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Embodied carbon in China's foreign trade: An online SCI-E and SSCI based literature review

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ABSTRACT

This paper systematically presents a survey of the empirical literature studying the embodied CO_2 emissions in China's foreign trade (ECCT). Based on the bibliometric method and the online version of Science Citation Index-Expanded (SCI-E) and Social Sciences Citation Index (SSCI), this study summarizes the latest publications regarding ECCT in peer-reviewed journals in terms of quantities, most productive countries, institutions, authors, citations, and disciplines. By using synthetic analysis of keyword frequency, this study reveals the most popular methodologies applied in measuring ECCT, discusses the variation of numerical results in the literature, and reasons and countermeasures for the results uncertainties. Continuous investigation of the literature releases the methodology employed for measuring ECCT becoming more reasonable and the results more critical. However, the numerical results of ECCT are of great discrepancies within given year by different considerations on methodology specification, accounting principles, and data sources and processing. For instance, the estimates of CO_2 embodied in China's exports changed from 478 Mt to over 3000 Mt and those of in China's imports ranged from 140 Mt to over 1700 Mt in 2007. Therefore, overcoming data inherent limitations and reducing discrepancies among available databases should be urgently considered. The results imply that the prospective research tendencies on ECCT are to (1) improve China's regional input-output data and energy intensity data to more precise estimates under global perspective; (2) estimate China's carbon emission at firm level by different firm ownerships in production and consumption worldwide; (3) assess China's carbon emission from processing or non-processing trade by compiling more detailed multi-regional input-output table; (4) evaluate city level carbon mitigation capacity in China under global MRIO model; (5) explore new carbon management experience in China's carbon trading market and new trade expansion policy of '*one belt and one road*' in her new growth era.

1. Introduction

Climate change has been widely recognized as the global major environmental issue. Whether the global warming is an anthropogenic phenomenon or not is impossible to justify nowadays. However, it is obvious that the atmosphere has been undergoing a tremendous surge of CO_2 from the global industrialization. The anthropogenic greenhouse gases (GHGs) emissions are the main cause of global climate change according to Intergovernmental Panel on Climate Change (IPCC) [1,2]. Embodied carbon in international trade plays a crucial role in international negotiation on global climate change [3]. With the research outputs expanding substantially in recent years, embodied

Abbreviations and definitions: ECCT, Embodied CO_2 emissions in China's foreign trade; PBE, Production-based CO_2 emissions; CBE, Consumption-based CO_2 emissions; EEE, Embodied CO_2 emissions in the exports from an economy; EEI, Embodied CO_2 emissions in the imports from an economy; EEB, Balance of embodied CO_2 emissions in international trade from an economy; EE-IOA, Environmentally extended input-output analysis; EEEP, Ratio of the EEE out of the PBE; EEIP, Ratio of the EEI out of the PBE; EEBP, Ratio of the EEB out of the PBE; ETS, Emission trading system; SCI-E, Science Citation Index-Expanded; SSCI, Social Sciences Citation Index; GVCs, Global value chains; MT, Million tonnes; SRIO, Single region input-output model; BTIO, Bilateral trade input-output model; MRIO, Multi-region input-output model; CGE, Computable general equilibrium model; SDA, Structural decomposition analysis; IDA, Index decomposition analysis; SPD, Structural path decomposition; LCA, Life cycle analysis; PA, Price adjustment method; RME, Raw material equivalents; PPP, Purchasing power parity; MER, Market exchange rate

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carbon in China's foreign trade (ECCT) has attracted a growing attention globally. Although China's carbon emissions declined from 2013 because of many carbon mitigation implements recently [4], for example, China dropped 2% and 3% carbon emission in 2014 and 2015 respectively since 2001 [5], being the top CO_2 emitter with huge economy amounts and high growth rates [6], China still took up 23.43% of global CO_2 emissions in 2014 [7]. Besides, China's coal consumption fell 2.9% and weakened by 3.8% in 2014 which is the lowest value since 1998 because of the expanding of Chinese economy at the slowest rate since 1990 [8]. Up to 90% of carbon emission were from fossil fuel combustion, in which coal took up over 60% in China, and over 85% of carbon emissions were produced by power generation and manufacturing sectors in 2012 [9,10].

As an ambitious country in curbing carbon emission, China had pledged to achieve her peak of carbon emission around 2030 by reducing nearly 65% carbon intensity comparing to 2005 levels and made her best utmost to peak early. China also planned to raise the ratio of non-fossil fuels in primary energy to 20% [11]. The US and China as two huge economies worldwide had reaffirmed the importance of strengthening bilateral cooperation in global climate change [12]. Furthermore, after COP 21 in 2015, they have been applying great efforts to bring Paris climate accord into force with more than 55 governments covering 55% of carbon emissions included to keep the warming tendency under agreed target of 2 C. China (20%), the US (18%), India (14%) and EU (12%) are collectively accounting for over 60% of global carbon emissions and China and the US pursue to limit global warming to 1.5 C [13]. However, as the precondition, given the uncertainties existing in national carbon emission and international carbon leakage, it is important to establish an understandable, acceptable and rational scheme on precise quantification of carbon among countries to establish global carbon emissions mitigation in order to conduct international commitment on carbon reduction under the principle of common but differentiated responsibilities and respective capabilities [14].

with the new developments on carbon mitigation cooperation from rest of world, for example, the 2030 targets and ETS reform in EU, the cooperation in US and Canada on methane emission cut in oil and gas sectors by nearly 45% in 2025 comparing to 2012 levels, and the Green climate found projects [15], China has implemented many strategies to reduce her carbon emissions, for example, the US-China climate leaders summit in 2015 and a series of native targets in China's 11th-12th Five-Year Plan (2006–2015). Under great pressure in environmental cost especially carbon emissions from consumption of fossil fuel, China's 13th Five-Year Plan (2016–2020) announces 5 billion metric tons of coal equivalent energy consumption cap [16] and plans to reduce energy intensity and carbon intensity by 15% and 18% respectively, five-sixths of which will be achieved by improving energy efficiency and shifting the industry structure from heavy to less energy-intensive sectors and one-sixth by renewable and nuclear energy [17]. Although coal demand in China dropped for continuous second year in 2015 (64%, comparatively reduced 3.7% in 2014 and 10% in 2011) with the growth rate of economy slowing down which may leads to China exceed her carbon target in 2020 by 10% [18], to balance regional economic growth and energy consumption reduction in China, the carbon reduction strategies should response to regional unbalance on economic developments, for example, the vast gap on per capita carbon emission and carbon emission intensity between developed regions like east coast and undeveloped regions from the north west [19], the energy consumption structure and energy density, and regional industry distribution in China [20,21]. As one of the effective carbon mitigation schemes being implemented in EU and the USA, China's carbon emission trading market will expand from the current seven pilots to nation level by 2017, and will encompass six industrial sectors as planed during China's 13th Five-Year Plan [22]. The establishment of carbon trading market in China could monitor and control carbon emission effectively for specific regions and industries as an important supplementary of the carbon tax and subsidies in China [23]. In sum, the individual carbon emissions should be measured initially to distribute the carbon responsibilities among regions in China as well as China and her trade partners. Given the fluctuation of the estimates on carbon emission for China in the literature, it is therefore crucial to systematically review the methods, data and principles during calculating carbon emission from the literature to more reasonable carbon evaluation framework [24].

As the largest developing country and top energy user in the world [25] whose carbon emission equals to the total emission from the US and the EU during 20121950–2012 [9], there is no doubt that China should be actively responsible for global climate change. However, to obtain more rational and effective climate policies for China or worldwide, some problems should be considered firstly – How much should China be charged for the global carbon emissions? How to define and measure the carbon responsibilities reasonably for one country? Should we suspect the current international principles calculating carbon emissions responsibility? How does the foreign demand contribute to China's carbon emissions? What makes China to be the top carbon emitter? Who should be responsible for CO_2 emissions embodied in China's foreign trade? How to divide the carbon emission produced from China and her trade partners? As is known, the satisfied answer should be obtained from China and her trade partners rather than China *per se* because of the increasing global economy integration, fragmentation of production and global value chains (GVCs). To answer the questions mentioned above, publications have shown a dramatic boom on quantitatively investigating China's embodied carbon in trade especially the balance of the embodied emissions for China [26–32]. With different motivations, data processing and models designing, the existed empirical studies on ECCT are with large variability. To obtain consistent empirical results of China's embodied carbon emissions; it is necessary to make a survey on researches of ECCT, compare the quantitative results and trace the results uncertainties systematically.

The ECCT has been surveyed in previous review studies with different perspectives, such as setting China along with other countries together to investigate China's carbon emissions; and integrating carbon emissions with other China's environmental issues. Liu and Wang [33] analyzed the CO_2 embodiment in international trade based on the quantitative literatures, and they confirmed an obvious imbalance of net CO_2 embodiment in goods trade between major developed countries and emerging economies. China is a net carbon exporting country in 1997–2006. Sato [34] reviewed the quantitative results of embodied carbon in international trade for some countries (China, the USA, Japan, the UK, Denmark, Brazil, and India) to compare and discuss the methodological and data issues contributing to the variability of the results covering over 50 papers. The quantitative results of ECCT had been listed along with other countries in this survey with a worldwide perspective; it's therefore not a specialized study of ECCT. Nejat and Jomehzadeh [35] reviewed the researches of the status and current trends of energy consumption, CO_2 emissions and energy policies in the residential sector, both globally and in 10 countries (China, the US, India, Russia, Japan, Germany, South Korea, Canada, Iran, and the UK). Hawkins and Ma [36] surveyed the studies of Chinese environmental issues using environmentally extended input-output analysis (EE-IOA), the results show that the EE-IOA is used to study the issues like energy, CO_2 and land use in China, and a large number of publications are on China's carbon emissions.

The bibliometric approach, as a powerful tool to explore, organize and analyze a large amount of information in a quantitative manner [37], has been widely applied to measure the development of a certain research field [38–41]. Zhang and Wang [42] evaluated the wetland research between 1991 and 2008 based on the Science Citation Index (SCI) published by the Institute of Scientific Information (ISI) using an effective bibliometric analysis. Fu and Ho [43] applied the bibliometric analysis to study the solid waste research to evaluate the current trends, using the literature in the SCI database from 1993 to 2008. Ferenhof and Vignochi [44] using bibliometrics studied the aspects of environmental management systems in small and medium enterprises incorporating their production processes based on scientific publications.

Recently, bibliometric analysis was used to review the research field of climate change, carbon emissions, EE-IOA and environmental topics for single country or worldwide. Wei and Mi [45] utilized the bibliometric method on climate policy modeling based on the online version of SCI-E from 1981 to 2013 and SSCI from 2002 to 2013 and summarized several hot research topics and methodologies in this field. Hawkins and Ma [36] applied the bibliometric analysis to survey the published articles regarding EE-IOA for China in peer-reviewed journals and provided a comprehensive overview of the body of literature. They examined the research impact, environmental issues addressed, and data utilized on the basis of online SCI-E and the SSCI. Mao and Liu [46] depicted existing research activities and future directions of alternative energy based on the SCI-E and the SSCI by bibliometrics.

The main purposes of this study are firstly to survey the quantitative results of the ECCT from the existed empirical studies; secondly study the involved methodologies and the variation of the quantitative results, thirdly track the potential issues and strategies of the results uncertainties. We focus on the ECCT rather than all the China' environmental issues studied by EE-IOA comparing with the work of Hawkins and Ma [36]. Furthermore, *vis-a-vis* the research by Sato [34], we particularly review and compare the variation of the ECCT with respect to more updated literature and discrepancies (for example, the data collecting and processing, the regional economic imbalance on carbon emissions) in measuring ECCT. It should be noted that, as far as we know, such a single survey focusing on ECCT has not been summarized yet.

The rest of the article is structured as follows. Section 2 provides the methodologies in searching for the existed studies on the issue of ECCT in the SCI-E and SSCI database. Section 3 describes the latest research by bibliometric analysis including quantities statistics, journals statistics, authors' statistics, institutions statistics, article citations statistics, and disciplines statistics. Section 4 presents a summary of the involved methodologies, accounting principles, and data sources, the variability of the empirical results on ECCT obtained by keyword frequency analysis, and then the potential reasons and strategies for such uncertainties are discussed. Section 5 releases some concluding remarks on future further research point of this field.

2. Methodology

The data in this study are obtained from the online version of SCI-E from 1981 to 2015 and SSCI from 2002 to 2015 from Web of Science. The updated searching date is September 1st, 2016. Although China's year of opening to the world economy was in 1978, we set the beginning year in 1981 when China's input-output data were available [47,48]. It is notable that only studies on embodied carbon in China's foreign trade from English peer-reviewed journals are collected. It should be noted that besides the literature from Chinese mainland, literature from Hong Kong after June 1997 and Macao after December 1999 are included in this study. Literature from Chinese Taiwan province are excluded.

Defining which articles should be included is important in this study. We firstly searched by keyword, title and abstract to lock the key journals, organizations and countries in this field, and secondly paid attention to the authors and references of the key papers with high citations. Following the method referred by Hoekstra [49], we obtained the articles by the descriptors of "embodied carbon", "China", "international trade or foreign trade", "policy or policies" and "Input-output analysis or models". The corrigenda, errata, announcements and books referring to economic impacts of environmental issues and environmental accounts structure and construction were excluded. Besides, papers discussing Chinese energy intensity or domestic carbon emissions were also excluded, and those calculating the global carbon flows and leakage referring to China were included.

To investigate the differences of the results, the frequency analysis of keyword was used to discover the keyword containing the empirical results (for example EEE and EEI) in the abstract, contexts and their references. Fig. 1 shows the research framework of this study. We firstly obtained the results by frequencies of keywords for each year and key authors; secondly, we summarized the results by publishing year, methodologies, data used; ultimately, we detailedly discussed the variability of the empirical results, and reasons and strategies of the uncertainties to get more reasonable results for ECCT.

3. Literature overview

3.1. General statistics

According to the results, there are 317 articles referring to the issue of ECCT. Especially, a significant recent boom on ECCT was released from 2010 to 2015 in the literature (see Fig. 2). From the growth rate of the publications recently, we could find that embodied carbon between China and other economies all over the world has been the hot topic since China's becoming the top carbon emitter in 2007. While with the available of the input-output database from GTAP, OECD, WIOD as well as Chinese government, the way of measurement of carbon emissions and the controversies on international carbon responsibilities have been lasting for nearly a decade with no effective results. Studies on multi-dimensional analysis on ECCT, for example, the accuracy of energy intensity, the regional input-output data, the

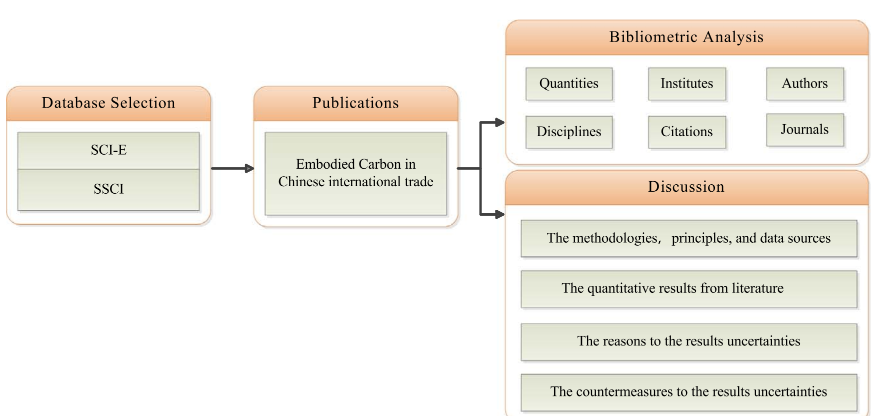


Fig. 1. The research framework of this paper.

regional carbon intensity, the trade benefit and environmental cost comparison, have been published in top journals like nature [21,50,51] and nature climate change [20,52] recently, which implies the important role of confronting China's carbon emission to the world carbon mitigation.

Fig. 3 illustrates the number of publications and the percentage of most productive countries in global level on ECCT. We could find that China was significantly the most productive country out of the top six countries. Different from the previous studies, we herein not only showed the worldwide timeline of papers (see Fig. 2), but also illustrated the quantities and dramatic increase of papers from China being the dominant country in this research field all over the world (see Figs. 3 and 4). We can also knew that over 20% publications from USA and England focused on China's embodied emissions in foreign trade. It could be concluded that the focus of the carbon responsibility allocation in the international climate change negotiation are mostly locked in the top emitter - China, and top carbon consumers - the USA, England and Japan. The research tendency from China shown in Fig. 3 indicates that China per se has been gradually raising the financial supporting on carbon mitigation research field in the past decade.

The academic development of studying on ECCT in China are plotted in Fig. 4 which could be divided into two stages. Stage 1 was from 1981 to 2009 in which the number of publications was few and stable, and the stage 2 was from 2010 to 2015 in which the number of academic publications increased with a high growing rate. The result shown in Fig. 3 was lower than the result in Hawkins and Ma [36], because this study just obtained papers related to ECCT but Hawkins and Ma [36] collected the whole publications using the EE-IOA method to China. In addition, the number of publications covered in this study focusing on ECCT is more helpful to investigate the variability of numerical results for ECCT from literature than Sato [34] who compared the quantitative results of embodied carbon in trade with a worldwide perspective. Comparing with the results in Fig. 2, it could be found that the international research cooperation in the past five years resulted in the growing tendency of publications of China and more and more oversea scholars showed their interests on the carbon emission and related climate change issues on China.

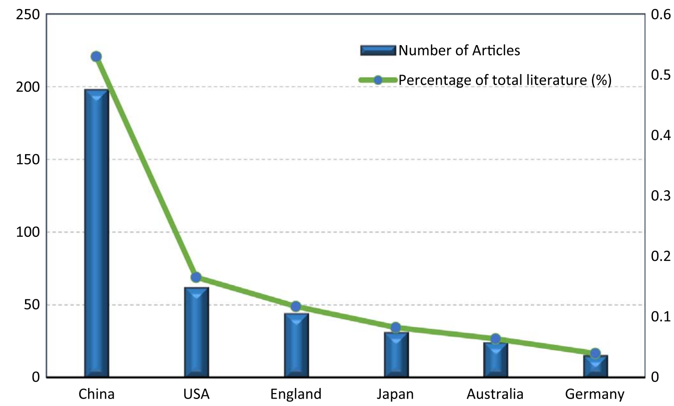


Fig. 3. The most productive countries on ECCT. Note: numbers of articles and their proportions in global publications for the top six countries.

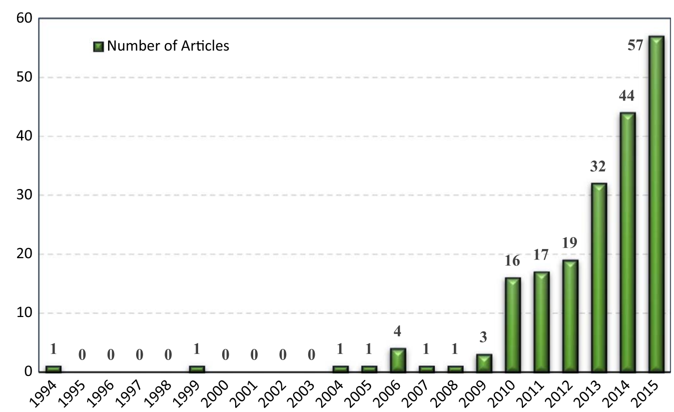


Fig. 4. The timeline of 198 ECCT articles from China. Note: This figure begins in 1994 since there is no publication on ECCT during 19931981–1993 and data are updated to 2015.

3.2. Journals statistics

According to the top 10 journals that have the most publications in the field of ECCT, four are from Netherlands, three are from the USA, and two are from the UK and only one from China (see Table 1). All the journals are originally on issue of environmental sciences, energy consumptions, emissions and environmental engineering. The top three journals (Energy Policy, Renewable & Sustainable Energy Reviews and Journal of Cleaner Production), as the most productive journals, had published 26% papers on the embodied carbon emissions from China from 1994 to 2015. From perspective of changes in impact factor of these journals, we found that most of the journals were with a positive growth rate except journals of Ecological Indicators and Ecological Modeling. The impact factor of Renewable & Sustainable Energy Reviews was with the most highly growth rate in the past decade which indicates its increasing importance as top journal in this research field.

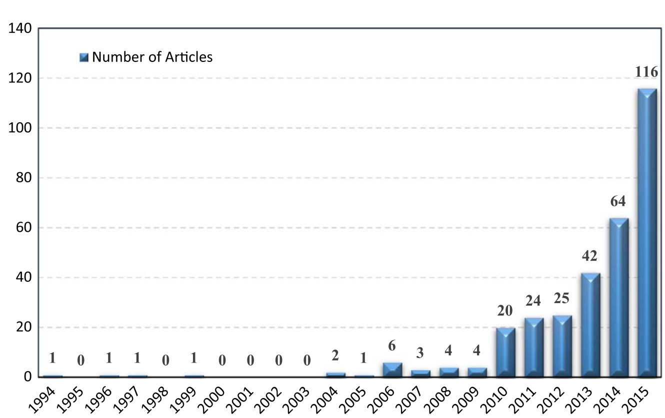


Fig. 2. The timeline of publications on ECCT. Note: This figure begins in 1994 since there is no publications on ECCT during 1981–1993.

3.3. Authors statistics

The top 10 most productive authors in the field of ECCT are listed in Table 2. We could know that the productive authors are from China mostly, but the citation results (see Table 4) shows that the highly cited paper are from other countries. The results show that Chen GQ from Peking University has published 26 papers being the most productive author in this field with the highest H-index. Chen GQ and Chen ZM are in the same lab named State Key Laboratory for Turbulence and Complex System in the Peking University. According to the results, top academic centers in China are sponsored by research foundations from Chinese governments (see Table 3). We also can see that the embodied carbon emissions in China have been studied by scholars from Singapore and England in Table 2, which indicates that the increasing attention to China's carbon emission in international trade and its role of mitigating carbon content during economic activities has been treated as an important global issue recently.

Table 1
Top 10 journals publishing articles on ECCT.
Source: Authors.

	Journal	NA[a]	P[b]	IF[c]	C[d]	Subject categories
1	Energy Policy	40	12.62	3.045	UK	Energy, Environmental studies
2	Renewable & Sustainable Energy Reviews	27	8.52	6.798	USA	Resources, Environmental impacts, Emissions
3	Journal of Cleaner Production	16	5.05	4.959	USA	Environmental sciences
4	Environmental Science & Technology	15	4.73	5.939	USA	Environmental sciences, Environmental engineering
5	Frontiers of Earth Science	14	4.42	0.760	China	Geosciences, Multidisciplinary
6	Energy Economics	13	4.10	3.025	Netherlands	Ecology, Environmental sciences
7	Energy	12	3.79	4.292	UK	Energy engineering
8	Communications in Nonlinear Science and Numerical Simulation	11	3.47	2.834	Netherlands	Mathematics, Interdisciplinary applications
9	Ecological Indicators	9	2.84	3.190	Netherlands	Resources and Environmental policies
10	Ecological Modeling	9	2.84	2.275	Netherlands	Ecosystems , Environmental pollution

Notes:
[a] NA is the number of articles published in current journal.
[b] P is the ratio of papers published in current journal out of all publications.
[c] IF is the impact factor in 2015.
[d] C is country that the journal being located.

Table 2
Top 10 productive authors on ECCT.
Source: Authors.

	Author	C[a]	NA[b]	NC[c]	P[d]	*H*-index[e]
1	CHEN GQ	China	26	575	22.12	16
2	CHEN ZM	China	24	462	19.25	16
3	LI JS	China	15	124	8.27	6
4	SHAO L	China	13	177	13.62	8
5	GUO S	China	13	106	8.15	6
6	CHEN B	China	11	112	10.18	7
7	ZHANG B	China	10	254	25.40	5
8	SU B	Singapore	9	256	28.44	7
8	GUAN DB	England	9	192	21.33	6
9	ANG BW	Singapore	7	238	34.00	7

Notes.
[a] C indicates country that the author's institution being located.
[b] NA means number of articles published by this author.
[c] NC means total citations of the author in this field.
[d] P is number of citations per paper.
[e] *H-index* is based on the number of papers of one author that are collected from the total publications in this study rather than the total number of papers published by the author to investigate the productivity and influence of one author in field of ECCT.

Table 3
Top 10 productive institutions on ECCT.
Source: Authors.

	Institution	T[a]	C[b]	NA[c]	P[d]
1	University of Chinese Academy of Sciences	Governmental organization	China	46	14.51
2	Peking University	University	China	39	12.30
3	Beijing Normal University	University	China	22	6.94
4	Renmin University of China	University	China	18	5.68
5	Tsing Hua University	University	China	12	3.79
6	National University of Singapore	University	Singapore	9	2.84
7	University of Leeds	University	UK	9	2.84
8	Harvard University	University	USA	7	2.21
9	University of Cambridge	University	UK	6	1.89
10	University of London	University	UK	5	1.58

Notes.
[a] T indicates type of institution.
[b] C indicates country that institution being located.
[c] NA means total number of articles from the current institution.
[d] P indicates percentage (%) of papers published by current institution to all the literature.

3.4. Institutions statistics

According to our results, there are nearly 100 different institutions showing research interest in this field around the world. University of Chinese Academy of Sciences is the top institution with a number of 46 productions (see Table 3). Besides, academic centers from China have taken up over half of the research centers and 60% publications out of the total publications on ECCT. It indicates that institutions from China have the exclusive research position among all the involved think tanks in the world. Considering the hot debate on how to curb climate change as a political and economic problems globally as well as China's status of world factory in the past two decades, it could be deduced that China's role in cleaner production and environmental protection become more important recently. Therefore, more institutions from top academic organizations have studied issues on China's carbon emission. As shown in Table 3, Institutions from the UK (University of Leeds, University of London and University of Cambridge) published 20 papers, and there are 16 papers from National University of Singapore and Harvard University.

3.5. Article citation statistics

The top ten most cited articles in the body of literature along with the journals involved and the time of the citations and countries addressed are shown in Table 4[1]. We summarized the important papers in this field with over 200 time's citation in this table. The most highly cited article was from Peters and Hertwich [3] and published in Environmental Science & Technology with 824 citations. Followed by article co-authored by Davis and Caleira [27] from the Department of Global Ecology in Stanford University and published in Proceedings of the National Academy of Science of the United States of America which was cited 719 times. The earliest work in this field by Wyckoff and Roop published in Energy policy had been cited nearly 400 times. Three studies from China had been cited over 200 times which

[1] The processing of self citation during bibliometric analysis are debatable and divergent up to now. The problem of self citation during processing the citation data for scholars could not be avoided completely in this study to keep the intact sense of the bibliometrics. Necessary (not intentional) self citation could be acceptable in bibliometric analysis. As explained by Aksnes [60] and Wolfgang et al. [61], reasonable self citation in the literature is rational and with little influence in measuring the citation times. The articles with high citations in this table are purposed to distinguish papers with high citations against other papers in this field, in other words, it is not to rank the citation of the publications but to just show publications with higher level here [62]. It is not appropriate to omit all the self citation case in special circumstance in bibliometrics. Moreover, a reasonable self citations are understandable and acceptable. To increase the implication and status in a specific research field, researchers in the same group or laboratory sharing a systematic research topics, usually cite theirs previous published papers to make some new contributions in their research field [63].

represented that studies from China has regularly performed theirs important role in this field worldwide. In addition, the boom of the literature citation from the results released that with China's being the top carbon emitter in the world [53] and the most important contributor to global climate change [54], embodied carbon from China has become a popular topic in the past decade [28,30,53–59].

3.6. Disciplines statistics

The study of ECCT is an interdisciplinary subject. From the SCI-E and SSCI database, over thirty subject categories are related to this topic. They can be divided into Environmental sociology ecology, Energy fuels, Business economics, Engineering, Science technology other topics, Geology and others. Publications from discipline of environmental sociology ecology, such as [28,64,67], account for 51.89% of the all publications (see Table 5). From the top disciplines, we could conclude that the phenomenon of inter-discipline are existed in this research field, for example, papers from the top journals are produced with Economy, Environment, Physics, Meteorology and Mathematics background recently. Moreover, the further detailed research could be launched than before since the development of the computing technologies, the cooperation established among disciplines makes the possibilities of deep investigation and research in integrated model on ECCT presently.

4. Discussion

4.1. The involved methodologies

From the literature, the input-output analysis [68–70] introduced in 1930s and latterly extended to EE-IOA [71,72], is dominant analysis method to analyze the environmental issues especially energy-related carbon emissions in China. As a systematical environmental analysis model, EE-IOA is popular to measure the ECCT in the past decade. By the results of the keyword frequency analysis, we found that the single region input-output (SRIO) model, bilateral trade input-output (BTIO) model, and multi-region input-output (MRIO) model are the top three models applied to enumerate China's embodied carbon in trade. Besides, the computable general equilibrium (CGE), the physical IO [73,74], the life cycle analysis (LCA) [75–77], and the hybrid MRIO-LCA [78–80] are also applied widely.

These methodologies, being complementary to some extent, provide different angles on the quantification of ECCT. Fig. 5 plots the strengths and caveats of the major strands of research methods that map and measure the embodied carbon in Chinese foreign trade. Firstly, the x-axis indicates the complexity of data sources demanded to carry out the assessment; secondly, the y-axis refers to the accuracy of the resulting quantification, in other words, to what extent the precision of such measure of embodied carbons aiming to assess; thirdly, the size of the circle represents the coverage of the assessment which means to what extent the content of the measure encompasses the dimension of the research field. Each dimension is from 0 to 1, higher values mean more complex data, and a more accurate final measure respectively. It is important to note that there are also many papers combining EE-IOA with the SDA [81–83], or IDA [84–86] to investigate the driving forces of the embodied carbon in international trade has been published.

The difference among the SRIO, BTIO and MRIO method on enumerating CO_2 emission is summarized in Table 6 and the timeline of the main researches on ECCT by using SRIO, BTIO and MRIO model are illustrated in Fig. 7. The SRIO analysis, assuming that imported goods and services are being produced with the same technology as the domestic products, is usually employed to measure embodied emissions connected to the total consumption for one country or region with the rest of world. Lin and Polenske [47] firstly explained China's energy use changes between 1981 and 1987 by using SRIO model and SDA in 1995. They argued that energy saving during research periods originally came from changes in production technology rather than changes in final demand shifts in China and the energy intensity decline since the energy efficiency improvements. Peters and Weber [63] analyzed how China's carbon emissions changed with her technologies, economic structure, and lifestyles by using the SRIO and SDA method. They found that China's production-related CO_2 emissions

Table 5
Top 6 hot disciplines on ECCT.
Source: Authors.

	Discipline	NA[a]	P[b]
1	Environmental sociology ecology	110	51.89%
2	Energy fuels	68	32.08%
3	Business economics	61	28.77%
4	Engineering	61	28.77%
5	Science technology other topics	12	5.66%
6	Geology	10	4.72%

Notes.
[a] NA means total number of articles from the current discipline.
[b] P means percentage (%) of papers published by the current discipline to all publications in the literature. Some articles are contained within one more disciplines, for the characteristic of interdisciplinary in the literature, by the web of knowledge, therefore the summation of the number of articles are not equal to total literature, and the summation of the percentage are over one.

Table 4
Highly cited articles on ECCT.
Source: Authors.

	Author	Ref.	Year	Journal	TC[a]	C[b]
1	Peters and Hertwich	[3]	2008	Environmental science & technology	824	Norway
2	Davis and Caldeira	[27]	2010	Proceedings of the National Academy of Science of the United States of America	719	USA
3	Weber et al.	[60]	2008	Energy Policy	464	USA
4	Ahmad and Wyckoff	[26]	2003	OECD publishing	437	Paris
5	Shui and Harriss	[30]	2006	Energy Policy	410	USA
6	Wiedmann	[61]	2009	Ecological Economics	498	England
7	Wyckoff and Roop	[62]	1994	Energy Policy	387	Paris
8	Peters et al.	[63]	2007	Environmental Science & Technology	363	Norway
9	Weber and Matthews	[64]	2007	Environmental Science & Technology	270	USA
10	Lin and Sun	[28]	2010	Energy Policy	214	China
11	Yan and Yang	[65]	2010	Energy Policy	212	China
12	Pan et al.	[29]	2008	Oxford Review of Economic Policy	208	China
13	Li and Hewitt	[66]	2008	Energy Policy	206	England

Notes.
[a] TC is total citations indicating the times cited in Web of Science Core Collection.
[b] C indicates country referring to the institution location of the first author.

increased by 59% from 2163 million metric tons (MMT) to 3440 MMT from 1992 to 2002, and the net trade had a small but significant effect on China's total emissions since equal growths in emissions from the production of exports and emissions avoided by imports. The efficiency improvements offset consumption growth partially and improving both production and consumption systems can reduce emissions potentially.

The BTIO model, considering the variability of CO_2 emission factor from different countries and decomposing international trade by trading partners, is mainly used to enumerate the carbon emissions induced by consumption abroad between trade partners for single country or region. Comparing to SRIO method, BTIO can get more accurate results by relaxing the import substitution assumption. Shui and Harriss [30] estimated the CO_2 embodiment in US-China trade during 1997–2000. By using data from the US Census Bureau, the CO_2 emission factor for US exports to China from the economic IO-LCA software developed by Green Design Initiative at Carnegie Mellon University, and the corrected CO_2 emission factor for Chinese exports to the US, they found that the CO_2 emission increase by 3% if the imported goods from China produced in the US and up to 14% CO_2 emitted by China for exporting to the US. In light of Shui and Harriss [30], the embodied emissions in China-UK trade was examined by Li and Hewitt [66], they released that the UK avoided 69 MT CO_2 emission since importing goods from China in 2004, and it means 186 MT CO_2 emission in China due to great carbon intensity of Chinese industry. The UK had exported 2.3 MT CO_2 to China in the same year. Besides, the sea transport of goods between the UK and China resulted in 10 Mt of CO_2 reducing globally in 2004. Su and Ang [87] employed the BTIO (EEBT) model and hybrid emissions embodied in trade (HEET) approach to examine the impact of the spatial aggregation on the estimates of the ECCT.

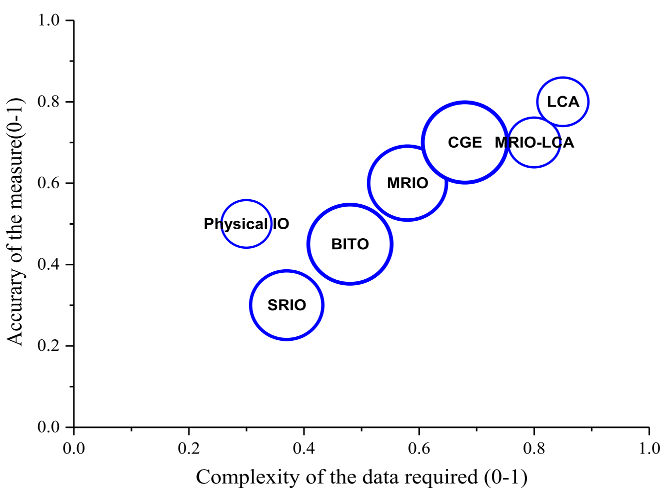


Fig. 5. The methodologies of measuring ECCT in literature. Notes: The size of the circles represents the coverage of each measure relatively to the size of embodied carbon in international trade, with larger circles standing for higher coverage. The x-axis (from 0 to 1) corresponds to the complexity of data required to compute the measure, with lower value indicates the lower complexity of the data required, and the y-axis (from 0 to 1) stands for the accuracy of the results, with higher value indicates the higher accuracy of the quantitative results.
Source: Authors.

Table 6
A brief comparison of the SRIO, BTIO and MRIO method on ECCT.
Source: Authors.

Criteria	SRIO	BTIO	MRIO
Method boundary	Domestic/RoW	Domestic/ partners	Global
Model Scale	Meso	Macro	Macro
Demander	Total consumption	Total consumption	Final consumption
Assumptions	Serious	Moderate	Relax
Data requirement	Low	Moderate	High
Data requirement for Bilateral trade	None	Based on total demand	Based on intermediate and final demand
Aggregation degree	Low	Low	High
Application scale	Single Country	Main trade partners	Worldwide
Complexity	Low	Moderate	High
Re-export	Exclude	Exclude	Include
Transparency	High	High	High
Accuracy	Low	Moderate	High
Feedback effects	No	Yes	Yes
Policy implications	Low	High	High

Note: Row indicates the rest of the world.

The MRIO model, distinguishing the direction of imported goods from the intermediate inputs and final consumption endogenously, can perfectly capture the re-exported products and the feedback effects to track complete carbon footprint at national and supranational level [61]. From the keyword frequency analysis, a large number of papers applied the MRIO model to study ECCT especially in the latest decade. Liang and Fan [100] established a MRIO model for Chinese energy use and CO_2 emission by dividing China into eight regions. Their results revealed that population growth significantly affected both of the energy requirements in and out of the regions itself. They found relative errors between emissions caused and emitted by a region is significant, and hence different identification of responsibility would result in different impacts in China's environmental policy reform. Weber et al. evaluated China's contribution to global climate change. They argued that 33% (1700 Mt) of China's domestic CO_2 emissions in 2005 were exported which increased from 12% (230 Mt) in 1987 steadily. The growth rate of China's total emissions was lower than that of the exported emissions in 2002–2005. Davis and Caldeira [27] examined the global carbon flows based on GTAP-7 and released that 23% (6.2 GT) of global CO_2 emissions primarily from China exported to developed countries in 2004. Su and Ang [101] analyzed the feedback effects by using a MRIO model and the data of Asian international input–output table 2000 [102]. They noted that the results of MRIO were lower than those of BTIO. In addition, China emitted 2655.8 Mt CO_2 emissions under the MRIO, but 2670.1 Mt CO_2 emissions based on the consumption-based principles by considering the feedback effects. With sector classification more detailed and better coverage of world economies, such estimation for carbon emissions can be more effective and accurate. Besides, the effects of spatial aggregation and the difference of processing and normal exports under MRIO on ECCT were discussed by [87] and [31].

The other methods estimating embodied emissions plotted in Fig. 5 are showing a growing boom in the literature. Especially the MRIO-LCA (hybrid) and LCA are bottom-up process-based method considering the sector disaggregation to depict the sector level emissions [30]. The CGE model can be used to measure and simulate the volume of the embodied emission from changes in socioeconomic structure [103]. The physical IO model only use the physical quantity data relatively [104].

4.2. The involved accounting principles

To better understand the responsibility of GHGs emissions between consumers and producers, a definite and rational principle of measuring the carbon responsibility should reach an agreement globally. From the results of the literature review, the popular principles involved in measuring the carbon emissions are the production-based (or territorial) accounting principle and the consumption-based (or upstream) accounting principle in the literature. In addition, the common but differentiated responsibility [105], the shared producer and consumer responsibility [106], and the income-based principles [107] are also discussed.

The production-based accounting principle implemented by United Nations Framework Convention on Climate Change (UNFCCC) and Kyoto Protocol is the dominant framework on measuring the industrial GHGs emission responsibilities of countries. Because of the disapproval from the non Annex-1 and some Annex-1 countries with respect to production-based accounting principle (see Fig. 6), the progress of the international climate change negotiations is less effective in carbon mitigation. Alternatively, the consumption-based accounting principle had been argued strongly, based on the carbon footprint and carbon leakage in trade, as a substitution.

Recently, studies juxtapose both of the consumption and production based emissions to demonstrate the impact of trade on the national emission inventory. As Fig. 7 illustrates, we can learn that CO_2 emissions are significantly different in China from the Production-based and Consumption-based principles in 2009. With the increasing volume of international trade in countries like China, a more reasonable accounting principle is urgently in need. However, justice and fairness on allocating carbon responsibility are complex and targeted on global scale.

4.3. The involved data sources

The IO table and carbon emission data-gathering problems in China have thus far been acutely focused globally. It cannot be denied that the data sources and processing would lead to the variation of the results. Wang [50] argued that China had the capacity to abate carbon emissions if she can deal with the problem in data gathering and implementing reliable system for gathering carbon data as soon as possible. With the efforts implemented from the Chinese government

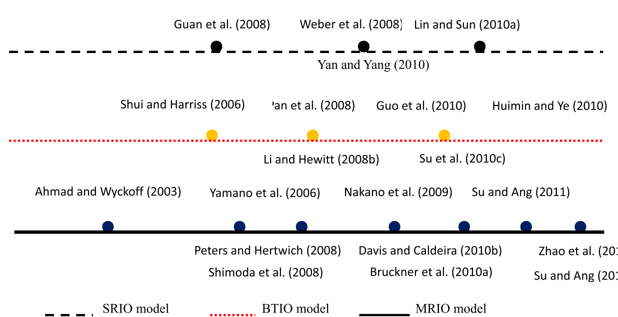


Fig. 6. The timeline of the main research on ECCT by using SRIO, BTIO and MRIO model. Notes: The primary literature on MRIO model in 2015 are as follows: Liu et al. [88], Liu [9], Zhong et al. [89], Xia et al. [90], Schandl et al. [91], Zhang [92], Liu et al. [10], Su and Ang [93]; Jianyi et al. [94], Aichele et al. [95], Zhang and Tang [96], Xie et al. [97], Jiang et al. [98], Nejat et al. [99].

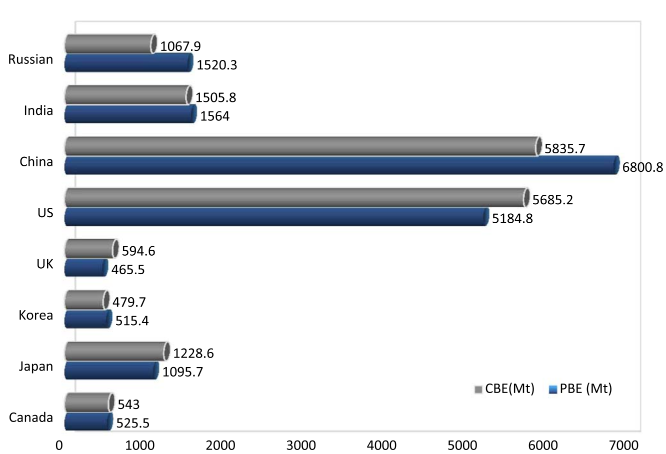


Fig. 7. The PBE and CBE from major economies in 2009. Source: The data are available at: http://www.stats.oecd.org.

and institutes abroad, the Chinese IO table has become more available with higher quality.

The main available input-output database used in ECCT from the literature are summarized in Table 7. The input-output tables, energy data, CO_2 emission data, trade data and other economic data applied in calculating ECCT can be obtained from various sources. With different data processes, it may lead to the results variation. The uncertainties resulted from data sources and processing, the impact of the regional economic imbalance on Chinese IO tables will be discussed in Section 4.5.

On the other hand, the energy data can be obtained from the China statistical yearbook and GTAP database. The carbon intensity data can be obtained from International Energy Agency (IEA) and World Resources Institute (WRI). The CO_2 emissions are usually calculated based on the IPCC guidelines in 2006 and Chinese energy statistics. For ease of explanation, some authors just use the CO_2 emissions data from their own or other previous literature. In addition, the national carbon emission data can be obtained original from the World Input-Output Database (WIOD) database. It should be noted that some studies just use the data and coefficients from other countries to represent Chinese data, more details are surveyed in [36].

4.4. The quantitative results of ECCT from literature

Based on the results of the keyword frequency analysis, we track the empirical results of ECCT from the key papers (and their references), authors, organizations, and then try to summarize the empirical results for ECCT one by one. In the light of the analysis process in previous studies [34,36,49], the aggregate results are summarized in Appendix A. From the literature, under different research motivations, uncertainties in PBE, CBE, EEE, EEI and EEB can be investigated from the methodologies, data processing and assumptions from the authors. The ECCT in literature are so volatile in the same year with same calculating principles under different data sources and processing. Meanwhile, even with same assumption on the carbon emissions coefficient, the different estimate of ECCT can be found, such as [125] and [126] with different sources of IO data in the same year.

4.4.1. The fluctuation of the PBE and CBE

From the set of literature covered in this study, the earliest estimate of China's PBE and CBE are 1569.2 Mt CO_2 emissions and 1426.9 Mt CO_2 emissions in 1985 estimated by Shimoda and Watanabe [112] by using a MRIO model and data from the Asian international input-output table from IDE (see Table 7). They released that the net export CO_2 emission from China was positively, and indicated that China was a net carbon exporting country in 1985. In fact, Liu [9] estimated China's CO_2 emissions from 1970 to 2012, we could obtain the earliest PBE nearly 0.7 Gt in 1970 in this report. He applied his own estimated China's energy data based on mine-level and factory-level energy use data to calculate China's carbon emission, and finally argued that methodologies and verifications in full transparency towards better energy and emission data for China are urgent needed.

The estimate of yearly PBE and CBE suffered a drastic fluctuation. As shown in Fig. 8, the PBE is varying from over 2700 Mt CO_2 emissions [127] to over 3000 Mt CO_2 emissions [60] in 1995 with the change rate of over 9%. In addition, the small variation of estimate on PBE in 1997, 2000, 2001, 2003, 2004 and 2005 can be learned from Appendix A. Contrarily, the PBE in 2002 is between 2600 Mt CO_2 emissions [109] and 3600 Mt CO_2 emissions [60] with the change rate of around 39%, such large variation also can be found in 2007. Weitzel and Ma [128] applied the MRIO method to measure the PBE in 2007 and they came to nearly 4000 Mt CO_2 emissions, comparing to the estimate from Yan and Yang [65] by using a SRIO model, they are lower than over 50%.

Besides, the fluctuation tendencies of yearly PBE are rising regularly. The PBE is around 3000 Mt CO_2 emissions in 1995 and

Table 7
The main available input-output databases including China.
Source: This table is partially adopted from Amador and Cabral (2014).

Institution Source	Countries	Year (sectors)	References
NBS-PRC	1	1987(33),1990(33),1992(33),	[60,63,108,109]
(National Bureau of Statistics of the People's Republic of China)		1995(33),1997(40),2000(40), 2002(122),2005(42),2007(135), 2010(42),2012(139)	
IDE-JETRO	10	1975(76),1980(76),1985(76),	[87,110–112]
(Institute of Developing Economies-Japan External Trade Organization)		1990(76),1995(76),2000(76), 2005(76)	
WIOD (World Input-Output Database)	40	1995(35)–2011(35)	[113,114]
OECD Database (Organization for Economic Co-operation and Development)	57	IO table 1995(34)–2011(34) ICIO table 1995(34), 2000(34), 2005(34), 2008–2011(34)	[115–118]
GTAP (Global Trade Analysis Project)	140	Base year 2004(57),2007(57), 2011(57)	[27,119,120]
EORA (The University of Sydney)	187	1990(159)–2011(159)	[121,122]
EXIOBASE (http://www.exiobase.eu/)	43	Base year 2000(163),2007(163)	[123,124]

Notes: The NBS-PRC produced its first national IO table for China in 1987 and its first trial IO table in 1970s in 1991, and the detailed IO tables (110 sectors or more) in 1987, 1992, 1997, 2002, 2007, 2010 and 2012 were published. Besides, the IO tables for municipalities (Beijing, Shanghai, Tianjin and Chongqing) were also released. China's domestic regional (8-region and/or 30 region) IO table compiled by NBS-PRC had been released in year of 1997, 2002, 2007, 2010 and 2012 (The data available at http://data.stats.gov.cn/).

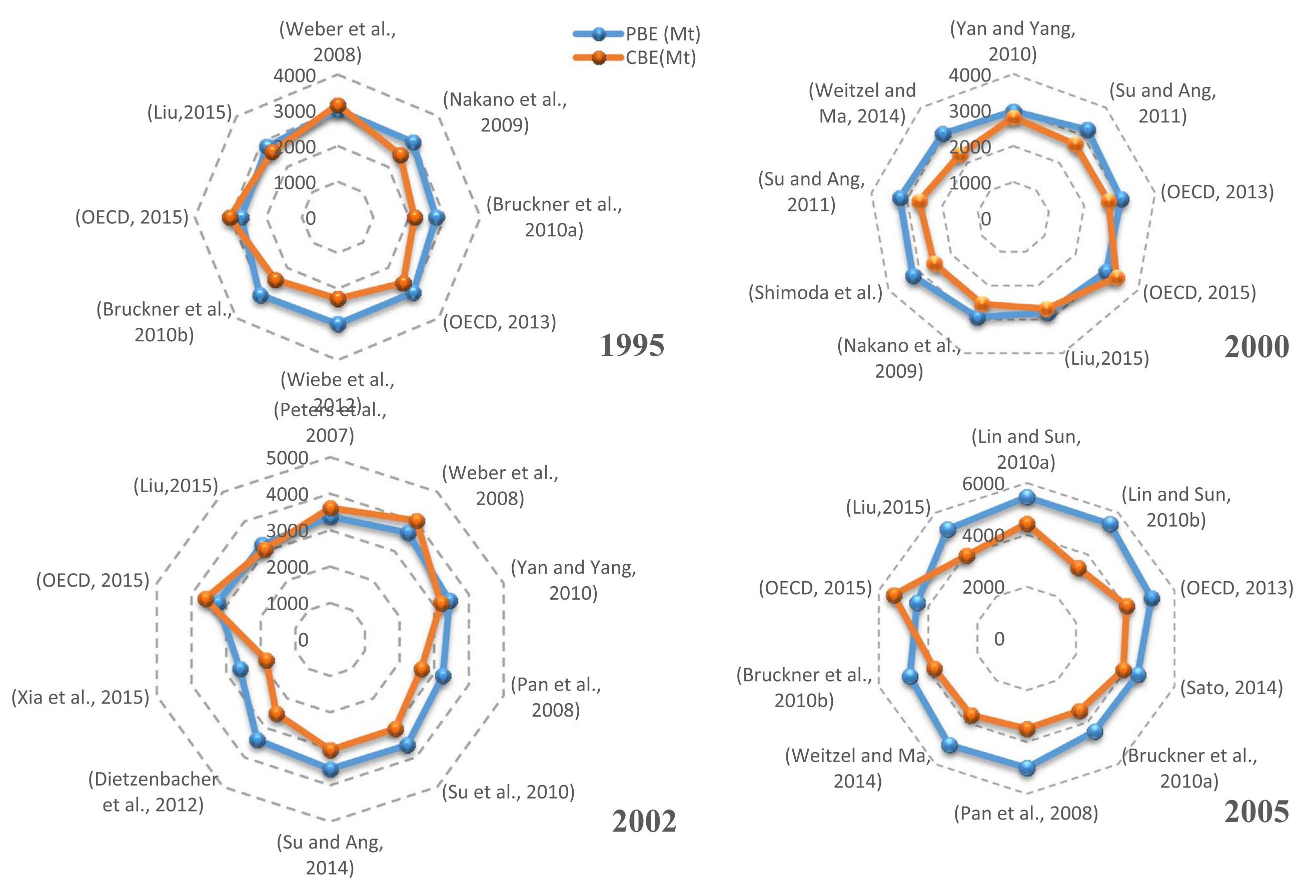


Fig. 8. The PBE and CBE in 1995, 2000, 2002, and 2005 from the literature.
Source: Appendix. A and supplementary information in csv file.

2000. Continuously, the values of PBE are up to over 3000 Mt CO_2 emissions in 2002 and 5000 Mt CO_2 emissions in 2007. To some extent, we can see the effects of the Asian financial crisis in later 1990s, and the entering into the WTO in earlier 2000s to China's economy, in particular, the increasing of the energy consumption and the acute global academic attention (see Fig. 2) to Chinese economy growth and resulted carbon emissions in the past decade.

On the other hand, we can learn that the CBE is varying from 2152 Mt CO_2 emissions [127] to over 3000 Mt CO_2 emissions [129] in 1995 with the change rate of over 20% from Fig. 8. Moreover, the CBE in 2002 is varying from 1841 Mt CO_2 emissions [109] to 4030 Mt CO_2 emissions [60] with a great variation rate of over 54%. Comparing with the existed studies, Xia and Fan [109] used a non-competitive DPNHIO (extended IO models, more details see [130]) model to measure the ECCT in Chinese processing and non-processing exports sectors with new assumptions of estimating the emission intensity in China, and disaggregated the energy sectors into three parts like domestic use of energy, processing exports and non-processing exports. The estimate of CBE in 2004 demonstrates a dramatic variation with the change rate of 35% implying more uncertainties in data processing from the literature (see Appendix. A). As expected, wider fluctuation can be found in 2005 (from 3,370 Mt CO_2 emissions to 5400 Mt CO_2 emissions). To understand the performance of the discrepancies in ECCT, it is valuable to discuss the variations emerging from the methodologies data and assumptions in greater details. It seems that the estimates of CBE in 2000 (from 2305 Mt CO2 emissions to 2794 Mt CO2 emissions) are with little inconsistencies. Commonly, a higher PBE than CBE could be resulted from the economy with same trade structure from overseas like China because of the difference of the production-based and consumption-based principle on assessing CO_2 emission.

It is meaningful to discuss that the gap between PBE and CBE became larger more or less from 1995 to 2005 in Fig. 8. In other words, different from the gap between PBE and CBE from 2000 to 2002, both increasing in PBE and CBE from 2002 to 2005 reveal an increasing volume of EEB of China. We should firstly note the energy consumption rather than the economic growth, to some extent, whilst the low energy efficiency by PBE. Secondly, the increasingly development of Chinese international trade and the abroad intensified demand of the high carbon embodied goods especially in 2005 may contribute to such gap. For example China had exported net 656.68 Mt CO_2 emissions to the US which took up 11.67% and 13.9% of the total CO_2 emissions in China [131] and the US [132] respectively in 2005.

4.4.2. The fluctuation of the EEE and EEI

The EEE and EEI of ECCT had been estimated from 1987 to 2011 (see Appendix. A), which show a big volatility significantly. For example, on the one hand, the EEE in 2000 is from 350 Mt [65] to 1000 Mt CO_2 emissions [126], and the same or even more bigger difference can be found in 2002, 2003, and 2004; On the other hand, the EEE in 2001 is from 2849 Mt CO_2 emissions [65] to 2930 Mt CO_2 emissions [29], and the small variation can be learned in 1997 and 1998. However, the EEI of ECCT in 1997 is varying from 102 Mt CO_2 emissions [26] to 700 Mt CO_2 emissions [60]. The big fluctuation in EEI can also be found in the rest years.

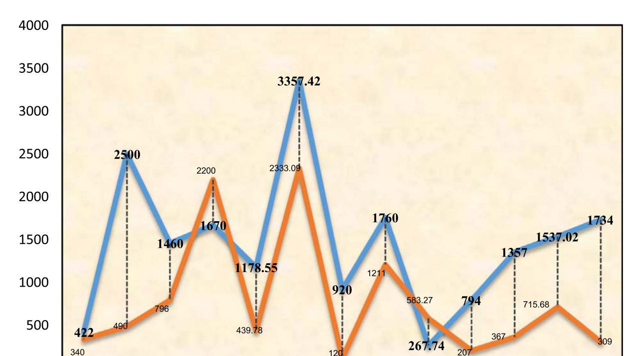
The EEE of ECCT in 2005 is changing from 422 Mt CO_2 emissions to 3357 Mt CO_2 emissions, and the EEI is varying from 120 Mt CO_2 emissions to 2333 Mt CO_2 emissions. Given the carbon intensity in China is higher than most other countries/trade partners, does China always have the higher EEE than EEI? The answer is no. Different from other results, Weber and Peters [60] got the higher EEI than EEE in 2005, using the SRIO model and the IO table from NBS-PRC (see Table 7). They found China clearly avoided large CO_2 emissions from 1987 to 2005. To explain the abnormal estimate, they noted that the EEI in 2001 should be estimated to be 216 Mt CO_2 emissions when they illustrated the EEI up to 1170 Mt CO_2 emissions in 2002.

The changes of the EEE and EEI are significantly different under different models in the same year. The most waving characteristics for EEE and EEI can be found specifically by detailedly checking the EEE and EEI from the reported results in Appendix. A. As shown in Fig. 9 for 2005, the variability of the EEE and EEI from the MRIO are smaller than SRIO. The average fluctuation of the EEE and EEI based on BTIO are smaller than those of based on SRIO. In the results of the each model, the variations also exist in the same year. For example, in terms of the EEE and EEI in SRIO, we can see that the values of EEE and EEI from [28] are larger than others which means that the carbon embodied in China's exports are more than that of imports with the increasingly demand abroad of the energy intensive goods produced by the high carbon embodied intermediate goods imported or domestically. Contrarily, the EEE and EEI from [133] are with little gap compared with the other results applying the SRIO model. They identified the volume of domestic and imported goods in the inter-sector input and final use in IO table by data from China Customs Statistical Yearbook released officially in China.

Lin and Sun [28] measured the EEE and EEI of ECCT by SRIO and BTIO in 2005 respectively. They argued that the EEE and EEI should be calculated by using the emission factors of the exporting and importing countries to avoid overestimate the imported and re-exported emissions in China, since Chinese producing process is more carbon intensive than her trade partners. As shown in Fig. 9, we can see the obvious difference in the results of EEE and EEI in 2005 between the two methodologies. In addition, Zhao and Zhang [114], by considering the impact of global vertical specialization on ECCT and using the IO tables from the WIOD (set 1995 as base year), measured ECCT by differentiating the domestic sourced CO_2 emissions from the foreign sourced emissions and the re-exported emissions embodied in international trade. Their results of EEE and EEI covered the average results by the MRIO model in 2005 (see Fig. 9).

4.4.3. The fluctuation of the EEB

Based on equation EEB=PBE-CBE=EEE-EEI and the results from the literature, the EEB are calculated in Appendix. A. As mentioned in Sections 4.4.1 and 4.4.2, we can get some clue about the variation of the EEB for ECCT indirectly. Figs. 10 and 11 show the variation of EEE, EEI and EEB in 2002 and 2007 respectively. From the tendency of the EEB, the great variation within every year cannot be ignored. For example, The EEE in 2007 changed from 478 Mt CO_2 emissions to over 3000 Mt CO_2 emissions, the EEI varied from 140 Mt CO_2 emissions to over 1782 Mt CO_2 emissions, and the EEB is range between 102 Mt CO_2 emissions and over 2900 Mt CO_2 emissions (see Fig. 11). The



	L1	L2	L3	L4	L5	L6	L7	L8	L9	L10	L11	L12	L13
EEE(Mt)	422	2500	1460	1670	1179	3357	920	1760	267.7	794	1357	1537	1734
EEI(Mt)	340	490	796	2200	439.8	2333	120	1211	583.3	207	367	715.7	309

Fig. 9. The EEE and EEI of ECCT from literature in 2005. Notes: L1=(Zhang, 2012)-SRIO; L2= (Ren et al., 2014b)-SRIO; L3=(Yao et al., 2008)-SRIO; L4=(Weber et al., 2008)-SRIO; L5=(Yan and Yang, 2010)-SRIO; L6=(Lin and Sun, 2010)-SRIO; L7=(Ren et al., 2014)-SRIO; L8=(Huimin and Ye, 2010)-BTIO; L9=(Lin and Sun, 2010)-BTIO; L10=(Sato, 2014)-MRIO; L11=(Bruckner et al., 2010a)-MRIO; L12=(Zhao et al., 2014)-MRIO; L3=(Weitzel and Ma, 2014)-MRIO.
Source: Appendix. A and Supplementary information in csv file.

parallel circumstance also can be checked in 2002 (see Fig. 10), 2004, and 2006. It seems the estimate fluctuation in 2007 is smaller than 2002.

The largest EEB in 2002 and 2007 are estimated by [126], they obtained the IO table data from the OECD database and replaced the IO table in 20042001–2004 with 2000, 20102006–2010 with 2005. Based on the emissions avoided by imported (EAI) assumptions, they got adjusted technical factor for China's import by assuming China only trade a single "virtual country". From the EEI plotted in Figs. 10 and 11, with higher EEE, we can conclude a higher EEB for China consequently. In addition, the smallest EEB in 2002 and 2007 are obtained by Zhang [133], as mentioned 4.4.2, followed by Weber and Peters [60], they avoided double counting on the goods and services in the bonded areas by customs data in IO table.

The estimate of EEB is affected by the assumption about the importing country *pe se* and its trade partners. In addition, Xia, Fan [109] applied South Korea's technical coefficients as those of China's trade partners to study ECCT, they certified if technical coefficients of South Korea are employed to measure the carbon avoided via import, China is found to be a net importer of embodied carbon in 05,2001–2005, and a net exporter from 2006 to 2009, then turned to be a net importer in 2010. However, the technical coefficients from South Korea would underestimate the EEI, then if the EEE is consistent, the EEB of ECCT would higher and China would be a net carbon exporter. From the literature, although EEB in 2005 fluctuated actively (see Fig. 11), it could be concluded that most of the estimates are located between 500 Mt and 1500 Mt. By checking the technical coefficients used in those papers, comparing to SRIO and BTIO, the MRIO is the most precise model to estimate variation of production level among trade partners. Literature considering the differentiation in economic technique and energy intensity between China and her trade partners could get the more accurate net carbon emission embodied in international trade.

With the development of international trade, the fragmentation of the production and consumption worldwide has attracted more and more attentions. As plotted in Fig. 10, the similar EEE may lead to a totally different EEB with the different consideration on EEI, which indicates that the assumption of the imported goods should greatly change the EEB finally. Wiedmann [61] reviewed the MRIO model used for consumption-based emission, he argued the adjustment of imported goods consumed in domestic inter-sector input and finial consumption can bias the estimation to a large extent. The carbon emission embodied in the re-exported goods produced by the imported intermediate input should be divided from the domestic inputs. Therefore, he concluded the accuracy of MRIO and more complex extended IO models should be deduced to handle the uncertainties in estimating embedded carbon in trade Fig. 12.

4.5. Reasons and countermeasures to the results uncertainty

Considering the differences existed in the estimate of the ECCT as summarized in Section 4.4, it is impossible to plot a general trend or level for the change of ECCT. As a result, it should be borne in mind that finding the potential reasons for such uncertainty and reducing the variation in estimating ECCT is meaningful to policy implications.

4.5.1. The methodology specification

The MRIO has been the most popular method to measure the carbon emissions embodied in China's foreign trade. With wider availability of the increasing capacity on computing technology and economic accounts, environmental accounts and foreign trade data, many recent literature juxtapose carbon emission by MRIO model. The complex feedback and spillover effects between trade partners can be perfectly plotted by combining the domestic technical coefficient matrices with the import matrices from multiple countries or regions into one large coefficient matrix in the MRIO model. In fact, it is worth

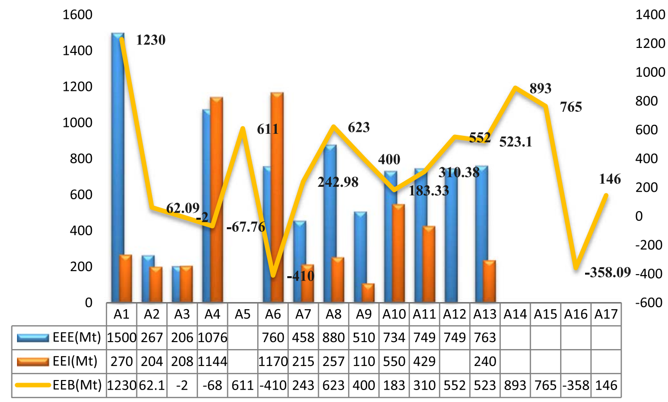


Fig. 10. The EEE, EEI and EEB of ECCT from literature in 2002. Notes: A1=(Ren et al.,2014b); A2=(Wei et al., 2011); A3=(Zhang, 2012);A4=(Peters et al., 2007); A5=(Qi et al., 2008); A6=(Weber et al., 2008); A7=(Yan and Yang, 2010); A8=(Pan et al., 2008); A9=(Ren et al.,2014); A10=(Huimin and Ye, 2010); A11=(Zhao et al., 2014); A12=(Su et al., 2010); A13=(Su and Ang, 2014); A14=(Dietzenbacher et al., 2012); A15=(Xia et al., 2015); A16=(OECD, 2015); A17=(Liu, 2015).
Source: Appendix. A and Supplementary information in csv file.

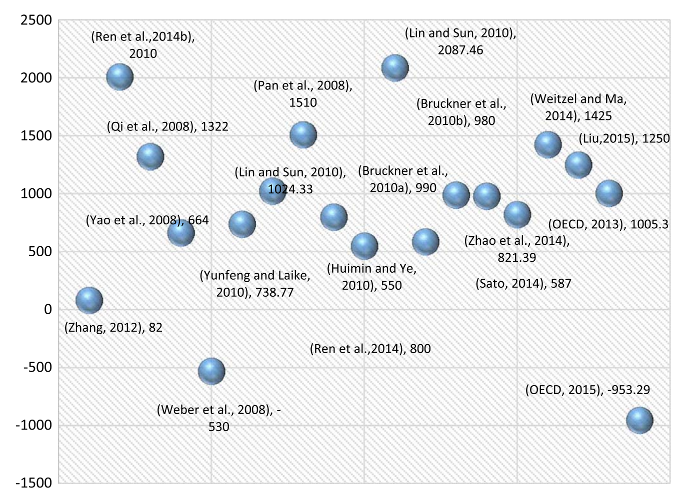


Fig. 11. The variation of EEB from literature in 2005 (Mt CO2 emission).
Source: Appendix. A and Supplementary information in csv file.

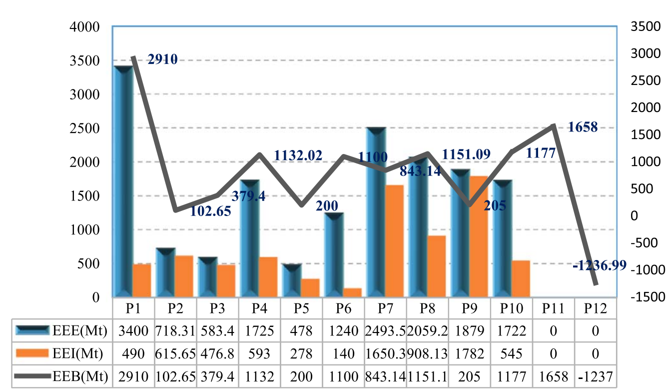


Fig. 12. The EEE, EEI and EEB of ECCT from literature in 2007. Notes: P1=(Ren et al.,2014b); P2=(Wei et al., 2011); P3=(Zhou and Yang, 2011); P4=(Yan and Yang, 2010); P5=(Zhang, 2012); P6=(Ren et al.,2014); P7=(Huimin and Ye, 2010); P8=(Zhao et al., 2014); P9=(Weitzel and Ma, 2014); P10=(Qi et al., 2014); P11=(Xia et al., 2015); P12=(OECD,2015). EEB for P11 and P12 are calculated by EEB=PBE-CBE in Appendix. A.
Source: Appendix. A and supplementary information in csv file.

to note that the MRIO and its extended forms can be various with different modeling background and available data lags [61,104,134,135]. However, with the differentiated technologies from multiple countries being considered, the international IO databases, such as the WIOD, GTAP, EORA, and GRAM [136] have been developed to catch the carbon emission flows in terms of country, region, municipal, sector, and product. China's carbon footprint has been estimated from the macro to micro scale as shown in the literature [137]. Based on extended MRIO model, it is meaningful to track the carbon flows globally from cradle to grave. The structural path analysis (SPA) [138], the structural path decomposition (SPD) [139], the RAS structural decomposition approach [140,141], the MRIO-LCA [142,143], GTAP-MRIO [136,137,144] and carbon emissions measurement integrating with the GVCs can be used for investigating the environmental impact of ECCT from the international supply chains [145].

However, there exist inherent uncertainties in MRIO [61] which only be discussed recently. Firstly, the assumption of the production technology of trade (import) goods are identical to the importing country which could cause unbalanced allocation on technology differentiation among trade partners; secondly, data located on the off diagonal matrix in MRIO table related to trade relationships between trade partners only can stand the supplying sectors from specific country to the other, but have no clues on how to distribute those import goods or service in imported countries by sectoral level, therefore, the imputation techniques with inherent assumption usually being applied to produce the trade flow matrix of the off diagonal matrix as a replace; thirdly, the level of sector aggregation or disaggregation could impact the estimate. Lenzen and Pade [146] tested the variation caused by the sector aggregation from 10 to 133 sectors, they concluded that the merge of the electricity production to water and gas production could significantly resulted in the variation in estimate, moreover, Su and Ang [32] concluded that around 40 sectors could obtain the stable and reasonable estimate for an economy by testing the effect of the sector aggregation.

Comparing with the MRIO model, the SRIO and BTIO model have their own merits as well as shortcomings in measuring the carbon emission in the earlier literature. The SRIO could be used to measure the carbon emission for a unique country with the merit of low requirement of data source to input-output table and trade data under competitive circumstance. However, the import substitution assumption [29,147] and the emission avoided by importer assumption [28] under SRIO approaches with lower requirement on data would definitely lead to biases in carbon emission embodied in imports. From the literature, it is inadvisable to adjust the carbon coefficient from other countries for China's imports [30,65]. For a large country like China, the production technologies are with high extent of variation among regions since the economic imbalanced background, the characteristics of carbon factor and production technologies, if possible, should be better considered provincially or regionally to study the location of the carbon emissions clearly and obtain more accurate results of ECCT.

Comparing with the SRIO model, the BTIO method divides the domestic and imported good and service as the improvement. However, with the failure of dividing the imported intermediate input and the final demand from the import goods, the BTIO (EEBT) would mix the sectoral carbon emissions embodied in some imports goods by sector aggregation. In spite of the relaxing assumption on carbon factors, only considering carbon emissions between main trade partners in BTIO model cannot draw the detailed carbon flow during international trade [104,148]. Therefore, the sector disaggregation should be a more accurate way to estimate embodied carbon in the further study. Besides, it is the energy intensity in China that cannot be assumed as a whole roughly. For example, with the large amount of exports and imports in China's eastern coastal regions and theirs economic hinterland, the processing trade with low profits and high carbon responsibilities should be reasonably measured. The carbon emission sourced within and without China therefore should be clarified. Therefore, more detailed multi-regional input-output table, energy use account and robust emission evaluation method should be developed for each of the economies at global scale respectively [9].

4.5.2. The accounting principle specification

Shall we turn to consumption-based accounting principle now? As discussed in Section 4.2. We can conclude that the better way to get progress in the international climate change negotiation is ending the current unreasonable production-based accounting principle [134] as soon as possible for more effective carbon abatement progress. For instance, large developing counties like China and India would show more confidence on the GHG reduction if the carbon responsibility can be divided more fair and reasonable between the real carbon consumer and producer.

China would be an obviously net carbon exporter if the re-exported goods produced by high imported intermediate goods and embodied with low Chinese domestic carbon commonly being considered to be Chinese carbon responsibility [143]. The wider discussion on the consumption based accounting principle can be found in [27,106,142]. As a better choice of carbon responsibility, the common but differentiated responsibility, uncovering the indirect carbon emission for government and even clearly showing the sources of GHG emission for the consumers, is perfect but with great obstruction coming into force. However, international cooperation, such as the cleaner technology transfer and streamlining the clean development mechanism should be considered to implement between developed and developing countries.

4.5.3. The data source specification

The data source uncertainties mainly lie in the reliability of the underlying statistics for the IO table, the normalization for emission data [140], and the impact of sector aggregation or spatial disaggregation. Besides, the price adjustment and the disposition of the trade data with different policy consideration on methodology design can vary the EEB of the ECCT by biased estimate on PBE, CBE, EEE, and EEI. To obtain more accurate estimate for ECCT, these uncertainties should be under control during the initial statistics rather than being overlooked.

Firstly, the IO table and emission data in China should be with high quality. The biases existed from the processes of gathering supply-use tables (SUT), input-output tables (IOT), international trade data and emission data should be controlled in China. The number of the commodities, sectors and the methods of reconciling the various datasets must be uniformed initially [149]. Although Chinese government has implemented measurements to data collection, the questioned and disputed voice never stop [63,73,74,145,150]. The SUT is the basic database for the industry by industry IOT, to avoid the uncertainties during this process, the SUT is directly employed in MRIO model recently which however increase the uncertainties simultaneously. The IOT, for ease of explain, are usually aggregated in fewer sectors which would contribute a fuzzy result of the consumption coefficient. The trade data should carefully match the IO table in trade partners. In particular, under BITO or MRIO model, the trade data should be allocated reasonably. It would be difficult but helpful that the emission data in China should be gathered in sector level to describe more issues of carbon emission embodied in Chinese export. Meanwhile, due to the different regional industrial structures in China, the emission data should be collected regionally to track and abate the carbon emission at region/sector level in China purposely [151].

Secondly, Chinese IO table and energy intensity data should be more detailed, standard and well-gathered. From the literature, the popular databases used in analyzing the ECCT are from the NBS-PRC, the IDE-JETRO, GTAP, OECD, WIOD, EORA and EXIOBASE. The Chinese national IO table, regional IO table, provincial IO table and the large municipal IO table collected originally or updated by special technique (such as the RAS method [134,140,152]) are available online now. In addition, the Asian IO tables produced by IDE-JETRO and the ICIO database released by OECD database are also widely used for ECCT recently. Since the database of GHGs and sector coverage in IO table are organized systematical different, the aggregation is unavoidable. Studies should pay attention to the errors resulted from the sector aggregation when the number of sectors from the IO database does not match that from the energy sectors. Existed studies show that the highly aggregated sectors would result in a higher estimate of carbon emission than the results with sector disaggregation process. It should be noted that more assumptions and uncertainties would emerge in sector disaggregation as trade off. More detailed discussions about the degree of aggregation in the IO tables can be learned from [108,153].

Thirdly, the large scale computer systems should be developed for large scale of data involved which would beyond the calculation capacity of the personal hardware resources. To capture the real carbon flows for China worldwide, the data from multi-country should be gathered within an international criterion [121]. Therefore, the MRIO should make full use of the large scale computer system to try to demonstrate the main features of the carbon emission flows [134,144]. Current understanding of the natural and social sciences of GHGs is still need to be improved with the development of the data gathering approach and the methodology extended. Although the GTAP-E model, the EORA model, the GRAM model and the CGE model have been build up to deal with such issue, the processes seem like a black box. As a summary, it is important to build up a national calculation system currently including all the elements, such as the Chinese regional carbon emission database, the producing process, the trade and transportation process, the feedback and spatial mechanisms, to capture the carbon emissions. Most of the existed studies are relative static and policy oriented [35,143]. To limit the uncertainties during environmental impact evaluation, it is important to develop an integrated MRIO model with large scale computer system for China to describe the embedded emissions globally.

5. Concluding remarks

The mitigation of the domestic carbon emissions and ECCT are not only an economic issue but also a political game for China. Ambitious commitments and efforts have thus far been made to control carbon emissions by Chinese government. Although the uncertainties of numerical investigation of ECCT are large and varying, the estimates remain reasonable and practical in providing insights and policy implications on Chinese carbon reduction in international trade. In particular, most of the articles on ECCT published by authors from China are financially sponsored by Chinese government. With the international climate change negotiation reaching more effective global agreement [154], as the largest developing country and top carbon emitter, China should handle her carbon emission and keep a good balance between the economic growth and environmental protection [155].

The increasing number of the studies on ECCT makes it possible to compare the methodologies, data sources, and estimated results of the ECCT critically. To assess the existing level of numerical understanding of the ECCT, this study provides a comparative review of the quantitative estimates on ECCT by surveying the empirical results from the literature based on the online version of SCI-E from 1981 to 2015 and SSCI from 2002 to 2015. It should be noted that only the English language peer-reviewed journal articles are surveyed, consequently, the conclusions drawn herewith for ECCT cannot be extended to Chinese or other non-English-language literature. In the discussion, we learn that studies on ECCT are robust in the past decade, and the series of IOA approaches are dominant methodologies used to analyze ECCT, and the obvious inconsistencies and uncertainties can be found by comparing reported results taken from the literature.

The MRIO model and its extensions have been the dominant method to measure the environmental issues all over the world especially for China. With the increasing improvements on China's energy intensity and carbon emission intensity data, and more detailed IO tables (such as the expansion of regional and municipal IO tables), the boom of the EE-IOA studying on CO_2 emissions embodied in international trade for large carbon consumer and producer (such as the EU, USA, China, and India) would be more prosperous in next decade for the white-hot debate on carbon responsibility distribution in global climate change negotiation. As discussed by Dietzenbacher and Lenzen [156], the MRIO model will be used to draw the connection between the economic and the environmental issues closely with the building of the giant database including detailed data worldwide. As a hub for global trade, China has thus far been studied by using GMRIO model to estimate the environmental impact with several perspectives [114,138].

Continuous investigation of the literature releases the fluctuation of PBE, CBE, EEE, EEI and EEB of the ECCT. Based on the equation EEB=PBE-CBE=EEE-EEI, we get the EEB of ECCT in Appendix. A. From the results, the variation of PBE and CBE has shown a big difference in 2002, the PBE is between 2606 Mt CO_2 emissions and 3620 Mt CO_2 emissions with the change rate of around 39%, and the CBE in 2002 is changed from 1841 Mt CO_2 emissions to 4030 Mt CO_2 emissions with a great variation rate of over 54%. With different research motivations and assumptions in modeling, the EEE and EEI of ECCT are inconsistent. Especially in 2007, the EEE changed from 478 Mt CO_2 emissions to over 3000 Mt CO_2 emissions, and the EEI ranged from 140 Mt to over 1700 Mt CO_2 emissions. Moreover, the EEB varied between over 100 Mt CO_2 emissions and over 2900 Mt CO_2 emissions dramatically.

Uncertainties from methodological selection, assumption, data sources and data processing existing within ECCT evaluation process should be reduced in the further study. The technology assumption during emission calculation could contribute some biases to the estimation. For instance, in the earlier literature, some imported goods could be assumed having the same production technology with the domestic goods. However, some was divided into the two parts that used in intermediate input and final demand domestically in the imported country. In fact, the real situation are some exported goods are produced totally domestically, some are produced jointly by imported goods and domestic inputs, and some are produced by re-imported intermediate goods mixed with domestic inputs. Therefore, it's a challenge to distinguish different sourced trade goods and service flows in model design on calculating the carbon emissions.

It is urgent to overcome the uncertainties on data collection during estimation in further study for more reliable policies on carbon abatement based on carbon evaluation in China. High-quality database on China's national and regional data should be collected and released with low discrepancies. Particularly, it is necessary to avoid inconsistencies between the aggregated regional and national Input-output data and energy intensity as well as the gap among China's domestic IO data and other available database (for example, WIOD, OECD and Eora). For example, recently a new tendency in ECCT study is to consider the differentiation lying in China's regional economy, energy use structure, and carbon intensity to more effective carbon control policies in region (province or city) level in China [147,150]. The estimate of regional ECCT can describe the regional carbon flows between China and her trade partners (as well as regional carbon flows in China) which would be benefit to allocate regional carbon responsibility and fulfill China's carbon mitigation target effectively whilst make some possibilities on international carbon mitigation. However, the prerequisite is to build a new database with different sourced databases with purposed policy consideration.

The different considerations on sector classification among different database should be considered when China's regional or national data need to be merged into other database which should be based on more identified data sources. For example, to our knowledge, there are some variations between China's aggregated national IO data aggregated by her regional IO data and official national IO data. For example, the discrepancies existed in the aggregated sectoral input-output data and sectoral energy use resulted from different assumption on the original sectoral design and energy use categories. Moreover, the discrepancies are vast among current available databases. Some discrepancies also could be tested between China's input-output data in WIOD and National Bureau of Statistics from China when we try to merge China's regional IO data into WIOD database. The consistency of the sectoral total output and its energy intensity in different database should be avoided by comparing and adjusting among different database in further research for globalized studying the energy and carbon flows embodied in trade flows.

Recently the building of the inter-country and inter-regional input-output table could show more linkage between sectors, regions, and cities between trade partners [157]. From the current of this tendency, it could be found that scholars tends to divide China into pieces by different consideration and merge them with other countries, for example, the transnational interregional input-output table for China, Japan and Korea in 2015 by IDE-JETRO (by region, The data are available at http://www.ide.go.jp/English/Data/Io/index.html), inter-country input-output (ICIO) table by OECD (by processing or non-processing trade, the data are available at http://www.oecd.org/sti/ind/input-outputtablesedition2015accesstodata.htm), and the city level multi-regional input-output table (MRIOT) produced by 185 countries and 30 Chinese regions (including four provincial municipalities) based on Eora and China's IO data [157].

New explorations on lowering uncertainties in methodology design should be focused seriously in further study. As the most popular model on estimating carbon emission, MRIO has many merits based on Leontief inverse matrix, but also some shortcomings itself. Relaxing the assumption and following the real economic activities should be the basic idea in building more reliable carbon emission assessment skeleton. One possibility is transferring linear relationships among sectors to non-linear relationships based on certain constrain to more objective estimates [158,159]. The reality situation of the economic productivity and energy intensity factor are totally different even in one country, as a result, the environmental cost for the same quantity of certain goods are also different among countries. How to estimate the different carbon intensity on the basis of carbon flows internationally with different productivities from various regions or countries by using the non-linear input-output system is a challenge in this field.

Another possibility to reduce the uncertainties in methodology design is to integrate the Leontief and Ghosh model under the IO system to calculate the carbon linkage among sectors and countries. Chinese government has shown her ambitious reform in both of supply-side and demand-side, therefore, the combining of the two models from different side of the economy could show more interesting results comparing with previous studies [160,161]. Besides, the impact from different property (firm ownership) of the enterprises in China should be considered [24]. The producer and consumer of China's carbon emission in and out of her territory should be divided explicitly in the future work by compiling the firm level IO table in China, in hence, the carbon emission produced by foreign propertied enterprise and consumed by demand from overseas but pollution emitted in China could be distinguished from native demanded emissions.

In conclusion, given ambitious carbon emission reduction commitments (COP 21) in Paris in 2015 from 147 countries, and the establishment of Chinese carbon trading market in 2017, as well as China's 'one belt and one road' expansion strategy in her new economic plan recently [162], it is meaningful to study emission between China and her potential closed trade partners, which would imply more useful policies on regional energy cooperation and integrated carbon reduction mechanism among countries involving 'one belt and one road' economic areas in further study. As it is known to all, China's carbon emissions have been an acute topic to the global climate change. More in-depth insights on model modification and accurate estimate for carbon emission assessment would be discussed in the near future.

With the upgrade of processing trade and new trade tendency and strategies implemented in China, China's embodied carbon emission should be estimated in temporal and spatial perspectives to obtain more comprehensive carbon control measures. The firm level assessment under different ownerships for China could help to format systematic regional carbon reducing strategies; the city level assessment under the extended global MRIO model could help to reduce carbon emission internationally; and the provincial level measurement could be treated as a necessary tool to carbon trading market in China. Moreover, other important research ideas related to embodied carbon emission is the decomposition analysis of the changes of driving forces. From the literature, it could be concluded that the mixed temporal and spatial decomposing analysis under time series data of input-output by SDA are the prevalent module in analyzing driving forces. Finally, the large scale computer systems and big data technology should be employed to track the worldwide carbon flows to better understand China's embodied carbon in international trade with multidimensional perspective.

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Appendix A

See Table A1.

Table A1
The empirical results of ECCT from the Literature.
Source: Authors.

Data year	Author /Year	Model	PBE (Mt CO_2)	CBE (Mt CO_2)	EEE (Mt CO_2)	EEEP (%)	EEI (Mt CO_2)	EEIP (%)	EEB (Mt CO_2)	EEBP (%)
1985	Shimoda et al., 2008	MRIO	1569.20	1426.90					142.30*	9.07
1985	Liu,2015	MRIO	1600.00**							
1986	Liu,2015	MRIO	1800.00**							
1987	Weber et al., 2008	SRIO	2010.00	2170.00*	230.00	11.44	390.00	19.40	−60.00*	−2.99
1987	Zhang, 2012	SRIO	471.42	509.00	66.00	14.00	104.00	22.00	−38.00	−8.00
1987	Liu,2015	MRIO	1900.00**							
1988	Liu,2015	MRIO	2090.00**							
1989	Liu,2015	MRIO	2100.00**							
1990	Weber et al., 2008	SRIO	2230.00	2290.00*	360.00	16.14	420.00	18.83	−60.00*	−2.69
1990	Zhang, 2012	SRIO			97.00	19.00	103.00	20.00	−6.00	−1.00
1990	Liu,2015	MRIO	2100.00**							

(continued on next page)

Table A1 *(continued)*

Data year	**Author /Year**	**Model**	**PBE** (Mt CO_2)	**CBE** (Mt CO_2)	**EEE** (Mt CO_2)	**EEEP** (%)	**EEI** (Mt CO_2)	**EEIP** (%)	**EEB** (Mt CO_2)	**EEBP** (%)
1991	Liu,2015	MRIO	2200.00**							
1992	Weber et al., 2008	SRIO	2410.00	2550.00*	420.00	17.43	560.00	23.24	−140.00*	−5.81
1992	Zhang, 2012	SRIO			119.00	20.00	149.00	26.00	−30.00	−5.00
1992	Liu,2015	MRIO	2400.00**							
1993	Liu,2015	MRIO	2500.00**							
1994	Liu,2015	MRIO	2600.00**							
1995	Weber et al., 2008	SRIO	3010.00	3150.00*	570.00	18.94	710.00	23.59	−140.00*	−4.65
1995	Zhang, 2012	SRIO			156.00	20.00	256.00	33.00	−100.00	−13.00
1995	Nakano et al., 2009-MER	MRIO	2977.00	2477.00					500.00	16.80
1995	Bruckner et al., 2010a	MRIO	2759.00	2152.00	727.00	26.35	120.00	4.35	607.00	22.00
1995	OECD, 2013	MRIO	2986.10	2599.30					386.80	12.95
1995	Zhao et al., 2014	MRIO			502.12		141.16		360.96	
1995	Wiebe et al., 2012	MRIO	2993.00	2285.00	829.00	27.70	121.00	4.04	708.00	23.66
1995	Bruckner et al., 2010b	MRIO	3079.00	2473.00					607.00	19.71
1995	OECD, 2015	MRIO	2705.04	3021.58					−316.55	11.70
1995	Liu,2015	MRIO	2790.00**							
1996	Zhao et al., 2014	MRIO			489.19		158.69		330.50	
1996	Liu,2015	MRIO	2700.00**							
1996	OECD, 2015	MRIO	2744.10	3090.51					−316.55	−12.62
1997	Weber et al., 2008	SRIO	3210.00	3330.00*	580.00	18.07	700.00	21.81	−120.00*	−3.74
1997	Yan and Yang, 2010	SRIO	3313.13	2969.08*	494.23*	14.92	150.18	4.53	344.05*	10.38
1997	Qi et al., 2008	SRIO							310.00**	
1997	Zhang, 2012	SRIO			169.00	21.00	222.00	28.00	−53.00	−7.00
1997	Huimin and Ye, 2010	BTIO			513.00**		165.00**		348.00**	
1997	Ahmad and Wyckoff, 2003	MRIO	3068.00	2708.00	463.00	15.09	102.00	3.32	361.00	11.77
1997	Zhao et al., 2014	MRIO			549.91		177.02		372.89	
1997	Su and Ang, 2010a	MRIO	3258.90	2873.68	535.40	16.43	150.18	4.61	385.22***	11.82
1997	OECD, 2015	MRIO	2723.85	3062.90					−339.06	−12.62
1997	Liu,2015	MRIO	2600.00**							
1998	Yan and Yang, 2010	SRIO	3029.19	2859.29*	292.78*	9.67	122.88	4.06	169.90*	5.61
1998	Qi et al., 2008	SRIO							320.00**	
1998	Huimin and Ye, 2010	BTIO			490.86**		177.00**		313.86**	
1998	Zhao et al., 2014	MRIO			588.42		184.91		403.51	
1998	OECD, 2015	MRIO	2822.66	3139.44					−316.75	−11.22
1998	Liu,2015	MRIO	2700.00**							
1999	Yan and Yang, 2010	SRIO	2992.12	2835.05*	297.30*	9.94	140.23	4.69	157.07*	5.25
1999	Qi et al., 2008	SRIO							390.00**	
1999	Huimin and Ye, 2010	BTIO			520.00**		172.00**		348.00**	
1999	Zhao et al., 2014	MRIO			549.92		222.60		327.32	
1999	OECD, 2015	MRIO	2768.31	3040.36					−272.15	−9.83
1999	Liu,2015	MRIO	2700.00**							
2000	Ren et al., 2014b	SRIO			1000.00**		250.00**		750.00**	
2000	Qi et al., 2008	SRIO							450.00**	
2000	Yan and Yang, 2010	SRIO	2966.52	2793.97*	350.69*	11.82	178.14	6.01	172.55*	5.82
2000	Huimin and Ye, 2010	BTIO			623.00**		367.00**		256.00**	
2000	Su and Ang, 2011	BTIO	3200.80	2670.10					530.60	16.58
2000	OECD, 2013	MRIO	3037.30	2685.60					351.70	11.58
2000	Nakano et al., 2009	MRIO	2935.00	2547.00					388.00	13.22
2000	Shimoda et al.	MRIO	3220.80	2537.00					683.80*	
2000	Zhao et al., 2014	MRIO			607.63		296.38		327.32	
2000	Su and Ang, 2011	MRIO	3200.80	2655.80					545.00	17.03
2000	Weitzel and Ma, 2014-REM	MRIO	3052.00	2305.00	915.00	29.98	168.00	5.50	747.00	24.48
2000	OECD, 2015	MRIO	2978.69	3310.05					−331.37	−11.12
2000	Liu,2015	MRIO	2800.00**							
2001	Qi et al., 2008	SRIO							595.00**	
2001	Yan and Yang, 2010	SRIO	3107.99	2929.85*	358.96*	11.55	180.82	5.82	178.14*	5.73
2001	Pan et al., 2008	SRIO	3050.00	2480.00**				0.00	570.00	18.69
2001	Ren et al., 2014a	BTIO			440.00**		60.00**		380.00**	
2001	Ren et al.,2014b	BTIO			1200.00**		260.00**		940.00**	
2001	Huimin and Ye, 2010	BTIO			634.00**		440.93**		193.07**	
2001	Peters and Hertwich, 2008	MRIO	3289.20	2703.70	803.00*	24.41	217.00*	6.60	585.47*	17.80
2001	Zhao et al., 2014	MRIO			626.13		354.24		271.89	
2001	OECD, 2015	MRIO	3083.47	3396.17					−312.70	−10.14
2001	Liu,2015	MRIO	2900.00**							
2002	Wei et al., 2011	SRIO			267.07		204.08		62.09	
2002	Zhang, 2012	SRIO			206.00	25.00	208.00	25.00	−2.00	0.00
2002	Peters et al., 2007	SRIO	3364.00		1076.00	31.99	1143.76	34.00	67.76	2.01
2002	Qi et al., 2008	SRIO							611.00**	
2002	Weber et al., 2008	SRIO	3620.00	4030.00*	760.00	20.99	1170.00	32.32	−410.00*	−11.33
2002	Yan and Yang, 2010	SRIO	3440.60	3197.62*	458.46*	13.33	215.48	6.26	242.98*	7.06

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Table A1 *(continued)*

Data year	**Author /Year**	**Model**	**PBE** (Mt CO_2)	**CBE** (Mt CO_2)	**EEE** (Mt CO_2)	**EEEP** (%)	**EEI** (Mt CO_2)	**EEIP** (%)	**EEB** (Mt CO_2)	**EEBP** (%)
2002	Pan et al., 2008	SRIO	3250.00	2627.00	880.00	27.08	257.00	7.91	623.00	19.17
2002	Ren et al.,2014	BTIO			510.00**		110.00**		400.00**	
2002	Ren et al.,2014b	BTIO			1500.00**		270.00**		1230.00**	
2002	Huimin and Ye, 2010	BTIO			733.54**		550.21**		183.33**	
2002	Zhao et al., 2014	MRIO			749.01		428.63		310.38	
2002	Su et al., 2010b	MRIO	3587.80	3035.80***	748.86	20.87			552.00***	15.39
2002	Su and Ang, 2014a	MRIO	3558.90	3035.80***	763.20	21.44	240.10***	6.75	523.10***	14.70
2002	Dietzenbacher et al., 2012	DPNHIO	3406.00	2513.00		0.00			893.00*	26.22
2002	Xia et al., 2015	DPNHIO	2606.00	1841.00		0.00			765.00*	29.36
2002	OECD, 2015	MRIO	3247.23	3605.32					−358.09	−11.03
2002	Liu,2015	MRIO	3200.00**							
2003	Qi et al., 2008	SRIO							860.00**	
2003	Yan and Yang, 2010	SRIO	4061.64	3678.03*	661.46*	16.29	277.85	6.84	242.98*	5.98
2003	Pan et al., 2008	SRIO	3855.00**	3000.00		0.00			855.00**	22.18
2003	Ren et al.,2014	BTIO			630.00**		130.00**		500.00**	
2003	Ren et al.,2014b	BTIO			2400.00**		400.00**		2000.00**	
2003	Huimin and Ye, 2010	BTIO			1027.00**		733.23**		293.77**	
2003	Zhao et al., 2014	MRIO			980.60		548.05		432.55	
2003	OECD, 2015	MRIO	3695.27	4176.83					−481.56	−13.03
2003	Liu,2015	MRIO	3800.00**							
2004	Wang and Watson, 2007				1490.00		381.00		1109.00	
2004	Qi et al., 2008	SRIO							1132.00**	
2004	Yan and Yang, 2010	SRIO	4847.33	4271.37*	935.40*	19.30	359.44	7.42	575.96*	11.88
2004	Pan et al., 2008	SRIO	4550.00	3370.00**		0.00			1180.00**	25.93
2004	Ren et al.,2014	BTIO			760.00**		120.00**		640.00**	
2004	Ren et al.,2014b	BTIO			3900.00**		490.00**		3410.00**	
2004	Huimin and Ye, 2010	BTIO			1399.23**		920.26**		472.97**	
2004	Davis and Caldeira, 2010b	MRIO			1600.00**		280**		1320**	
2004	Atkinson et al., 2011-PPP	MRIO	4310.00	3100.00	1400.00	32.48	300.00	6.96	1100.00	25.52
2004	CarbonTrust, 2011	MRIO	4834.00	3740.00	1374.00	28.42	280.00	5.79	1094.00	22.63
2004	Zhao et al., 2014	MRIO			656.41		591.36		28.90	
2004	IEA, 2007	MRIO			1600.00					
2004	OECD, 2015	MRIO	4112.81	4837.21					−724.40	−17.61
2004	Liu,2015	MRIO	4700.00**							
2005	Zhang, 2012	SRIO			422.00		340.00		82.00	
2005	Qi et al., 2008	SRIO							1322.00**	
2005	Yao et al., 2008	SRIO			1460.00		796.00		664.00	
2005	Weber et al., 2008	SRIO	5030.00	5560.00	1670.00	33.20	2200.00	43.74	−530.00*	−10.54
2005	Yan and Yang, 2010	SRIO	5429.30	4690.53*	1178.55*	21.71	439.78	8.10	738.77*	13.61
2005	Lin and Sun, 2010a	SRIO	5457.92	4433.59	3357.42	61.51	2333.09	42.75	1024.33	18.77
2005	Ren et al.,2014	BTIO			920.00**		120.00**		800.00**	
2005	Ren et al.,2014b	BTIO			2500.00**		490.00**		2010.00**	
2005	Huimin and Ye, 2010	BTIO			1760.00**		1211.00**		550.00**	
2005	Lin and Sun, 2010b	BTIO	5457.92	3370.46	267.74	4.91	583.27	10.69	2087.46	38.25
2005	OECD, 2013	MRIO	5062.40	4057.10					1005.30	19.86
2005	Sato, 2014#	MRIO	4508.00	3921.00	794.00	17.61	207.00	4.59	587.00	13.02
2005	Bruckner et al., 2010a	MRIO	4449.00	3459.00	1357.00	30.50	367.00	8.25	990.00	22.25
2005	Pan et al., 2008	SRIO	5000.00	3490.00**					1510.00**	30.20
2005	Zhao et al., 2014	MRIO			1537.02		715.68		821.39	
2005	Weitzel and Ma, 2014	MRIO	5090.00	3665.00	1734.00	34.07	309.00	6.07	1425.00	28.00
2005	Bruckner et al., 2010b		4748.00	3757.00					980.00	20.85
2005	OECD, 2015	MRIO	4449.74	5403.02					−953.29	−21.42
2005	Liu,2015	MRIO	5200.00**							
2006	CASS.,2007##				1846.00		800.00		1000.00	
2006	Qi et al., 2008	SRIO							1766.00**	
2006	Pan et al., 2008	SRIO	5500.00	3840.00					1660.00**	30.18
2006	Yan and Yang, 2010	SRIO	6017.69	5038.47*	1483.99*	24.66	504.77	8.39	979.22*	16.27
2006	Ren et al.,2014	BTIO			1160.00**		240.00**		920.00**	
2006	Ren et al.,2014b	BTIO			3100.00**		480.00**		2620.00**	
2006	Huimin and Ye, 2010	BTIO			2164.23**		1336.58**		827.65**	
2006	Zhao et al., 2014	MRIO			1839.40		771.68		1067.72	
2006	OECD, 2015	MRIO	4736.93	2913.52					−1176.59	−24.84
2006	Liu,2015	MRIO	6200.00**							
2007	Wei et al., 2011	SRIO			718.31		615.65		102.65	
2007	Zhou and Yang, 2011	SRIO			583.40		80186.00–476.80		40106.60–379.40	
2007	Yan and Yang, 2010	SRIO	6499.11	5367.09*	1725.02*	26.54	593.00	9.12	1132.02*	17.42
2007	Zhang, 2012	SRIO			478.00	32.00	278.00	19.00	200.00	13.00
2007	Ren et al.,2014	BTIO			1240.00**		140.00**		1100.00**	
2007	Ren et al.,2014b	BTIO			3400.00**		490.00**		2910.00**	
2007	Huimin and Ye, 2010	BTIO			2493.45**		1650.31**		843.14**	

(continued on next page)

Table A1 *(continued)*

Data year	**Author /Year**	**Model**	**PBE** (Mt CO_2)	**CBE** (Mt CO_2)	**EEE** (Mt CO_2)	**EEEP** (%)	**EEI** (Mt CO_2)	**EEIP** (%)	**EEB** (Mt CO_2)	**EEBP** (%)
2007	Zhao et al., 2014	MRIO			2059.22		908.13		1151.09	
2007	Su and Ang, 2014a	MRIO	6358.90		1770.20	27.84				
2007	Weitzel and Ma, 2014	MRIO	4190.00	3985.00	1879.00	44.84	1782.00	42.53	205.00	4.89
2007	Qi et al., 2014	CGE			1722.00		545.00		1177.00	
2007	Xia et al., 2015	DPNHIO	4727.00	3069.00					1658.00*	35.08
2007	Liu, 2015	MRIO	8500**		1200.00**	14.11	700**	8.23	500*	5.88
2007	OECD, 2015	MRIO	5079.86	6316.85					−1236.99	−24.35
2007	Liu,2015	MRIO	6200.00**							
2008	Ren et al.,2014b	BTIO			3500.00**		500.00**		3000.00**	
2008	Ren et al.,2014	BTIO			1100.00**		180.00**		920.00**	
2008	OECD, 2013	MRIO	6506.80	5204.60					1302.20	20.01
2008	Zhao et al., 2014	MRIO			2540.66		1392.60		1148.06	
2008	OECD, 2015	MRIO	5924.86	6491.46					−1196.60	−22.60
2008	Liu,2015	MRIO	6400.00**							
2009	Ren et al.,2014b	BTIO			2800.00**		480.00**		2329.00**	
2009	Ren et al.,2014	BTIO			800.00**		100.00**		700.00**	
2009	OECD, 2013	MRIO	6800.80	58355.70					965.10	14.19
2009	Zhao et al., 2014	MRIO			2398.96		1423.70		975.26	
2009	OECD, 2015	MRIO	5924.13	6795.11					−870.97	−14.70
2009	Liu,2015	MRIO	7100.00**							
2010	Ren et al.,2014b	BTIO			3400.00**		500.00**		2900.00**	
2010	Ren et al.,2014	BTIO			800.00**		100.00**		700.00**	
2010	OECD, 2015	MRIO	6289.29	7254.46					−965.17	−15.35
2010	Liu,2015	MRIO	7900.00**							
2011	Ren et al.,2014	BTIO			830.00**		120.00**		710.00**	
2011	OECD, 2015	MRIO	6960.58	7956.28					−995.70	−14.30
2011	Liu,2015	MRIO	8400.00**							
2012	Liu,2015	MRIO	8600.00**							

Notes: This table are mostly derived from a working paper in Chinese by ourselves named 'Current Situation and Prospect on Embodied Carbon in International Trade: A Perspective from Bibliometrics' and updated and improved based on the research topic in this review. *values are obtained by EEB=EEE-EEI=PBE-CBE. **values are taken from the figure in the literature approximately. *** Values are calculated by authors based on the literature. # Sato updated this data in (Sato, 2014). ## This value is taken from Wang and Watson (2008). RME= Raw material equivalents. PPP= Purchasing power parity. MER= Market exchange rate. The EEB value from Huimin and Ye [163] is carbon value, and have been converted into carbon dioxide in this table (CO_2 emission factor of each energy type except electricity =(average net calorific power * carbon emissions coefficient *(44/12) * carbon oxygenation efficiency) / the coefficient to transform standard coal). The EEB value from Qi et al. (2008) is estimated in two upper and lower limits. We choose the lower limit value of the EEI to estimate the EEB since the carbon coefficient from Japan (with high energy efficiency) being the carbon coefficient to the import would not underestimate the EEB in China. The Chinese CO_2 emissions data from Bruckner (2010) include emissions from Hong Kong and Taiwan. The EEE from (Su et al. (2010b)) is the value taken by 42 sectors, they developed a test of the impact of sector aggregation on EEE and found around 40 sectors were appropriate for an economy.

Appendix B. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.rser.2016.10.009.

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