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Article

Carbon Footprints and Embodied Carbon Flows Analysis for China's Eight Regions: A New Perspective for Mitigation Solutions

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Abstract: Carbon footprints have been widely employed as an indicator for total carbon dioxide released by human activities. In this paper, we implemented a multi-regional input-output framework to evaluate the carbon footprints and embodied carbon flows for the eight regions of China from consumption-based perspective. It is found that the construction, electricity/stream supply, and machine manufacturing rank as the top sectors with the largest total carbon emissions. The construction sector alone accounts for 20%–50% of the national emissions. Besides the sectoral carbon footprints, regional footprints and their differences in carbon emissions were also observed. The middle region had the largest total carbon footprints, 1188 million ton, while the capital region ranked the first for its per capita carbon footprint, 7.77 ton/person. In regard to the embodied carbon flows within China, the study detected that the embodied carbon flows take up about 41% of the total carbon footprints of the nation. The northwest region and the eastern coast region are found to be the largest net embodied carbon exporter and importer, respectively. Further investigation revealed significant differences between production-based and consumption-based carbon emissions, both at sectoral and total amounts. Results of this paper can provide specific information to policies on sectoral and regional carbon emission reduction.

Keywords: carbon footprints; multi-regional input-output model; embodied carbon; regional differences; construction; sectoral emissions

1. Introduction

Carbon footprint accounting has been proved to be a good approach to indicate the total carbon emissions of a person, a sector, a region and a nation [1–8]. The concept of carbon footprint refers to the total carbon dioxide discharged to the atmosphere [9]. Since the total amount of carbon dioxide is not only dependent upon the direct emitters but also indirectly through the emitters' supply chain, this concept can help us identify the "hidden carbon emitter" that cannot be detect from superficies. A related concept is "embodied carbon", which is defined as the volume of carbon transferred from one sector/region to another, measured over the full supply chain. Thus, the carbon footprint of a sector/region refers to the total carbon emissions from the inhabitants of the sector/region. This concept is of great importance to the accounting of carbon emissions.

With rapid economic development and high industrial energy consumption, China is now the top greenhouse gases (GHGs) emitter in the world—taking up 23.9% of the global emissions in the year 2010 [10]. A series of studies have tried to find out the solution to curb the emissions from many aspects [11–15], among which, accounting of the embodied carbon and carbon footprints of China are the major concerns. Lin employed an input–output model to evaluate the embodied carbon dioxide in international trade between China and other countries [16]; Liu detected the energy embodied in international trade of China [17]; Shui did a research on the embodied carbon in US–China trade [18]; while Li focused on the carbon emissions between China and UK [19]; Liu investigated the embodied energy use in China's industrial sectors using an IO model [20]; Zhu conducted an calculation and decomposition of indirect carbon emissions from residential consumption in China [21]; Chen explored the sectoral carbon footprints in 2007 of the whole country and in another paper, the carbon footprints of Beijing [22].

As shown above, previous studies mainly focused on the carbon footprints of the whole nation, a single region, or the interdependency between China and other countries, while few researchers paid attention to China's regional carbon footprints and the relationships between these internal regions, especially at the sectoral level. For a big country like China, where huge regional differences exists, it is very urgent to investigate how the regions are different in sectoral carbon emissions, what are the directions of the embodied carbon flows, and what are the driving forces of carbon emissions in every region. The above-mentioned information can help detect where the highest carbon intensities are, and thus help to identify how to curb its emissions in China.

There are two methods in the carbon footprints accounting—one is the life cycle analysis (LCA), the so-called "bottom up" approach, and the other is the input–output analysis (IOA). LCA has advantages over IOA in the embodied carbon evaluation of single products because it collects production information from the technical details [23–29], but it shows shortcomings in the carbon calculation of an area, which needs massive data support and truncation errors [30]. So recent studies that focus on all sectoral products mostly use IOA to calculate the regional and national carbon footprints. IOA is a top-down economic technique using sectoral monetary transactions data to account for the interconnections and interdependencies of sectors developed by Leontief in the 1930s [31]. It uses mathematical routines to specify how substances flow among sectors through supply chains. It can track all direct and indirect resource use embodied in consumption [32]. IOA has been recently applied to the studies on impacts including both environmental and social or various resources embodied in the products, unexceptionally, the embodied carbon as carbon footprint [33–37].

There are mainly two types of IOA literatures—the one based on the single-regional input–output (SRIO) model and the other based on multi-regional input–output (MRIO) model. The first approach is mainly used to analyze a single region issue and the data needs are simple. However, in all research that employs SRIO model, there must be a strong assumption that the sectors of external regions have the same emission intensities as the studied region. Obviously, this may lead to incorrect results [16,17,38]. On the other hand, MRIO contains sectors in all trade partners and can obtain a more accurate result [33,34,39–42], which is of great importance when studying the relationships between multiple regions. So, if data are available, it is more reasonable to apply MRIO. In our study, we employ an eight-region MRIO model that covers most areas of China, except Hong Kong, Macao and Taiwan.

There are two main objectives of this article. One is to probe the carbon footprints at sectoral level so that we can access which sectors put the most pressure on the atmosphere. The other one focuses on the carbon flows embodied in inter-regional trade. Through these accountings, we can provide abundant information about carbon emission characteristics in China and support the making of low-carbon policies.

2. Methodology and Data

2.1. Methodology

In a MRIO framework, the technical coefficient matrix A can be calculated by

$$A^* = [A^{rs}],\ A^{rs} = [a_{ij}^{rs}],\ a_{ij}^{rs} = z_{ij}^{rs} / x_j^s \tag{1}$$

where z_{ij}^{rs} is the intermediate input from i^{th} sector in region *r* to j^{th} sector in region *s* and x_j^s is the output of j^{th} sector in region *s* of which the latter can be written as:

$$X^* = \begin{bmatrix} x^1 \\ x^2 \\ \vdots \\ x^n \end{bmatrix} \tag{2}$$

and the relevant final emissions can be shown as

$$Y^* = \begin{bmatrix} y^{11} & y^{12} & \cdots & y^{1n} \\ y^{21} & y^{22} & \cdots & y^{2n} \\ \vdots & \vdots & \ddots & \vdots \\ y^{n1} & y^{n2} & \cdots & y^{nn} \end{bmatrix} \tag{3}$$

where y^{rs} is the trade from different sectors in region *r* to region *s* as final consumption.

In consistence with the traditional single-region IO framework, the equilibrium in MRIO framework can be displayed by

$$\begin{bmatrix} x^1 \\ x^2 \\ \vdots \\ x^n \end{bmatrix} = \begin{bmatrix} A^{11} & A^{12} & \cdots & A^{1n} \\ A^{21} & A^{22} & \cdots & A^{2n} \\ \vdots & \vdots & \ddots & \vdots \\ A^{n1} & A^{n2} & \cdots & A^{nn} \end{bmatrix} \begin{bmatrix} x^1 \\ x^2 \\ \vdots \\ x^n \end{bmatrix} + \sum_s \begin{bmatrix} y^{1s} \\ y^{2s} \\ \vdots \\ y^{ns} \end{bmatrix} \tag{4}$$

where each sub-matrix represents the interactions between different regions and A^{rs} is the intermediate input matrix for region *r* to region *s* as described above.

The equation can be rewritten as:

$$X^* = A^* X^* + Y^*$$

then

$$X^* = (I - A^*)^{-1} Y^* \tag{5}$$

and

$$L^* = (I - A^*)^{-1} = \begin{bmatrix} L^{11} & L^{12} & \cdots & L^{1n} \\ L^{21} & L^{22} & \cdots & L^{2n} \\ \vdots & \vdots & \ddots & \vdots \\ L^{n1} & L^{n2} & \cdots & L^{nn} \end{bmatrix} \tag{6}$$

The vector of direct carbon coefficients is extended as:

$$W^* = \begin{bmatrix} W^1 & 0 & \cdots & 0 \\ 0 & W^2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \ldots & W^n \end{bmatrix} \tag{7}$$

where W^r is the direct carbon coefficients vector of region *r* which is the sub-matrix of the block matrix W^* of which each row only contains the carbon emission coefficients for the target region with zeros for the rest.

The total carbon emission coefficients can thus be derived by:

$$D^* = W^* L^* = \begin{bmatrix} W^1 & 0 & \cdots & 0 \\ 0 & W^2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \ldots & W^n \end{bmatrix} \begin{bmatrix} L^{11} & L^{12} & \cdots & L^{1n} \\ L^{21} & L^{22} & \cdots & L^{2n} \\ \vdots & \vdots & \ddots & \vdots \\ L^{n1} & L^{n2} & \cdots & L^{nn} \end{bmatrix} = \begin{bmatrix} D^{11} & D^{12} & \cdots & D^{1n} \\ D^{21} & D^{22} & \cdots & D^{2n} \\ \vdots & \vdots & \ddots & \vdots \\ D^{n1} & D^{n2} & \ldots & D^{nn} \end{bmatrix} \tag{8}$$

where D^{rs} is the row vector whose element D_j^{rs} denotes the carbon totally displaced by region *r* to regions to generate one monetary unit of final demand in *j*th sector of region *s*.

The regional carbon footprint (RCF) can be divided into two parts, the internal and external carbon footprints. The formal known as the internal RCF (IRCF) is the domestic carbon released to the atmosphere of goods and services consumed by the inhabitants of the region. The latter known as the external RCF (ERCF) is the carbon emission of external goods and services consumed by the inhabitants of the highlighted region, which equals the embodied carbon imported into the region.

Within the consumption-based MRIO framework, the RCF indicator can be logically connected with the concept of final emissions defined in the IO model. The IRCF can be calculated as:

$$IN^r = \begin{bmatrix} D^{r1} & D^{r2} & \cdots & D^{rn} \end{bmatrix} \begin{bmatrix} y^{1r} \\ y^{2r} \\ \vdots \\ y^{nr} \end{bmatrix} + E_{hh}^r \tag{9}$$

where IR^r represents the IRCF in region *r*. The first term in the equation denotes the domestic carbon emissions in region *r* for producing goods and services for the domestic final consumption in region *r*, which can also be decomposed into sub-sector scale. This component of IRCF in fact consists of three contents, which are (1) carbon embodied in domestic intermediate input for producing domestic final consumption in region *r*, and carbon embodied in exports as intermediate input to other regions to supply, (2) final demand, and (3) intermediate input again imported by region *r* as final and intermediate consumption respectively. E^r_{hh} is the direct carbon emissions by household in region *r*. The ERCF of region *r* can be derived as follows:

The carbon footprint of region *r* supplied by region s through trade can be calculated as

$$CF^{sr} = \begin{bmatrix} D^{s1} & D^{s2} & \cdots & D^{sn} \end{bmatrix} \begin{bmatrix} y^{1r} \\ y^{2r} \\ \vdots \\ y^{nr} \end{bmatrix} \tag{10}$$

where CF^{sr} is the carbon discharged by region *r* originates in regions and thus the ERCF of region *r* can be calculated by:

$$ER^r = \sum_{s,s\neq r} CF^{sr} \tag{11}$$

where ER^r is the ERCF of region *r*.

Therefore the RCF of region *r* can be calculated by adding up IRCF and ERCF:

$$CF^r = IN^r + ER^r \tag{12}$$

where CF^r represents the total RCF of region *r*.

2.2. Economic Data

The multi-regional input–output table of the 8 regions of China originates from the book: *2002–2007 China Regional Input-Output Tables* published by *China Statistics Press* [43]. The division of sectors and areas are show in Table 1 and Figure 1. It should be noted that the data does not cover Hong Kong, Macao and Taiwan.

Table 1. The division of sectors.

Number	Sector	Number	Sector
1	Agriculture	10	machine manufacturing
2	coal mining	11	transport manufacturing
3	food manufacturing	12	electric manufacturing
4	textiles clothing	13	other manufacturing
5	wood processing	14	electric and steam supply
6	paper printing	15	construction
7	petroleum processing	16	transport and warehousing
8	nonmetal manufacturing	17	other service
9	iron smelt		

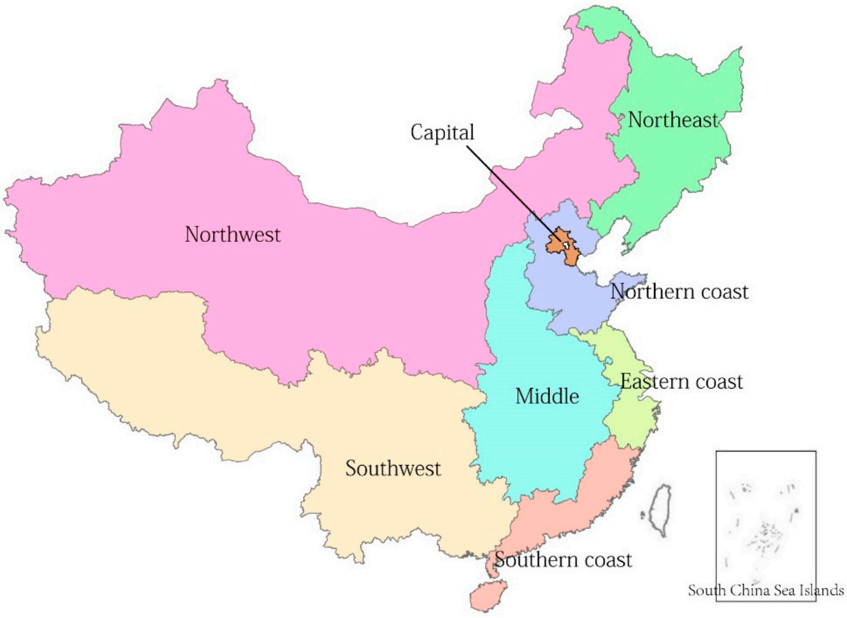

Figure 1. The division of eight regions in this study.

2.3. Carbon Emission Data

In order to get the sectoral carbon emission data, firstly we should obtain all kinds of primary energy and secondary energy consumption data for every sector in each region, and then multiply the specific energy data with the corresponding carbon emission factors [44]. Under the current statistical framework, two yearbooks contain energy consumption data for the nation, including *China Energy Statistical Yearbook* and *China Economic Census Yearbook*. We can acquire such detailed energy data for the sector of agriculture, construction, electric and steam supply, transport and warehousing and other service at provincial level from *China Energy Statistical Yearbook* [45], while specific energy data for the rest industrial sectors only stays at the national level. On the other hand, from *China Economic Census Yearbook* [46], sectoral total standard coal data for every province can be obtained, which however, cannot be translate into emission data directly. We assumed that the same sector in different provinces share the same energy consumption structure, so that we can allocate the national emission data to provinces according to their shares in national standard coal consumption. At last, the provincial data can be aggregated to regional one.

It should be reminded that we define direct emissions as the carbon dioxide directly released by the sector, so the emissions from electricity and steam consumed by other sectors are not involved in the sectoral direct emissions but are included in the original sectors.

3. Results

3.1. Direct and Total Carbon Emission Coefficients

We list direct and total carbon emission coefficients for every sector in every region in Tables 2 and 3. These sectors are listed because of their high value or great importance in economics.

Table 2. Direct carbon emission coefficients, ton/ten thousand Yuan.

No. of Sectors	Northeast	Capital	Northern Coast	Eastern Coast	Southern Coast	Middle	Northwest	Southwest
1	0.23	0.48	0.11	0.27	0.20	0.24	0.33	0.25
2	1.05	0.26	0.47	0.61	0.18	0.97	0.81	1.19
6	0.46	0.14	0.41	0.31	0.26	0.45	0.72	0.62
7	0.76	0.62	0.75	0.45	0.35	1.21	1.85	1.68
8	2.62	1.61	1.41	1.65	2.05	2.15	4.49	5.23
9	2.41	1.23	1.89	0.77	0.47	1.56	2.21	1.77
10	0.18	0.08	0.13	0.07	0.09	0.15	0.17	0.17
11	0.08	0.06	0.11	0.05	0.04	0.14	0.08	0.08
12	0.05	0.01	0.05	0.02	0.02	0.05	0.09	0.04
14	11.79	4.90	11.16	7.70	5.06	10.56	20.03	6.71
15	0.06	0.11	0.24	0.07	0.05	0.08	0.15	0.08
16	1.07	0.66	0.88	0.75	0.93	1.00	1.71	1.32

Table 3. Total carbon emission coefficients, ton/ten thousand Yuan.

No. of Sectors	Northeast	Capital	Northern Coast	Eastern Coast	Southern Coast	Middle	Northwest	Southwest
1	0.94	1.66	1.33	0.99	0.71	1.06	1.73	0.85
2	2.54	1.60	4.05	2.85	1.29	3.33	2.71	2.90
6	2.09	1.78	2.99	1.89	1.58	2.47	3.36	2.28
7	2.41	2.30	3.81	2.36	1.87	3.44	5.06	3.90
8	5.99	4.19	4.72	4.53	5.19	5.33	8.74	8.32
9	5.68	3.83	5.85	3.28	2.60	4.66	6.75	4.50
10	2.61	1.92	3.62	2.18	1.68	2.70	4.17	2.25
11	1.94	1.60	2.83	1.91	1.33	2.54	2.46	2.05
12	2.43	1.17	3.59	1.59	1.14	2.35	2.61	2.24
14	19.02	11.51	15.70	13.52	10.08	14.57	28.16	10.98
15	3.04	2.86	3.43	2.89	2.94	3.13	3.79	3.34
16	2.21	1.68	2.59	1.66	1.49	2.35	3.40	2.44

Direct carbon emission coefficients represent the direct carbon dioxide released to produce one monetary value of output. They can show the carbon emission intensities apparently. As shown in Table 1, electric and steam supply (sector 14) is the most carbon-intensive sector with more than 10 tons of carbon dioxide emissions for each ten thousand Yuan of sectoral output, much higher than the other sectors. In fact, the sector of electric and steam supply makes up 46.2% of direct emissions in all economic departments. Among the rest of the sectors, coal mining (sector 2), paper printing (sector 6), petroleum processing (sector 7), nonmetal manufacturing (sector 8), iron smelt (sector 9) and transport and warehousing (sector 16) also rank high in carbon intensities. In the current emission reduction policies, some sectors are paid emphatic attention such as the electric industry, the cement industry and the steel industry. It somehow corresponds to the "carbon-intensive sectors" identified in our calculation.

We can obtain the potential sectoral carbon emission capacity from the total carbon emission coefficients. As shown in Table 2, electric and steam supply (sector 14) still tops the list for total carbon emission coefficients, but the gap between electric and steam supply and other sectors is not as huge as the direct carbon coefficients. Other carbon-intensive sectors also have higher values in total carbon emission coefficients, such as coal mining, nonmetal manufacturing, and iron smelt, *etc.* Moreover, the construction sector (sector 15) is another sector that has high potential carbon emission coefficients ranging from 2.8 to 3.8 ton/10^4 Yuan. These sectors can be defined as "potential high carbon-intensive sectors".

If taking both the direct and total carbon emission coefficients into comprehensive analysis, sectors that have higher indirect carbon emissions than direct ones can be detected. Machine manufacturing (sector 10–13) and construction (sector 15) are sectors of this kind with emission multiplier (total carbon emission coefficients divided by direct ones) amounting over 20. The reason for this is the enormous input from carbon-intensive sectors such as electric and steam supply (sector 14), iron smelt (sector 9) and nonmetal manufacturing (sector 8). Therefore, when facing with emission constraints, these sectors should be taken particular consideration.

3.2. Regional Carbon Footprints

Domestic carbon footprints refer to the carbon emissions cause by internal consumption activities from its local production, while total carbon footprints represent the carbon emissions from production of all areas caused by domestic consumption. As shown in Figure 2, the middle region ranks the first in total carbon footprints with an amount of 1188 million ton, followed by the eastern coast region and the northern coast region, which amount 940 million tons and 860 million tons, respectively. Above all, total carbon emissions in these three regions are much higher than the rest. With regard to domestic footprints, the middle region has the highest value in domestic carbon footprints with 674 million tons, while the eastern coast region and the northern coast region both amount approximately 500 million tons, while the least value appears in the capital region with an amount of 79 million tons resulting from the small total output of the entire economy. Besides, the middle region and the eastern region have the largest external carbon footprints—about 514 million tons and 449 million tons, respectively. On the other hand, it is unexceptionally that the capital region becomes the smallest embodied carbon importer, but its ratio between external carbon footprints and domestic carbon footprints of the capital region is 1.7, which makes this region the only area where external carbon footprint is larger than internal one.

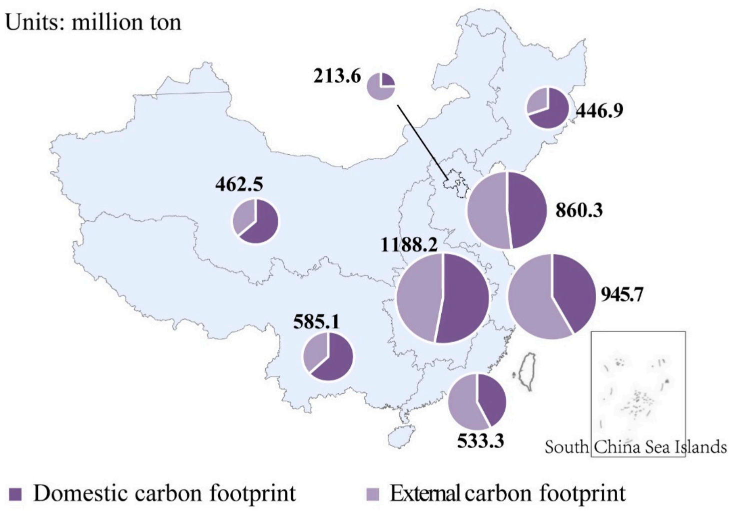

Figure 2. Domestic and total carbon footprints for eight regions.

If dividing the total carbon footprints by population, we can obtain information about this index excluding the impacts from population factor. As shown in Figure 3, the per capita carbon footprints (CFP) differ greatly in the eight regions. The national CFP is 4.03 tons/year (demonstrating in red line in Figure 3), while in the capital region, this indicator increases to 7.77 tons/year, approximately twice the amount of the average one. The eastern coast region, the northern coast region and the northeast region are the rest three areas that have a volume over the average CFP, with amounting 6.5 ton, 5.3 tons and 4.1 tons, respectively. CFP in the southwest region is the lowest among all regions. The value is only 2.4 tons, which may be caused by the consumption structure. More meaningful details can be obtained when decomposing the total sectoral carbon footprints to specific sectors.

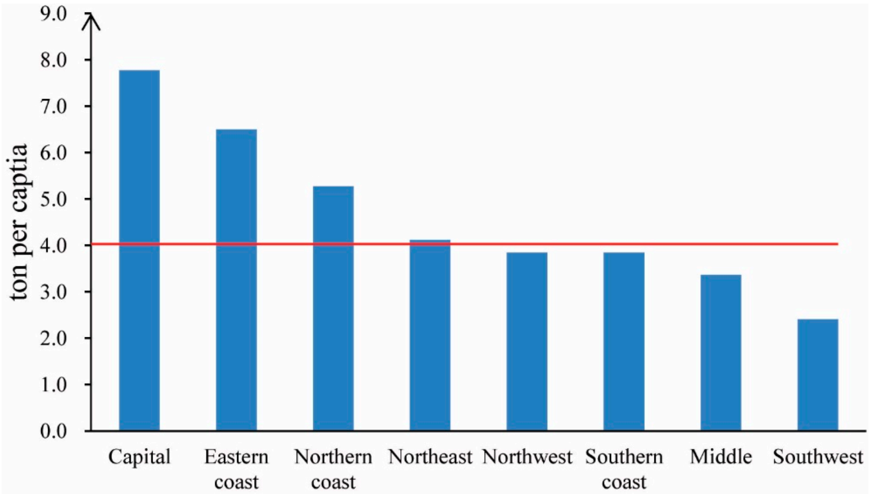

Figure 3. The total carbon emissions by each person in the eight regions and the nation.

Figure 4 displays the sectoral decomposition in total carbon footprints for eight regions. In general, construction, electricity and stream supply, machine manufacturing, transport and warehousing, food manufacturing and other services are the main final carbon emitters. It is interesting to see that the electric/steam supply sector makes up almost 50% of all direct emissions, but in the total carbon footprints, it is only responsible for 10%–20%. The construction sector has the opposite characteristics. Its share in the total carbon footprint can take up to 20%–50%. The reasons are various by sectors. For electric/steam supply sector, it is not surprising because of the high carbon coefficients and the enormous outputs; for industrial sectors such as food manufacturing and machine manufacturing, the high carbon footprints in fact results from the close linkages to sectors with high carbon emissions like electric/steam supply; the reason making construction a main emitter is the quite high fixed capital formation in every province resulting from the prosperous real estate industries.

In spite of the common characteristics they hold, the differences exist among different regions. Carbon footprints of the machine manufacturing sector (including machine, transport, electric manufacturing) are 227 million tons in the northern coast, accounting for over 25% in total industrial emissions. The share is the largest in all regions. The eastern coast region and the middle region show similar features in the sector of iron smelt, which takes up approximately 5% of the industrial carbon footprints, respectively. The electric/stream supply sector in the northwest region takes up 20% in the final carbon emissions. Besides, in the capital region, construction makes up nearly 50% of the total sectoral carbon footprints. It is very unusual when compared to other regions, indicating that the capital region has the highest development level of real estate among all regions. These details about carbon emissions can help identify the sectors that put larger pressures to the environment, thus can support the decision making on carbon emission reduction.

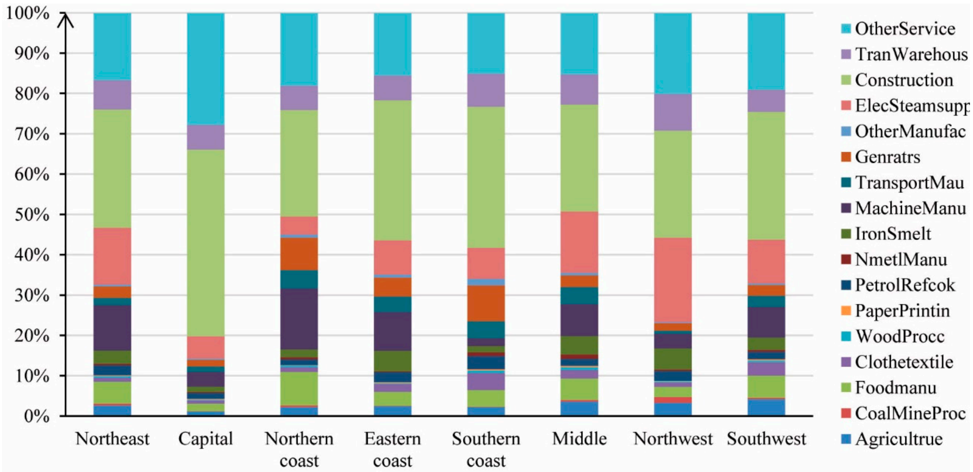

Figure 4. Sectoral decomposition in total carbon footprints of eight regions.

3.3. Embodied Carbon Flows

We visualize the embodied carbon flows in Figure 5. Different colors represent different areas and the width of the line in the circle implies the volume of the flows. A cluster of the same color rooted around the circle represent exported embodied carbon while the various colors represent the imported one. The three bars outside the circle have their respective meanings: the nearest bar show the formation of exported carbon while the middle bar for imported one, the absolute value is recorded around the circle in million tons.

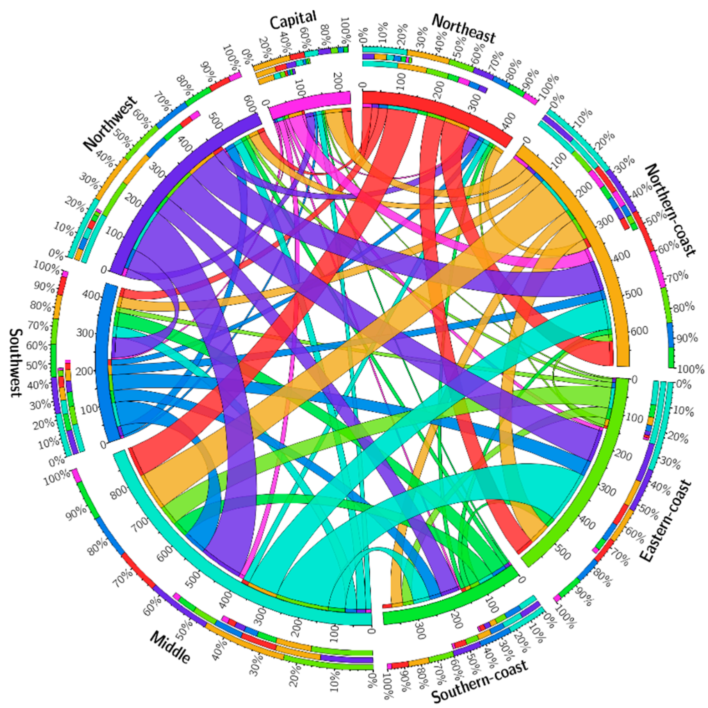

Figure 5. Embodied carbon flows between regions.

Firstly, some large embodied carbon flows can be obtained from Figure 5. The largest flow drifts from the middle region to the eastern coast region with a volume of 152.7 million tons, followed by flow from northwest region and the northern coast region to the middle region, with an amount of 126.0 million tons and 110.1 million tons, respectively. Regarding the total amount, the northwest region, the middle region and the northern coast region are big embodied carbon exporters. Their exporting trades have 473.5 million tons, 384.2 million tons and 342.9 million tons of embodied carbon, respectively. On the other hand, the middle region, the eastern coast region and the northern coast region are the major importers, absorbing 513.9 million tons, 449.4 million tons and 352.1 million tons of virtual carbon, respectively. It is meaningful to find that neighboring regions are more likely to have large flows, while distant regions show the opposite phenomenon, such as middle/eastern coast, northern coast/capital and northwest/middle. If comparing the total imported embodied carbon to the exported one, the northwest region, the northeast region and the southern region are the only three net exporters with an amount of 341.2 million tons, 195.8 million tons, and 18.7 million tons, respectively, while the eastern coast region is the largest net importer at a volume of 302.4 million tons, followed by the middle region (129.7 million tons). In general, the total amount of embodied carbon in trade is 2147 million tons, which make up 41% of all carbon emissions in China.

Furthermore, we separate the flows into sectors to acquire details about the formation of virtual carbon flows, as shown in Figure 6. Generally speaking, construction, machine manufacture, food manufacture, electric manufacture and the sector of other services are the leading contributors in carbon emissions embodied in trades among regions, and construction is the largest contributor—taking up around 20%–53% in all sectors. It indicates that the trade in construction sector may be a key point to the policy of carbon emission reduction.

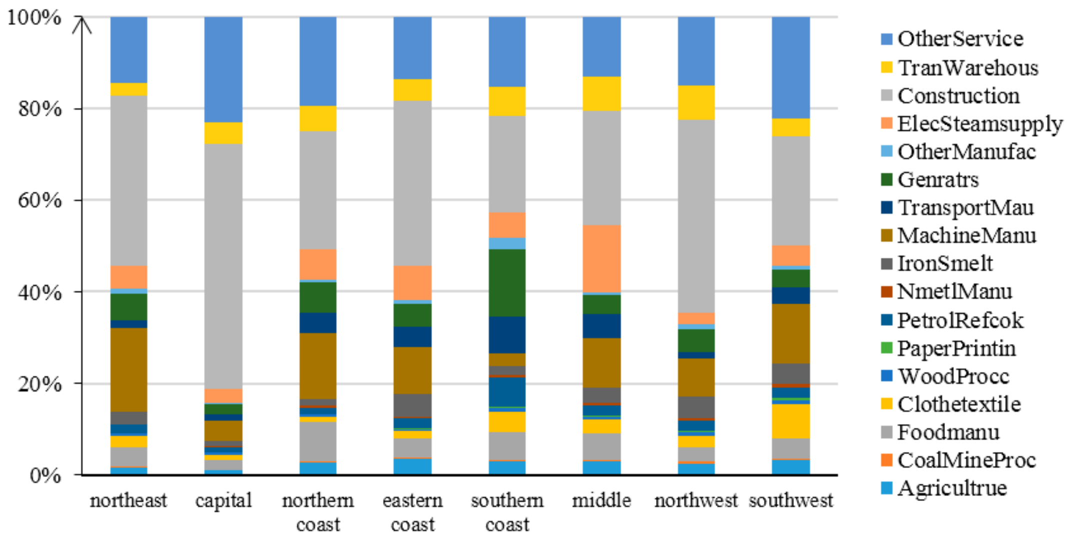

Figure 6. Embodied carbon flows import from each region at sectoral level.

Some significant results can be obtained from the aspect of imported embodied carbon. In the capital region, embodied carbon in the construction sector makes up 53.5% of the total imported carbon, and the tertiary sector also occupies a large part, indicating a strong vitality of housing and construction demand in this region; machine manufacture in the northeast region and the northern region are the major contributors of external embodied carbon; the middle region, which has the largest carbon footprints, absorb 7.5 million tons of virtual carbon through the trades in electric/stream supply sector. With all the detailed information, we now have a clear knowledge of sectoral emissions in trade for every region. Thus we can know which sector should be focused when dealing with interregional carbon emission problems.

3.4. Production-Based Emissions vs. Consumption-Based Emissions

Regional production-based emissions data is intuitive and always used in reports to indicate the domestic regional emissions. However, it is not accurate since that production-based emission is determined by domestic consumption, external consumption and foreign consumption altogether. To the contrary, consumption-based emission can show the real emissions caused by the area. As shown in Figure 7, in the perspective of production-based emissions, the middle region, the northern coast region and the northwest region are the three biggest emitters. Yet in fact, large shares of the emissions are caused by consumption needs from other regions and abroad. Therefore consumption-based emissions can indicate who should be responsible for emissions. The same results for sectoral emissions are illustrated in Figure 8. From the perspective of production-based emissions, electricity/stream supply, iron smelt, nonmetal manufacturing and petroleum processing are the major contributors to carbon emissions, but consumption-based accounting shows that the construction, electricity and stream supply, machine manufacturing, and other services are the main final carbon emitters. When conducting carbon emission reduction policies, it is more practical to put eyes on the large emitters based on consumption-based accounting.

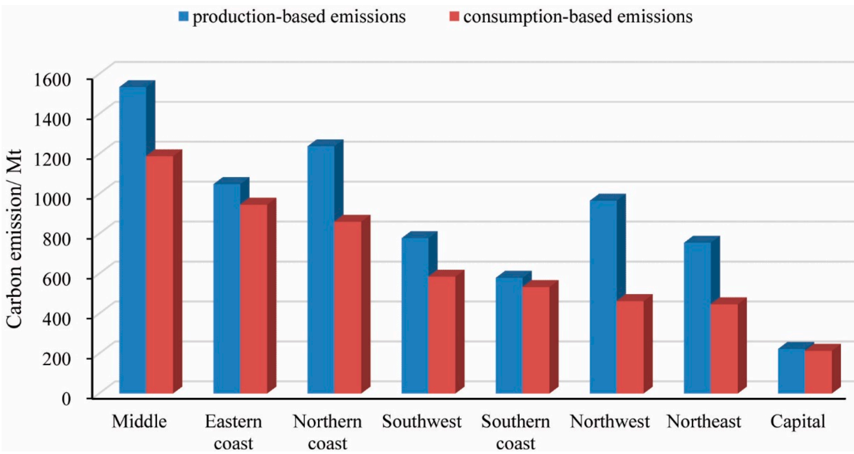

Figure 7. Production-based emissions *vs.* consumption-based emissions in China's eight regions.

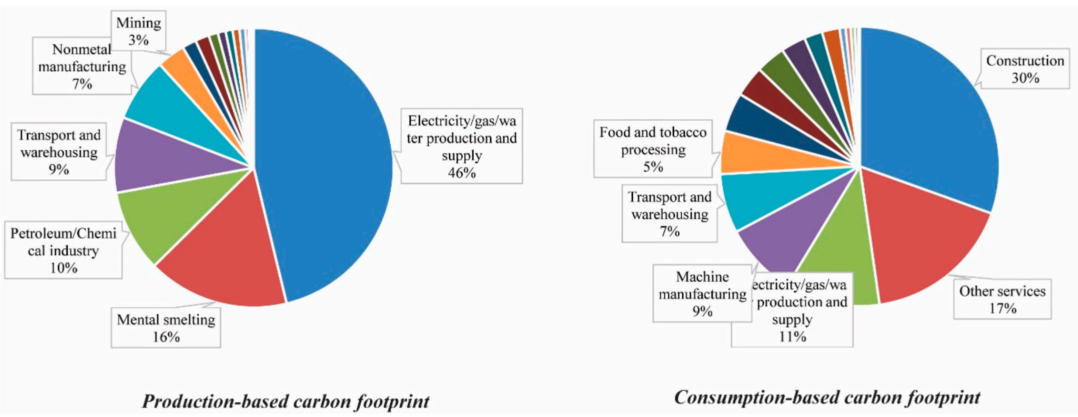

Figure 8. Sectoral production-based emissions *vs.* consumption-based emissions.

3.5. Policy Implication

It can be seen that carbon leakages has occurred between regions inside China just as the global case. Developed regions (as Eastern coast region, Southern coast region) outsourced production activities to less developed regions (as Northwest region) in a low efficient and high carbon way. Outsourcing of this kind can bring effective carbon control in developed regions, but pose huge mitigation pressures to poor regions, and boost the national carbon emission level [47,48]. Thus, in making multi-regional carbon policies such as carbon target allocation, the carbon leakage should be considered. Only after reducing carbon leakage, effective industrial transformation can be achieved.

Moreover, carbon leakage inside China is highly related to the differences of technological level. In regions of China, the labor and infrastructure cost in poor regions are much less than the developed regions, thus driving heavy industries and high carbon emission plants move to middle and western regions, where the technological level is often very backward. Thus, the central government has responsibilities to set up technological funds to encourage highly technology diffusion, and introduce strict carbon emission management approach to moved plants.

Meanwhile, the national carbon emission trade scheme (ETS) provides an effective way to reduce carbon leakage. Under the scheme of carbon emission trade market, carbon emission permits can be traded, thus lowing marginal mitigation costs. If all high carbon emission plants can be managed inside one uniformed system, extra carbon emission caused by plants moving can be avoided. Current ETS pilots are tested in several provinces and cities, and the national ETS should be constructed as soon as possible [49,50].

4. Conclusions

In order to provide specific information for carbon reduction policies in China, we investigate the regional carbon footprints and interregional embodied carbon flows for the eight regions at sectoral level based on a top-down framework of the multi-regional input–output model for the year 2007. This framework allows us to examine the major emitters and the linkages between interrelated regions in carbon emissions.

Carbon emission coefficients calculation can help identify where inefficiency happen. In our study, we find that sectors like electric/steam supply, coal mining, petroleum processing, nonmetal manufacturing, iron smelt and construction appear to emit more carbon dioxide for each unit of monetary output. Within these sectors, some emit carbon dioxide directly as electric/steam supply, nonmetal manufacturing and iron smelt, while some mainly emit indirectly through their upstream sectors along the supply chain, such as construction. This result may have significant meanings to current emission reduction strategies. Current policies mainly focus on the direct carbon emitters but ignoring total carbon emission coefficients from consumption-based perspective, which might lead to the left out of some real carbon-intensive sectors.

Regional carbon footprints at a sectoral level provide a way to access who are the major emitters. The middle region has the highest total carbon footprints with an amount of 1188 million tons, while per capita carbon footprint in the eastern coast region reaches 7.77 ton/year and occupies the first place. When decomposing the total carbon footprints to sectors, we find out that the construction sector takes up the largest part in total footprints, with a proportion of over 30% in most regions, especially in the capital region where this value increases to 50%, while in the study by Hertwich *et al.* [35] construction sector accounted for approximately 10% of the total carbon footprints globally under the same model. In the current economy of China, as the price of houses has not reached its peak, it stimulates the rapid development of the real estate industry, along with the demand for carbon-intensive products like cements, concrete iron and electricity. So when addressing the massive carbon emission problems in China, we should not only focus on carbon-intensive sectors like electric and iron smelt, but also the sector of construction together with other sectors in the supply chain. If the consumption demand can be limited, the emissions from the production side can truly be decreased.

Embodied carbon flows analyses can evaluate the current condition of virtual carbon trades within China, and identify the main sectors in embodied emission flows among different regions. Results show that interregional carbon flows take up 41% of the national carbon emissions, implying large amount of carbon is transferred among sectors and regions. Therefore, when addressing carbon emission reduction issues, it is more practical to focus on the large emitters based on consumption-based accounting, rather than the production-based one.

With the restriction of model and data availabilities, we only considered embodied carbon of domestic trade in this study, while excluding international trade. As a big exporting country, each region in China is highly connected with foreign countries by trades. Thus, it is very necessary to aggregate international trade into this model.

We only considered carbon footprint and embodied carbon caused by domestic trade in this study, however, water footprint and ecological footprint were also very important. Future research can integrate these three indicators and analysis of regional differences in a uniformed system, thus providing a more complete panorama of environment impact caused by domestic trade.

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Author Contributions

Xi Xie and Yongkai Jiang performed research and analyzed the data. Wenjia Cai designed research, analyzed the data and supervised the performing of the research. All authors participated in the writing of the paper. They all read and approved the final manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

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