# Income-based emissions of China's Jing-Jin-Ji megaregion at city level

Lixiao Xu[a], Guangwu Chen[a], Yafei Wang [a*], and Arne Geschke[b]

[a] School of Statistics and Institute of National Accounts, Beijing Normal University, Beijing 100875, China

[b] Centre for Integrated Sustainability Analysis, School of physics, The University of Sydney, New South Wales 2006, Australia

**Corresponding author:**

Yafei Wang

School of Statistics and Institute of National Accounts, Beijing Normal University, Beijing 100875, China

E-mail: ywang@bnu.edu.cn (Yafei Wang);

Telephone and Fax: +86-10-5880 1880.

**Abstract:** This paper uses the multi-regional input-output (MRIO) framework at city level to carry out the Jing-Jin-Ji income-based emissions for the year 2013. The work encompasses a range of advances that reach beyond the previous studies. (1) Calculate income-based emission at the city level. This can find the relationship between emissions mitigation and economic growth at city and sectoral level and guide new policies at industrial level from the income-based perspective; (2) Build a nested subnational MRIO table with cities and provinces in China, including 14 cities of Jing-Jin-Ji megaregion and 28 provinces of the rest of China; (3) Chose a meaningful latest year for 2013 when China central government was concerning about Jing-Jin-Ji Coordinated Development strategies. The results show the distribution of emissions enabled by primary input (income): (1) Higher production-based emissions always accompany higher income-based emissions. (2) Ten in fourteen cities have more than half of income-based emissions occur at domestic, except Beijing, Xingtai, Baoding and Langfang. (3) The main emitters of 14 cities of income-based emissions are developed provinces (such as Jiangsu, Guangdong, Shandong and Zhejiang) and resourceful provinces (including Inner Mongolia, Shanxi, Liaoning and Xinjiang); (4) Nine in fourteen cities are producers more than economic beneficiaries.

**Key words**: income-based accounting, MRIO, city emissions, emission balance

# 1. Introduction

Cities now are the core of emission reduction following its growing population, energy use, and economic development. Carbon dioxide emissions from energy use in cities grow by 1.8% per year (versus 1.6% globally) under business-as-usual scenarios between 2006 and 2030, with the share of global $CO_2$ from cities rising from 71% to 76%[1]. Cities, towns and urban neighbourhoods all over the world are pledging to reduce their carbon footprint by decreasing their volumes of greenhouse gas emissions in various ways[1].

China, as the biggest emitter country in the world, is fixed the world's eye on its effort of greenhouse gas (GHG) mitigation. Cities are development priorities all along and emission-intensive industries including mining, manufacturing and power generation [2] in cities are the key supporting industries. In the end of 2017, China's urbanization rate is approaching 58.52% and more and more people will flood into cities. The demand of energy and coal-oriented energy mix push cities play a leading role in mitigation. At COP21, the Chinese government pledged to reduce carbon intensity by 60-65% in 2030, relative to 2005[3]. It is necessary to understand Chinese cities' emissions in detail.

Production-based emission (PE), consumption-based emission (CE) and income-based emission (IE) are three perspectives of emission accounting methods. PE means the emission occurs during production, it is also called geographic emission. CE can be known footprint/upstream emission which records given final goods and services' relative emissions from production to consumption. IE, also named downstream emission, uncovers the emission occurs after primary input enters in production processes and links economic agency with emitter. Three kinds of emission shown above are all allocation methods of emission responsibility. PE allocates emission to who uses energy or materials generating emissions during production, and it does not consider production for whom and who earns economic benefits from production. CE solves the question production for whom. IE tells us who earns economic benefits from production.

The term of “income-based emission: is widely used after the research of Marques et al.(2012)[4], before that “downstream emission” is well known title. The new title addresses the problem the term “downstream responsibility” couldn’t inform the supply of primary input (in a broader view, primary input is an income) inputting to production processes that enable emission to occur[4]. Gallego and Lenzen(2005) [5], Lenzen and Murray(2010) [6] and Marques et al.(2012)[4] discussed downstream environmental responsibility in details, which means the emission enabled by primary suppliers. The applications of income-based responsibility are not common. Most of these studies selected the worldwide to apply the concept of income-based responsibility, like Marques et al.(2012) [4] (112 regions from GTAP 7.1), Marques et al.(2013) [7] (87 regions from GTAP 6) and Liang et al.(2017) [8] (41 nations/regions from WIOD).

Studies on emissions of cities are rich, but most focus on CE and PE of a given city or some given metropolises and use input-output tables to trace emission flows. We divide studies into three categories: (1)One single city, such as Norwegian city of Trondheim[9], Australian city of Melbourne [10], Chinese city of Xiamen [11]. (2)Several cities in one country, these studies take intercity trade into account, like Melbourne and Sydney [12], thirteen Chinese cities including Beijing, Shanghai, Tianjin, Chongqing etc. [13]. (3)Several cities in different countries, such as four cities of Berlin, Delhi NCT, Mexico City, and New York metropolitan area [14], five Chinese megacities (Beijing, Tianjin, Shanghai, Chongqing and Hong Kong) and the five largest Australian capital cities (Melbourne, Sydney, Brisbane and Perth)[15].

Current studies are limited by the availability of input-output tables (IO). Limitations are following: (1) Timeliness, IOs are not published timely as some economic indicators like GDP. According to the compilation requires time, cost and human resource, most of countries publish a table several years. (2)

Coverage, IOs are usually at subnational level and national level. Some developed cities compile its own single-region IO. And multi-region IO at city level is scarce. (3) Closed system of the input-output table, shortage of detailed basic materials leads researchers cannot modify IO to support their studies.

In this paper, we want to understand income enabled carbon emissions with PE and IE of Jing-Jin-Ji megaregion at city level. Income-based emission is not a novel term, however, it is an ignored concept in current literatures. Our contribution of this paper is following: 1) To our knowledge, this is the first time to discuss income-based emission at city level in China. 2) As the limitation of data availability, most of researches at city level always select several metropolises, this paper sets 14 cities of Jing-Jin-Ji megaregion as the scope of research. 3) We group IE based on which cities/provinces and sectors generate emissions.

The remainder of this paper is organized as follows: Section 2 introduces brief materials and methods about production-based, consumption-based and income-based emission. Section 3 tells data used in this paper in details. Section 4 displays calculations and Section 5 gives conclusions and discussions.

## 2. Materials and Methods

### *2.1 Leontief and Ghosh Input-output model*

Input-Output Analysis is an appropriate tool to accommodate the topic on economic flows of goods and services associated with interindustry activities both at intra-region and inter-region[16]. There are two famous models coming from input-output analysis, the Leontief model and the Ghosh model Which are derived from row balance and column balance of input-output table respectively.

The Leontief model could date back to Leontief's work[17, 18], and its another name is demand-pull input–output quantity model. It reveals the row balance of input-output table as the equation $x = \mathbf{T} + y$, here $x$ and $y$ mean the vectors of total input and the final demands respectively. The matrix $\mathbf{T}$ could also be shown like $\mathbf{T} = \mathbf{A}x$, $\mathbf{A}$ the direct-input coefficient matrix and its element $A^{ij} = T^{ij}/x^{j}$. Then we could move matrix $\mathbf{T}$ from right side of equation to left side and derive the Leontief model $x = (\mathbf{I} - \mathbf{A})^{-1}y$, where $(\mathbf{I} - \mathbf{A})^{-1} = \mathbf{L}$ means the famous Leontief inverse or the total requirements matrix[16].

The Ghosh model, the Leontief model's economically complete opposite, so-called supply-driven or cost-push input-output price model[19, 20] was developed by Ghosh[21]The Ghosh model derives from equation uncovering the linkage of the column of input-output table. The equation is given by $x = \mathbf{T} + v$, here $x$ and $v$ mean the vectors of total input and the primary input respectively. $\mathbf{T} = x\mathbf{B}$ indicates the matrix of intermediate input. Then we could get the Ghosh model as shown $x = v(\mathbf{I} - \mathbf{B})^{-1}$, where $(\mathbf{I} - \mathbf{B})^{-1} = \mathbf{G}$ means the Ghosh inverse[16]. The element $B^{ij}$ of $\mathbf{B}$ has been denoted the direct-output coefficients matrix, which is estimated as $B^{ij} = T^{ij}/x^{i}$.

In this study, we apply the models above to three different accountings, as production-based accounting, consumption-based accounting and income-based accounting.

## *2.2 Production-based accounting*

We calculate production-based emissions of 14 cities of Jing-Jin-Ji megaregion (see details in Table S1). The process uses the common tool, input-output analysis, and the model is the Leontief model, $\mathbf{Q} = \hat{q}(\mathbf{I} - \mathbf{A})^{-\mathbf{1}}\hat{y} = \hat{q}\mathbf{L}\hat{y}$ with $\mathbf{Q}$ indicating a $\mathrm{n} \times \mathrm{n}$ matrix meaning city carbon map which could find the initial emitters and the destinations of carbon flows.

Here, our production-based carbon emissions(PE) consider direct emitter(named producer) who emits the carbon emissions directly for producing goods and services, which has the same meaning with IPCC (2006) [22]. This is the first step of production processes. The equation is given by $\mathbf{Q}_{\mathrm{pro}} = \widehat{q^{\imath}}\mathbf{L}\hat{y}$, which $\widehat{q^i}$ indicates the emission intensity for producing per unit output of region $i$, $\widehat{q^i}$ is a diagonal matrix of a $\mathrm{n} \times 1$ vector. $\hat{y}$ is the diagonal matrix of $\mathrm{n} \times 1$ vector of final demands. Based on this equation, we do not consider the destination where the goods and services consumed after first step of producing processes. There is another emitter, final production emitter, concerned by researchers these years， like [23]. But we don't focus on it in this paper.

## *2.3 Consumption-based accounting*

Consumption-based emission(CE) is prevalent when many researchers question the rationality of production-based emission in allocation of emission responsibility of Kyoto Protocol. Consumption-based emission pays more attention on the final consumer who finally consumes the goods and services. Peters (2008) discussed the national emission from production-based to consumption-based for the territorial system boundary's debate[24]. As we focus on Jing-Jin-Ji megaregion including 14 cities listed in *The Jing-Jin-Ji Coordinated Development Strategy* set by the Chinese government, we do not consider international trade, just consider inter-cities trade and the trade between 14 cities and the rest provinces of China. The equation is given by $\mathbf{Q}_{\text{con}} = \hat{q}\mathbf{L}\widehat{y^{\cdot j}}$,based on an environmental-extended Leontief model, which $\widehat{y^{\cdot j}}$ indicates a diagonal matrix of a $\mathrm{n} \times 1$ vector of the final demand terms of region $j$, the dot "·" means sum of other regions' final demand, $y^{\cdot j} = y^{1j} + y^{2j} + \cdots + y^{nj}$, which $y^{1j}$ indicates final demand terms of region $j$ coming from region 1 and region $j$ is final consumer, region 1 is final producer.

## *2.4 Income-based accounting*

Income-based emission(IE) is estimated through the Ghosh model which is different with the production-based emission and the consumption-based emission. The model used to estimate income-based emission is an environmental-extend Ghosh model, which we add a variable of intensity (emission intensity in this paper) to the Ghosh model. The equation is given by

$\mathbf{Q}_{\text{income}} = \hat{v}(\mathbf{I}-\mathbf{B})^{-1}\hat{q} = \hat{v}\mathbf{G}\hat{q}$, or in its partitioned form as

$$\begin{bmatrix} Q^1 \\ Q^2 \end{bmatrix} = \begin{bmatrix} v^1 & \\ & v^2 \end{bmatrix} \begin{bmatrix} G^{11} & G^{12} \\ G^{21} & G^{22} \end{bmatrix} \begin{bmatrix} q^1 & \\ & q^2 \end{bmatrix} = \begin{bmatrix} v^1G^{11}q^1 & v^1G^{12}q^2 \\ v^2G^{21}q^1 & v^2G^{22}q^2 \end{bmatrix} \quad (1)$$

with $G^{ij}$ has been interpreted as measuring "the total value of production that comes about in region $j$ per unit of primary input in region $i$."[25], $q^1$ and $q^2$ the emission intensity vectors of region 1 and 2. Based on the connections between inter-industries from input-output table, we link the primary input $v$ with emission $\mathbf{Q}$ and could trace the enabled emission from the primary input. The enabled emission means it caused by the primary input(also named income).

## *2.5 Emission balances*

Three accountings above give us three perspectives to allocate the emission responsibility. They have the same goal which is reasonable allocation of responsibility and achieving reduction. PE is a direct allocation method based on direct emitter and CE and IE are indirect methods. As consumer is the last process of goods and services, CE traces the emission embodied in goods and services and reveals the linkage from consumer to producer. So CE is also named upstream emission. IE is opposite and uncovers the relationship from economic beneficiary to producer and is named downstream emission as beneficiary inputs the primary input to improve the production.

Then, we define two types of responsibility emission balances as the difference between the producer and economic beneficiary responsibility, and the difference between the producer and the consumer. This balance could be measured by equation (2) and (3) shown as following

$$\mathrm{BE}_r = \mathbf{Q}_{\text{income}} - \mathbf{Q}_{\text{pro}} \quad (2)$$

If $\mathrm{BE}_r > 0$, we could define the region as net benefit region, net loss region vice versa. Net benefit region means this region gains more benefit than its corresponding emission responsibility. And net loss region means this region does not take the equivalence ratio of benefit with its emission.

$$\mathrm{BE}_c = \mathbf{Q}_{\mathrm{con}} - \mathbf{Q}_{\mathrm{pro}} \tag{3}$$

If $\mathrm{BE}_c > 0$, we could define the region as net trade region. Net trade region means this region's emission embodied in goods and services consumed is larger than its directly emission occurring through its initial production process. Then we can say more emissions from other regions are generated for satisfying net trade region's final demand.

## 3. Data

Main kinds of data used in this paper are: (1) multi-regional input-output table; (2) emission data; (3) other indicators.

### 3.1 Multi-regional input-output table

The multi-regional input-output table used in this paper comes from Chinese IELab [26, 27]. IELab is built by Lenzen et al.(2012) [28], Lenzen et al.(2013) [29]. MRIO tables in Chinese IELab are following the standard supply and use table. In this paper, MRIO table is a 42-regions (details shown in Table S1) and 42-sectors (details shown in Table S2) table coming from according to our concrete research. We chose the year of 2013 as it's a meaningful year that the president Xi brought the promotion of *The Jing-Jin-Ji Coordinated Development* up[30].

### *3.2 Emission data*

We calculate the emission data of 14 cities according to the data of energy consumption and emission factors. Energy consumption is the core of calculation of carbon dioxide emission. In this paper, not only do we consider the main kinds of energy like coal, oil and gas, but also take other energy types, as gangue, coke, into account (see Table S3 in details). However, considering data missing and data overlapping, energy data coming from Statistical Yearbook could not estimate emissions directly and data adjustment is necessary. In Table S1, we list all regions in this study, and we collect data from two levels: 1) provincial level. In this study, there are 31 provinces. We get each province's energy consumption data from provincial Statistical Yearbook published in 2014, and the corresponding energy balance sheet comes from the *China Energy Statistical Yearbook-2014*[31]. Tibet is an exception, as we could not get energy consumption data and its energy balance sheet, then we set Tibet's energy consumption zero. Then we need to adjust the provincial level data through the method from Peters et al.(2006), details in Peters et al.(2006)[32]. 2) prefectural level. There are 12 prefectural cities' energy consumption data should be collected. We could find the majority data from cities' Statistical Yearbook. Maybe Sectoral energy consumption of some city could not be taken, we use each sector's percentage of total energy consumption (in unit of standard coal equivalent, SCE) and total energy consumption by sector to estimate sectoral energy consumption in physical unit, like Shijiazhuang, and Handan. Chengde is a special city that we could not find its energy data consumed in 2013, we estimated its data through energy consumption in 2014 and the corresponding output of industrial products in constant price. Shan et al.(2016) [33] introduced the details to construct $CO_2$ emissions inventory of Chinese cities. In this study, we use Shan et al.(2016)'s work to adjust our raw cities' energy data. However, we do some different steps to deal with the data. As we could not get the whole energy balance sheet in city level, we adjust data as following: 1) do not adjust the import and export energy consumption in city level; 2) If could find the table of "Input of Transformation", we just adjust the energy data based on these data and ignore the estimated energy balance sheet in city level through the provincial energy balance sheet, as Tangshan, Baoding, and Xingtai; 3) If could not find the data of input of transformation, we use data from estimated energy balance sheets to adjust energy consumption data.

The emission factors by sector and energy type come from a series of Liu's group, details in Liu et al.(2012) [34] and Liu et al.(2015) [35].

### *3.3 Other indicators*

Population and GDP come from Statistical Yearbook published by the local statistical departments.

## 4. Results

### *4.1 Income-based emission of 14 cities of Jing-Jin-Ji megaregion*

Using the model shown in Section 2.2-2.4, we calculate production-based emissions, consumption-based emissions and income-based emissions of 14 cities of Jing-Jin-Ji megaregion, the results are listed in Figure 1. And the rest of provinces' emissions can be found in Table S4. Different accounting method gives different results. Beijing, Tianjin, Shijiazhuang and Tangshan are top 4 cities who have higher production-based emissions and income-based emissions. Compared with PE and IE, the gaps between cities' CE are relatively small, and Beijing, Tianjin and Shijiazhuang are the top 3 cities. Tangshan's PE (151.9 $MtCO_2e$) is the highest, and its IE (123.3 $MtCO_2e$) is the second highest, however, its CE (32.1 $MtCO_2e$) is location in the middle position of the ranking. Higher PE and IE mean Tangshan is a production hub and inputs more energy, and Tangshan is also a primary supplier whose primary input enables larger emission occurring in downstream cities. Lower CE tells Tangshan is not a main consumer in Jing-Jin-Ji megaregion which further indicates Tangshan is a main producer in this big region. So it will take effect when policy-maker focuses on production and primary input to implement reduction. Beijing is a city has higher PE (76.2 $MtCO_2e$), CE (92.2 $MtCO_2e$) and IE (72.2 $MtCO_2e$), then it is not only a primary producer, but also a primary consumer.

However, we also take the emission efficiency into account, there are two types of efficiencies as emission per unit of GDP (E-GDP) and emission per capita (E-P). Table 1 gives the IE's emission efficiencies, other results can be found in Table S5. It obviously shows that higher emission does not mean lower efficiency (in general, lower efficiency is better). Beijing's IE are higher than most of cities, its IE-GDP are lower than other cities, as Beijing is the lowest city (37.0 t per million yuan) and followed by Tianjin (87.5 t per million yuan). And its IE-P is lower too. So we can say decreasing emission of Beijing could not improve emission efficiency effectively, and Beijing does not need to undertake more burden of reduction emission task. Tianjin, Shijiazhuang and Tangshan have different situations. These cities have higher emissions with higher emission efficiencies, then reduction measurements will have visible effects.

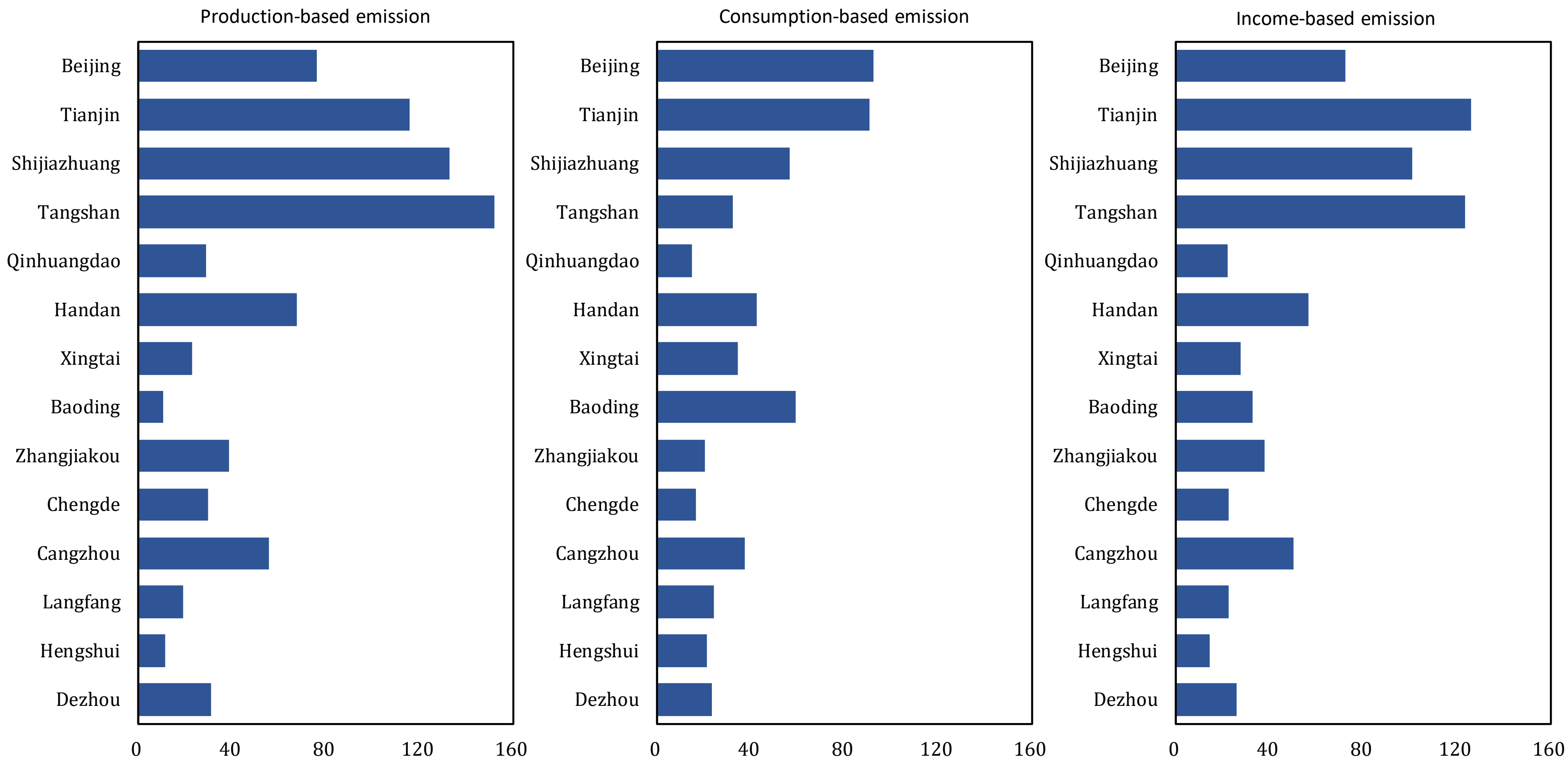


**Figure 1.** The results of three accountings (in units of MtCO2e) of Jing-Jin-Ji megaregion in 2013.

**Table 1.** The income-based emission of Jing-Jin-Ji megaregion in 2013

| | | Income-based emission | Income-based emission per unit of GDP | Income-based emission per capita |
|---|---|---|---|---|
| | | $MtCO_2e$ | $tCO_2e$ per million yuan | $tCO_2e$ per capita |
| 1 | Beijing | 72.2 | 37.0 | 3.5 |
| 2 | Tianjin | 125.7 | 87.5 | 8.7 |
| 3 | Shijiazhuang | 100.6 | 206.7 | 9.6 |
| 4 | Tangshan | 123.3 | 201.4 | 16.0 |
| 5 | Qinhuangdao | 22.0 | 187.8 | 7.2 |
| 6 | Handan | 56.5 | 184.7 | 6.1 |
| 7 | Xingtai | 27.6 | 172.0 | 3.8 |
| 8 | Baoding | 32.8 | 112.8 | 2.9 |
| 9 | Zhangjiakou | 37.8 | 287.2 | 8.6 |
| 10 | Chengde | 22.5 | 177.2 | 6.4 |
| 11 | Cangzhou | 50.0 | 165.8 | 6.9 |
| 12 | Langfang | 22.5 | 115.9 | 5.1 |
| 13 | Hengshui | 14.3 | 133.3 | 3.2 |
| 14 | Dezhou | 25.8 | 105.0 | 4.6 |

In Figure 1 and Table 1, we give the results of total emissions, then we group IE based on IE's geographical location, details shown in Figure 2. We rank 14 cities based on IEI from the highest to the lowest.

First, we split cities/provinces where enabled emission occurs into domestic (the blue part) and other places without the domestic (the orange part and the grey part). We can discover that the primary inputs of most of cities enable emission generated from the domestic, which means above 50% of IE of a given city emits in own city boundary. These cities are Tianjin (64.4%), Tangshan (79.4%), Shijiazhuang (73.7%), Handan (66.3%), Cangzhou (64.2%), Zhangjiakou (79.6%), Dezhou (72.0%), Chengde (70.0%), Qinhuangdao (72.4%) and Hengshui (50.6%). There are four exceptions of cities, like as Beijing (42.1%), Baoding (17.1%), Xingtai (45.4%) and Langfang (36.9%). The finding shows the government needs to focus more attention on own city boundary to reduce its IE, the production-based emission could be cut, as well.

Then, we separate cities/provinces where enabled emission occurs other places without the Fdomestic into intra-region (the orange part) and outside of region (the grey part). Here, we just give the four exceptions in details. We find that the part of outside of region always accounts for approaching 90 percent of the IE emitted by other places without the domestic, which means these four cities gain more economic benefits from emissions occurring outside of Jing-Jin-Ji Megaregion. Then we hold these four cities should pay more concerns on outside of region to reach its reduction goal.

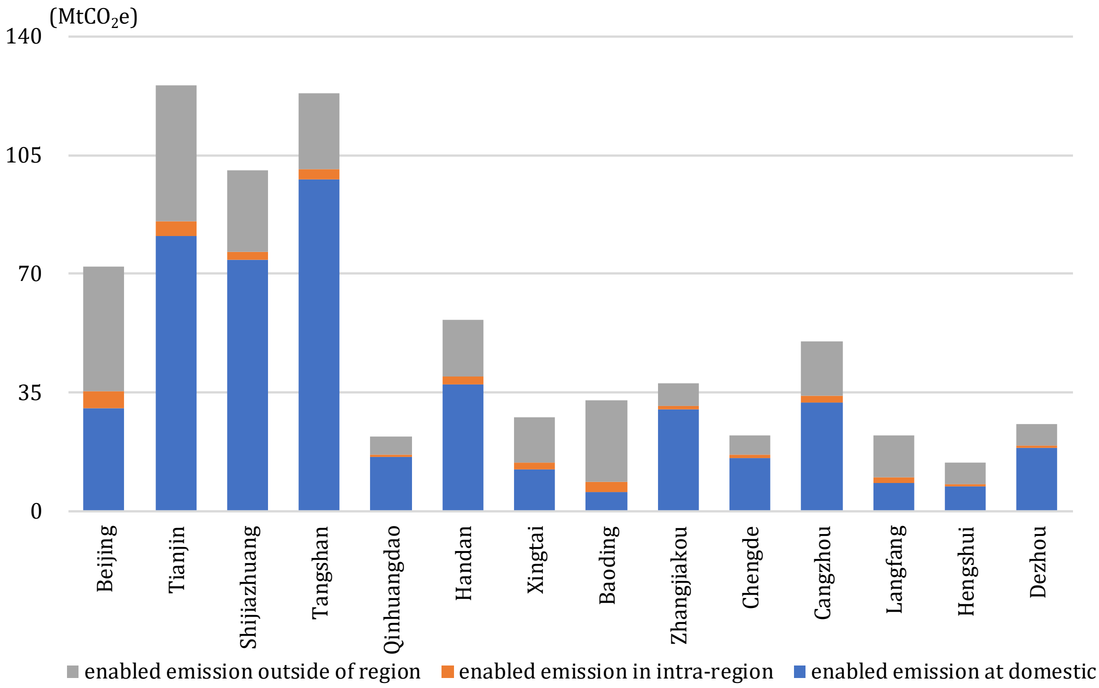


**Figure 2.** The clustering of income-based emissions (in units of MtCO2e) of Jing-Jin-Ji megaregion in 2013. Here, we group every city's income-based emission into three parts: ①enabled emission at domestic, which means a given city's primary inputs enable domestic emission generating. ②enabled emission in intra-region, which uncovers a given city's primary inputs enable emission occurring in Jing-Jin-Ji megaregion without the domestic. ③enabled emission outside of region, which identifies a given city's primary inputs enable emission generating outside of Jing-Jin-Ji megaregion (meaning the rest of China).

## *4.2 Enabled emission of cities/provinces and sectors*

In this section, we select some cities to identify the main enabled cities/provinces and sectors. Enabled cities and sectors are downstream emitters of GHG.

Figure 3 gives top 7 enabled cities/provinces and the corresponding emissions (display as the rows) of Beijing, Tianjin, Shijiazhuang and Tangshan. The result indicates that the domestic generates the most of emission enabled by domestic primary input. The enabled cities/provinces of these four cities shown in figure are similar but have different rankings and different enabled emissions. Similar enabled cities/provinces show these four cities have the similar economic linkage with these cities/provinces which could easily know coordinate development of these cities would promote cities' development. Except the domestic, other 13 cities of Jing-Jin-Ji megaregion could not be found in Figure 2 which indicates that Jing-Jin-Ji megaregion cannot develop without outside of region's support. As a word, inter-regional trade helps a given city's development. And the most important is that one of these enabled cities/provinces reduces its emission which will cause the IE's reduction of each city of Jing-Jin-Ji megaregion. Then, these 14 cities could cooperate to negotiate with these enabled cities/provinces to mitigation of emission.

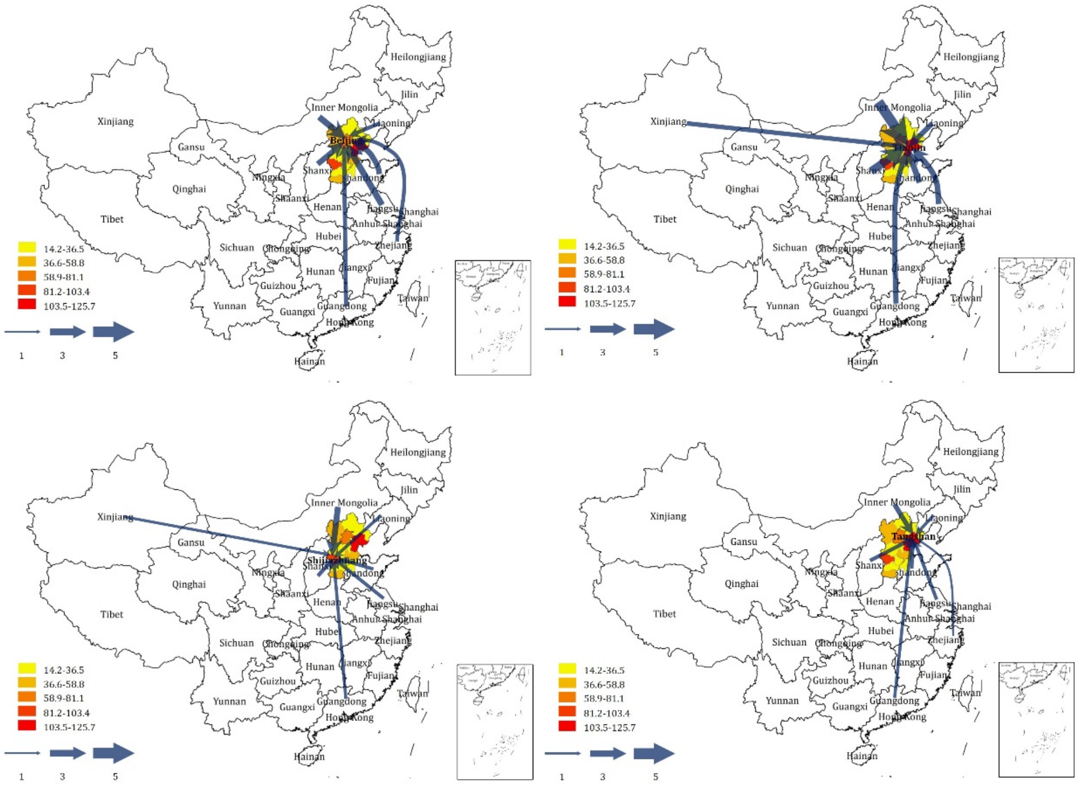


**Figure 3.** The top 7 enabled cities/provinces of Beijing, Tianjin, Shijiazhuang and Tangshan in 2013 (in units of $MtCO_2e$). Here, we use color bar to indicate 14 cities IE, and use rows to reveal main emitters of a given city's IE. Shandong means Shandong without Dezhou.

Table 2 gives enabled emissions of sectors of Beijing. The result of Tianjin can be found in Table S5. Both cities have higher IE, and the other one is Tianjin's primary input enables more domestic emission and Beijing's enables more emission outside Beijing.

Table 2 tells us an interesting finding: If we focus on enabled emission of specific sector, the primary input of the sectors of Beijing always enables emission of Beijing's sectors, although enabled emission generated outside of Beijing accounts for 57.9% of Beijing's IE. It shows that the local government should also pay attention to local sectors. The top sector in Table 2 is Production and Supply of Electric Power and Heat Power both listed under the economic beneficiary and enabled sector. It is a key sector which is listed under enabled sector 5 times, meaning that it’s an intensive-emission sector and its emission enabled by Smelting and Rolling of Metals, Chemical Industry, Real Estate, Information Transmission, Computer Services and Software.

Most of the main sectors of Beijing’s economic beneficiaries are belong to the tertiary industry which supports that Beijing is a service-oriented city. And the main enabled sectors are also coming from Beijing. Then Beijing gains the economic income and it also enables emission in local city boundary. We believe that there is a gap between Beijing’s current position in Jing-Jin-Ji megaregion and the desired state in *The Jing-Jin-Ji Coordinated Development Strategy*.

**Table 2.** The top 25 of enabled emission of sectors of Beijing in 2013 (in units of $MtCO_2e$).

| No. | economic beneficiary | enabled sector | Beijing's EI |
|---|---|---|---|
| 1 | Beijing-Production and Supply of Electric Power and Heat Power | Beijing-Production and Supply of Electric Power and Heat Power | 11.9 |
| 2 | Beijing-Post | Beijing-Post | 4.9 |
| 3 | Beijing-Wholesale and Retail Trades | Beijing-Wholesale and Retail Trades | 1.0 |
| 4 | Beijing-Leasing and Business Services | Beijing-Leasing and Business Services | 0.9 |
| 5 | Beijing-Real Estate | Beijing-Real Estate | 0.7 |
| 6 | Beijing-Information Transmission, Computer Services and Software | Beijing-Information Transmission, Computer Services and Software | 0.7 |
| 7 | Beijing-Agriculture, Forestry, Animal Husbandry & Fishery | Beijing-Agriculture, Forestry, Animal Husbandry & Fishery | 0.7 |
| 8 | Beijing-Financial Intermediation | Beijing-Financial Intermediation | 0.7 |
| 9 | Beijing-Smelting and Rolling of Metals | Beijing-Production and Supply of Electric Power and Heat Power | 0.5 |
| 10 | Beijing-Chemical Industry | Beijing-Production and Supply of Electric Power and Heat Power | 0.5 |
| 11 | Beijing-Construction | Beijing-Construction | 0.5 |
| 12 | Beijing-Hotels and Catering Services | Beijing-Hotels and Catering Services | 0.4 |
| 13 | Beijing-Real Estate | Beijing-Production and Supply of Electric Power and Heat Power | 0.4 |
| 14 | Beijing-Comprehensive Technical Services | Beijing-Comprehensive Technical Services | 0.4 |
| 15 | Beijing-Research and Experimental Development | Beijing-Research and Experimental Development | 0.3 |
| 16 | Beijing-Information Transmission, Computer Services and Software | Inner Mongolia-Production and Supply of Electric Power and Heat Power | 0.3 |
| 17 | Beijing-Public Management and Social Organization | Beijing-Public Management and Social Organization | 0.3 |
| 18 | Beijing-Manufacture of Nonmetallic Mineral Products | Beijing-Post | 0.3 |
| 19 | Beijing-Manufacture of Nonmetallic Mineral Products | Beijing-Manufacture of Nonmetallic Mineral Products | 0.3 |
| 20 | Beijing-Traffic, Transport and Storage | Beijing-Traffic, Transport and Storage | 0.3 |

## *4.3 Comparisons of different perspectives of allocations*

Three accounting methods represent three perspectives. We have discussed that production-based emission is direct emission, the others are indirect. And consumption-based emission focus on emission embodied in goods and services for satisfying consumers' final demand. It is a process from bottom to up, so the emission is also known as upstream emission. To some extent, income-based emission is opposite to CE. It traces who enables emission to occur which means who earns economic benefits. It is a top-down process and the emission is called downstream emission. So different method indicates different agent who needs to undertake the corresponding emission responsibility. PE's agent is the producer, CE and IE's are consumer and economic winner respectively.

PE is an official method authorized by the international organization. However, the different results shown in this paper tell us PE is not enough to complete the allocation of emission responsibility. CE has attracted attention from researchers for carbon leakage with regional trade. IE is overlooked heavily although economic interest is one of the main goals of development. In general, economic agents should bear emission responsibility which is according with interests earned.

Figure 4 shows two kinds of carbon balances (in units of MtCO2e) of 14 cities in 2013, including consumption to production $\mathrm{BE}_c$ (the left part), and income to production $\mathrm{BE}_r$ (the right part).

In the left part of Figure 4, nine in fourteen cities' $\mathrm{BE}_c$ are negative which means their PEs are larger than their CEs. It makes sense as Jing-Jin-Ji megaregion is an industrial base and heavily pollution region located in North of China. It shows that these nine cities emit for other provinces/cities' final demand and they bear more emission responsibilities than their consumption. In other side, we think these cities produce more goods and services to satisfy other provinces/cities' consumption. They are producers more than consumers.

In the right part of Figure 4, there are also nine cities' $\mathrm{BE}_r$ are negative. The same number of cities with $\mathrm{BE}_c$, but there is a litter difference of the specific cities. Beijing and Tianjin's states change, Beijing's $\mathrm{BE}_r$ is negative and its $\mathrm{BE}_c$ is positive, Tianjin is just opposite. Beijing's consumption embodies more emission than its PE and its PE is larger than IE which means Beijing is a consumer rather than a producer, And it earns less economic benefits than its production, in other words its production brings more benefits to other provinces/cities. Similarly, Tianjin is a producer and an economic winner at the same time. Considering Tianjin's highest income-based emission and about 65% of its IE generate at domestic, Tianjin could carry out two ways: (1) Identify the main sectors at domestic (shown in Table S5), such as Production and Supply of Electric Power and Heat Power, to regulate these sectors' energy consumption or chose clean energy; (2)Adjust its downstream trade partners, like choosing provinces/cities who have a lower emission intensity, to reduce its income-based emission which also could force trade partners to use less-intensive emission goods and services or develop technology to improve energy efficiency.

Xingtai, Baoding, Langfang and Hengshui are cities whose $\mathrm{BE}_c$ and $\mathrm{BE}_r$ are positive which indicate that they are consumers and economic winners. In the ranking of PEs of 14 cities, Xingtai, Baoding, Langfang and Hengshui are on the bottom of the ranking. The sector Production and Supply of Electric Power and Heat Power of Xingtai, Langfang and Baoding do not consume more energy which causes these three cities' PEs are smaller. Hengshui is limited by its scale of economy, its energy consumption is the smallest in Jing-Jin-Ji megaregion, so its PE is small too.

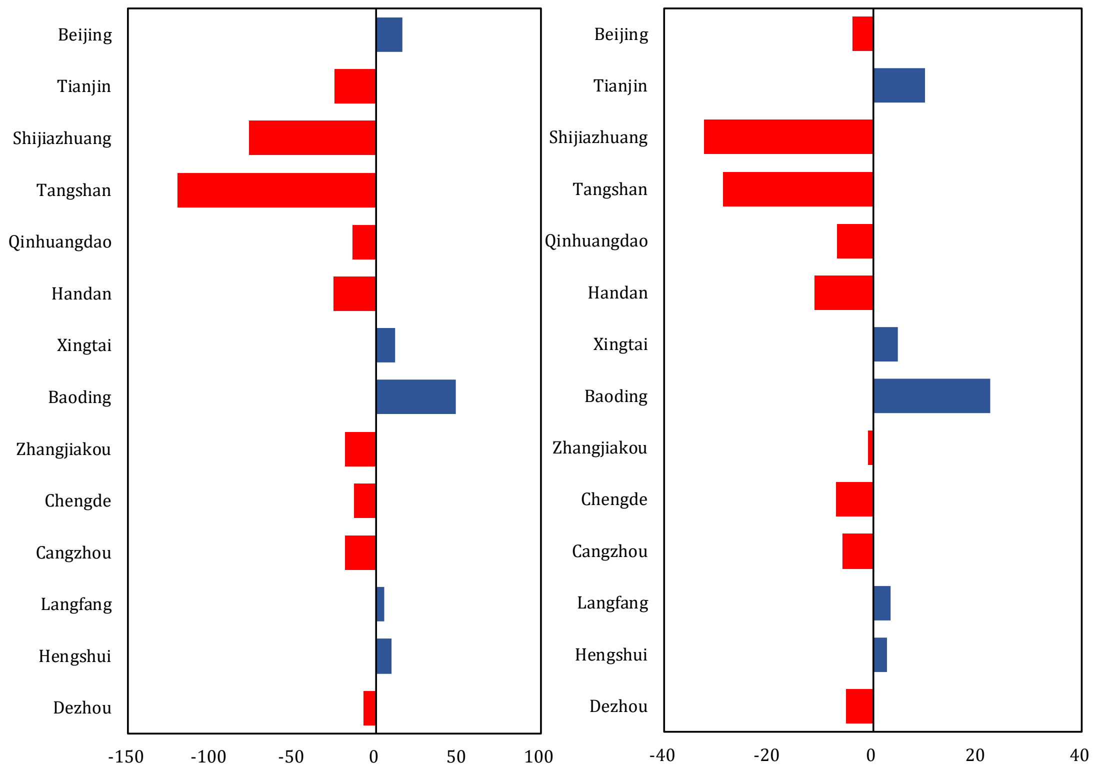


**Figure 4.** Two kinds of carbon balances (in units of $MtCO_2e$) of 14 cities in 2013, including consumption to production $BE_c$ (the left one), and income to production $BE_r$ (the right one). Here, dark blue bar means larger than production-based emission, the corresponding city could be as net trade/benefit city. And red bar means less than production-based emission.

### *4.4 Policy implications*

14 cities of Jing-Jin-Ji megaregion are concerned as *The Beijing-Tianjin-Hebei Coordinated Development Strategy* set by China central government in 2015. Each city has its own position, and they also have some common targets, such as establish regional transportation net, dock industry and improve the quality of the environment. Based on the results, this paper could provide some suggestions about environment.

Jing-Jin-Ji megaregion is a production center, however, not all cities have larger PE than IE. Tianjin, Xingtai, Baoding, Langfang and Hengshui are exceptions. Combining with IE's emitters, Tianjin and Hengshui are cities whose more than half of IEs occur at domestic. It will have direct effect when decision-makers take action on emission-intensive producer. If economic winners think about the reduction, they will consciously avoid entering into emission-intensive sectors. Then the sectors have to reduce its emission/emission intensity to attract primary input. Xingtai, Baoding and Langfang are located another situation that more than half of IEs generate at other places, especially outside of Jin-Jin-Ji megaregion. Inter-regional trade plays an important role on the allocation of emissions. These cities should cooperate with the key provinces to reduce emission.

## 5. Conclusions and discussion

This study discusses three emission accounting methods which uncovers different methods focus on different agents, production-based, consumption-based and income-based correspond producer, consumer and economic beneficiary. CE and IE link consumer and economic beneficiary with producer. CE calculates emission standing on the point of consumer and re-allocates producer’s emission. IE stands on the point of economic beneficiary and re-allocates too. These re-allocation methods support us understanding relative emissions of a role a given city playing. It can provide reference to decision-makers to set emission tasks and determine how to improve the environment.

Most cities have higher production-based emissions than other emissions which could support Jing-Jin-Ji megaregion as a production center to provide intermediate goods and services to other provinces. Take Tangshan as an example to discuss. Tangshan has the highest PE and the second highest IE and its CE ranks in the middle position. It is a typical industrial center and resource-based city which can explain Tangshan generates higher emission for production. And it owns rich energy resources such as coal, oil, natural gas, and supports other provinces/cities energy resources which makes emission occur, so it understands its IE is higher. So Tangshan's mitigation should concentrate on two aspects: (1) clean production, reduce emissions occurring during production. (2) technology development, produce clean energy to reduction from the emission sources.

Grouping work of IE based on emitters tells us domestic emission is the main reduction target and the main enabled provinces/cities except own are always out of Jing-Jin-Ji megaregion. We trace specific cities/provinces and sectors' emission enabled by Jing-Jin-Ji megaregion's primary input. The top 10 enabled cities/provinces of Jing-Jin-Ji megaregion are similar, like Jiangsu, Inner Mongolia, Shanxi, Shandong, Guangdong, Liaoning, Zhejiang and Xinjiang. These enabled cities/provinces could be divided into two categories: One is developed provinces, including Jiangsu, Guangdong, Shandong and Zhejiang. These provinces have close connections in trade with Jing-Jin-Ji megaregion. The other one is resourceful provinces, like Inner Mongolia, Shanxi, Liaoning and Xinjiang. The development of Jing-Jin-Ji megaregion couldn't without these provinces' supports.

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