2007. The horizontal axis represents the index of sectors as listed in SI Table S3. The vertical axis represents betweenness-based CO_2 emissions of sectors. Full results are shown in Table S4 in the Supporting Information.

DOI: 10.1021/acs.est.5b04855
Environ. Sci. Technol. 2016, 50, 1330−1337

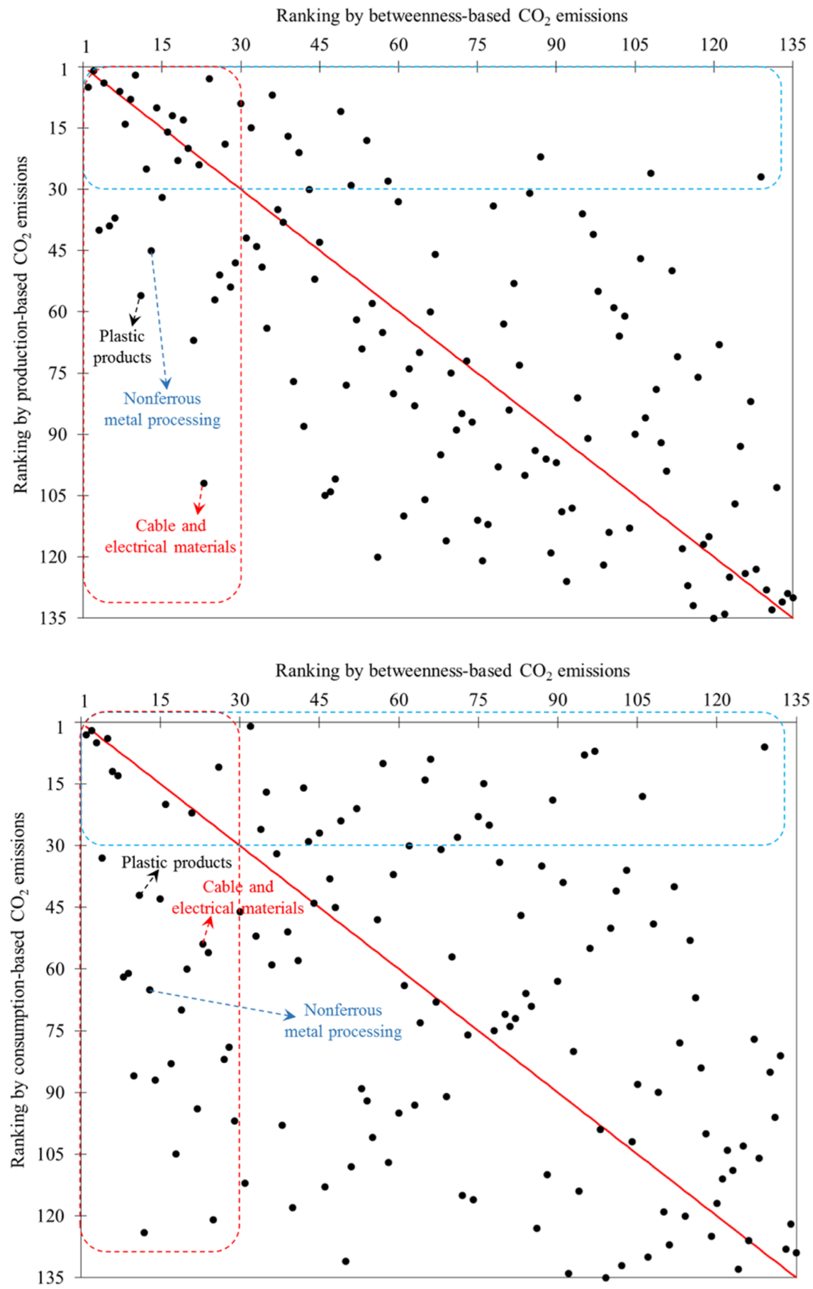


Figure 4. Comparison of the rankings of sectors by betweenness-based, production-based, and consumption-based CO_2 emissions. The horizontal axes show the ranking of sectors by betweenness-based CO_2 emissions, while the vertical axes show the ranking of sectors by production-based and consumption-based CO_2 emissions. The red solid lines indicate the same ranking by betweenness-based, production-based, and consumption-based CO_2 emissions. The red dashed boxes show sectors ranked top 30 by betweenness-based CO_2 emissions, while the blue dashed boxes show sectors ranked top 30 by production-based and consumption-based CO_2 emissions. Full results are shown in Tables S4 to S7 in the Supporting Information.

betweenness-based CO_2 emissions, transmitting 1.8 billion tonnes of embodied CO_2 emissions. It is the most important transmission sector for CO_2 emissions in China in 2007. The *electricity and heat power* sector ranks the second in betweenness-based CO_2 emissions by transmitting 1.8 billion tonnes of embodied CO_2 emissions. Other important transmission sectors include *metal products*, *steel-smelting*, and *motor vehicles*. Improving the efficiency of relevant input uses, not only just energy efficiency, in these sectors may help reduce CO_2 emissions from their upstream sectors while still providing sufficient supplies for downstream sectors, under certain assumptions (e.g., perfectly quantity-elastic supply or there are no other changes due to production efficiency improvement that affects the efficiencies or demand of upstream sectors).

Figure 4 compares the ranking of sectors by betweenness-based, production-based, and consumption-based CO_2 emissions. Most sectors do not lay on the red solid line which indicates the same ranking by betweenness-based, production-based, and consumption-based CO_2 emissions. The same situation is observed between betweenness-based CO_2 emissions and other IO metrics (Details in the Supporting Information). This implies significant difference in sector rankings between using betweenness-based CO_2 emissions and using other existing metrics. Taking sectors ranked top 30 for example (Figure 4 and Table 2), three sectors (*plastic products*,

DOI: 10.1021/acs.est.5b04855
Environ. Sci. Technol. 2016, 50, 1330−1337

Table 2. Sectors Ranked Top 30 by Betweenness-Based CO_2 Emissions in 2007 and Their Rankings by Production-Based and Consumption-Based CO_2 Emissions[a]

ranked by	betweenness-based CO_2 emissions	production-based CO_2 emissions	consumption-based CO_2 emissions
steel-processing	1	5	3
electricity and heat power	2	1	2
metal products	3	40	5
steel-smelting	4	4	33
motor vehicles	5	39	4
other general machinery	6	37	12
raw chemical materials	7	6	13
nonferrous metal smelting	8	14	62
petroleum refining and nuclear fuel	9	8	61
cement, lime and plaster	10	2	86
plastic products	11	56	42
cement and plaster products	12	25	124
nonferrous metal processing	13	45	65
coal	14	10	87
cotton textiles	15	32	43
crop cultivation	16	16	20
brick, tile, stone and other building materials	17	12	83
crude petroleum and natural gas	18	23	105
synthetic chemicals	19	13	70
chemicals for special usages	20	20	60
electronic element and device	21	67	22
paper and products	22	24	94
cable and electrical materials	23	102	54
iron-smelting	24	3	56
ferrous ores	25	57	121
wholesale and retail trade	26	51	11
chemical fertilizers	27	19	82
products of wood, bamboo, cane, palm, straw, etc.	28	54	79
chemical fibers	29	48	97
highway transport	30	9	46

[a]Note: Full results are shown in Tables S6 and S7 in the Supporting Information.

nonferrous metal processing, and *cable and electrical materials*) are ranked top 30 by betweenness-based CO_2 emissions, but are not in the top 30 for other existing metrics. These three sectors use products from carbon-intensive upstream sectors as intermediate inputs. They have relatively less production-based CO_2 emissions, indicating limited room for direct emission reduction. They also have relatively less consumption-based CO_2 emissions, because their products are not finished goods and less used by final users. Therefore, they may receive less attention from production-side (corresponding to production-based method) and demand-side (corresponding to consumption-based method) policies for CO_2 emission reduction. However, these sectors transmit relatively large amounts of CO_2 emissions embodied in their intermediate inputs from upstream sectors. Improving production efficiency (i.e., using less inputs producing the same amount of outputs) in these sectors might indirectly help reduce upstream CO_2 emissions by reducing the requirements of more carbon-intensive intermediate inputs from upstream sectors.

Furthermore, sectors falling into both the red and blue dashed boxes (Figure 4 and Table 2) are important for CO_2 emission reduction in terms of production-side (corresponding to production-based method), demand-side (corresponding to consumption-based method), and production efficiency improvement (corresponding to betweenness-based method) policies, for example, *steel-processing*, *electricity and heat power*, and *raw chemical materials*.

■ DISCUSSION

A large number of studies have been devoted to the identification of sectors that are important for mitigating environmental pressures of an economy. This has been done primarily from the production-based and consumption-based perspectives. This represents the two ends of a supply chain path generating environmental pressures: the sources (production-based accounting) and the consumption drivers (consumption-based accounting). The betweenness-based method proposed in this study aims to identify transmission sectors in an economy that are critical for the generation of upstream environmental pressures but not identifiable by existing production-based or consumption-based accounting. The identification of these critical transmission sectors represents untapped opportunity for mitigating supply chain-wide environmental pressures. In particular, policies encouraging transmission sectors to improve their overall productivity (i.e., using less intermediate inputs) can achieve upstream environmental pressure reduction. Such policies are likely welcomed by firms in identified transmission sectors, because using less intermediate inputs often leads to reduced production cost.

We demonstrate the betweenness-based method using China's IO table and CO_2 emission satellite account in 2007. Our results show that the betweenness-based method can identify critical transmission sectors that are not identifiable by production-based and consumption-based accounting, as well as other methods such as linkage analysis. This indicates that the betweenness-based method can provide novel insights on the role of sectors playing in economy-wide environmental pressures and complement existing methods for guiding sector-level environmental pressure mitigation strategies.

In particular, the 2007 Chinese CO_2 emission case study identifies important transmission sectors that are not considered as important by either production-based or consumption-based accounting, such as *plastic products*, *nonferrous metal processing*, and *cable and electrical materials*. Productivity improvement in these sectors, that is, using less inputs to produce the same amount of outputs, can significantly contribute to the reduction of upstream CO_2 emissions. For example, in the *plastic products* sector, policies encouraging firms to use more recycled materials or reduce material waste during production help firms in this sectors improve their productivity. As a result, upstream CO_2 emissions transmitted by the *plastic products* sector can be avoided. Our results show that reducing inputs required from other sectors for unitary output in the *plastic products* sector by 1% can lead to 2.7

DOI: 10.1021/acs.est.5b04855
Environ. Sci. Technol. 2016, 50, 1330−1337

million tonnes of CO_2 emission reduction from upstream supply chain paths passing through it.

Although the case study presented in this paper is for CO_2 emissions in China only, the betweenness-based method is generally applicable to other environmental pressures and other economies. In addition, this method can also be applied to economic analysis to identify key transmission sectors contributing to economic growth or employment.

It is worth noting that the betweenness-based method proposed in this study differs from production-based and consumption-based accountings in the way that it does not exclusively allocate the aggregated environmental pressure of an economy to each sector. Instead, it intentionally double counts environmental pressure associated with a particular supply chain path for all sectors the supply chain path passes through. In other words, the same environmental pressure is counted r times if there are r sectors between two ends of the supply chain path. Therefore, the sum of betweenness-based environmental pressure of all sectors is not equal to the sum of production-based or consumption-based environmental pressure which equals to the total environmental pressure of the economy.

We use supply chain paths extracted from SPA to measure the betweenness of sectors in this study. There also exist other approaches measuring the betweenness of sectors in IO networks, for example, strongest paths[36,37] and random walk.[15] Strongest path betweenness is based on the strongest path connecting two nodes of IO networks,[36,37] only considering limited number of supply chain paths in an IO network. Random walk betweenness counts the time a node is passed by a random walk between two other nodes.[15,16] It does not take into account link weights and node strengths in IO networks. The structural path betweenness considers all supply chain paths of an IO network. It also takes into account link weights and node strengths in IO networks. Comparing these approaches remains an interesting future research avenue.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.est.5b04855.

Full results and additional contents supporting the main text (PDF)

AUTHOR INFORMATION

Corresponding Author

*Phone: +1-734-763-8644; fax: +1-734-936-2195; e-mail: mingxu@umich.edu.

Notes

The authors declare no competing financial interest.

ACKNOWLEDGMENTS

The material is based upon work supported by the U.S. National Science Foundation (NSF) under Grant No. 1438197. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the NSF. Sai Liang and Shen Qu thank the support of the Dow Sustainability Fellows Program.

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