Promises and pitfalls in environmentally extended input-output analysis for China: a survey of the literature

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Abstract

As the largest developing economy, China plays a key role in global climate change. Environmentally extended input-output analysis (EE-IOA) is an important and insightful tool seeing widespread use in studying large-scale environmental impacts in China: calculating and analyzing greenhouse gas emissions, carbon and water footprints, pollution, and embedded energy. Chinese EE-IOA are hindered, however, by unreliable data and limited resolution. This paper reviews the body of literature regarding EE-IOA for China in peer-reviewed journals and provides an overview of the articles, examining their methodologies, environmental issues addressed, and data utilized. This paper further identifies the shortcomings in using input-output analyses to gauge environmental impacts in China. Potentially fruitful areas of expansion in Chinese EE-IOA research are denoted, including under-researched environmental issues, underutilized methodologies, and techniques to disaggregate data to move beyond the limitations inherent in official Chinese input-output data.

Keywords: China, input-output, disaggregation

JEL: C67; D57; F18; O53; Q4; Q5

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1.0 Introduction

Environmentally-extended input-output analysis (EE-IOA) has, from the earliest stages of its development in the 1960's and 1970's by Leontief, Ford, Hannon, Bullard and Herendeen, been used to study air pollution and energy (Leontief 1972, Bullard and Herendeen 1975, Herendeen, Ford et al. 1981, Hannon 2010). Since then, it has become a valuable tool for calculating CO2 emissions in countries throughout the world in a wide variety of ways. Within the last 10 years, it has seen increasing use in determining the embodied energy and CO2 emissions in China (Li, Zhang et al. 2007, Su and Ang 2010, Su, Huang et al. 2010, Liu, Geng et al. 2012, Chen and Chen 2013, Shao, Wu et al. 2013, Su and Ang 2013).

While EE-IOA would seem a natural tool to capture both the direct and indirect contributions of China's economic growth to environmental impacts, the methodology is hindered by data availability, reliability, and resolution. The literature review presented in this paper illustrates how authors have succeeded, to greater or lesser degrees, in resolving the conflicts of scale between available data sets to analyze a variety of environmental impacts. This literature review provides a comprehensive overview of the use of EE-IOA to analyse Chinese environmental impacts, surveying the entirety of the literature between 1995 and 2013.

Section 2.0 (Literature Review) of this paper provides a quantitative survey of the body of English-language, published EE-IOA journal articles, describing the range of environmental issues analysed in the literature, how trade is modeled, methodological tools used in conjunction with EE-IOA, the data sets utilized, and the level of sector resolution and aggregation in the data used. Section 3.0 (Shortcomings in Chinese Data) qualitatively describes the biggest obstacles to effective use of EE-IOA in China, including data sources, the Chinese "Other" or "Error" column in data sets, and importantly, data aggregation. Section 4.0 (Room for Expansion) addresses under-analyzed environmental issue areas, underutilized input-output methodologies, and methods for disaggregating data. Finally, Section 5.0 (Conclusions) offers a view of the state of Chinese EE-IOA literature, where it can develop and grow, and how new tools and topics will help drive it forward.

2.0 Literature Review

This section proposes to provide a comprehensive survey of the body of Chinese EE-IOA literature through 2013 along with offering historical context and perspective on the development of methodologies used in conjunction with EE-IOA. This section includes description of the literature selection criteria and a general overview of the scale of published research in the field. The section further presents analysis and discussion of the research impact of published articles, the environmental issue areas studied, perspectives on the analysis of trade and environmental impacts, methodologies used in conjunction with EE-IOA, data sets, and sector resolution and aggregation.

2.1 Literature Selection Criteria

A comprehensive listing of articles studying China using environmentally extended input-output analysis (EE-IOA) was compiled using Rutger Hoekstra's EIO Archive and the Thompson Reuters Web of Science search tool (Hoekstra 2013). Hoekstra's 2010 *(Towards) a complete database of peer-reviewed articles on environmentally extended input-output analysis* prepared for the 18th International Input-Output Conference introduced the criteria he used for assembling a comprehensive listing of all EE-IOA articles published in peer-reviewed journals. Hoekstra's 2010 listing was current through 2009, but his online EIO Archive is current through 2011 (Hoekstra 2010, Hoekstra 2013). Hoekstra's criteria for inclusion in the database included the following:

- "Only articles from English peer-reviewed journals are included.
- Only articles that analyse environmental pressures (emissions, energy or other resources) are included. This includes analyses of the intensity of environmental pressures (i.e. per unit output or value added).
- Corrigenda, errata, announcements and book reviews are excluded.
- Articles are included if they have one or more of the following characteristics:
    - The Leontief inverse is represented mathematically;
    - Empirical results are provided which show that the Leontief inverse has been applied (i.e. they include indirect effects that are based on the fixed technical coefficient assumption);
    - The EE-IO literature, or a specific method is reviewed;
    - Editorials of special issues and articles which provide a "way forward" for future work in EE-IO (including work on databases)"

Hoekstra also noted two notable areas that fall outside the criteria include articles dealing solely with the economic impacts of environmental issues (although papers that include this along with an investigation of environmental pressures are included) and environmental accounts describing only data structure and compilation. Also absent from Hoekstra's database are non-published literature such as conference proceedings and working papers. Hoekstra's search criteria have yielded 510 EE-IOA papers from 1969 to 2011.

For this literature review, Hoekstra's 510 listed EE-IOA papers were reviewed for content about China. Articles providing quantitative EE-IOA analysis for China, either by itself or in conjunction with other nations, were extracted from Hoekstra's database for further analysis. Of the 510 articles listed in the EIO Archive, 60 articles included analysis for China, starting from 1995.

As Hoekstra's database is current only through 2011, this literature survey utilized Hoekstra's search, selection, and exclusion criteria to identify articles from 2012 and 2013. Using Web of Science and searching specifically for studies on or including China, this search yielded 42 additional articles for 2012 and another 44 articles for 2013. As indicated in Figure 1, below, the articles from 2012 and 2013 represent explosive growth in the field of using EE-IOA for China. The articles from 2012 and 2013 more than double the articles published up to that point and now comprise the majority of material published on the subject. Searching with Web of Science for 2012 and 2013 also yielded 5 conference proceedings on EE-IOA in China. As these proceedings represent a marginal portion (approximately 5 percent) of the English-language Chinese EE-IOA studies, it is unlikely that this material would substantially alter the results determined in the sections below. Keeping with Hoekstra's original selection criteria, these proceedings have been left out of the survey of the literature. While it is important to understand the historical context of EE-IOA in China as represented by the studies accounted for in Hoekstra's database, Hoekstra's 2010 review is insufficient to illustrate the use of EE-IOA currently used to study topics in China (Hoekstra 2010). The survey presented in this text amasses the most recent research and observes the trends, movement, and momentum of the current body of work.

2.2 Overview

Combined with the articles extracted from Hoekstra's database for the period from 1969 to 2011, the 2012 and 2013 articles make a total of 146 Chinese EE-IOA papers in peer-reviewed journals. Articles were contributed by 276 authors in 51 journals between 1995 and 2013. Appendix A includes a table listing all of the EE-IOA papers addressing Chinese issues published between 1995 and 2013 and a complete bibliography of the listed papers.

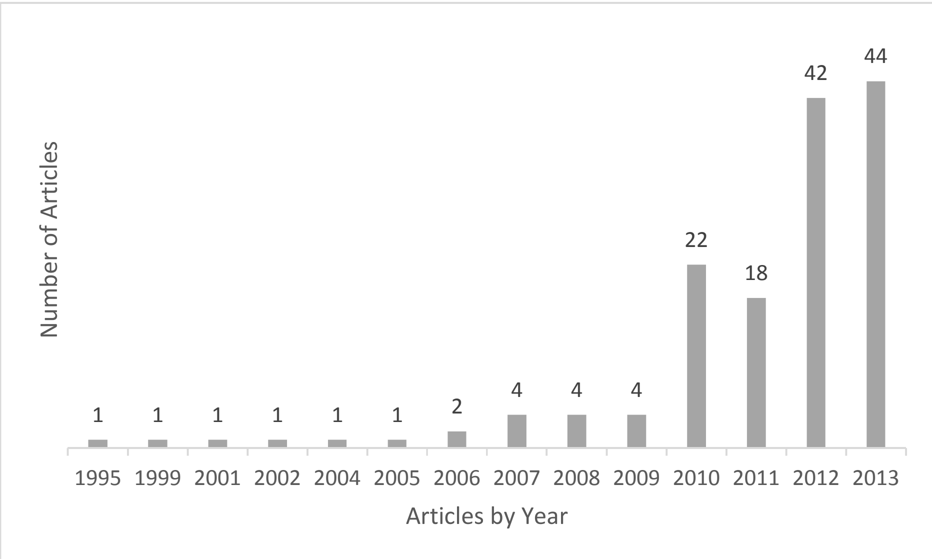

Figure 1. Number of Chinese EE-IOA articles (1995-2013)

Hoekstra notes a period of quick expansion in the EE-IOA literature between 1995 and 2009, with particularly rapid expansion between 2005 and 2009 (Hoekstra 2010). A similar period of expansion is reflected in the numbers for Chinese EE-IOA articles, although expansion in the Chinese studies appears shifted to lag approximately five years behind the rest of the body of literature. Within Hoekstra's own archive collection between 1969 and 2011, Chinese EE-IOA papers make up 12 percent of the total number of papers.

2.3 Journals, Authors, and Citations

As a substantial subset of the general EE-IOA literature, Chinese EE-IOA papers follow some of the trends described by Hoekstra in his 2010 review with regard to journals and authors, but particularly with the rapid expansion of the literature in 2012 and 2013, increasing specialization is leading to divergence among Chinese EE-IOA authors from the rest of the EE-IOA literature. The influence of journals and authors are examined here along with impact of citations with respect to authors and environmental issue areas.

2.3.1 Journals

Chinese EE-IOA articles between 1995 and 2013 have been published in 51 different journals. Table 1, below, lists the top ten journals for Chinese EE-IOA papers by the number of articles published. With 38 of the 146 total studies, *Energy Policy* has published more Chinese EE-IOA papers than any other journal. The top ten journals shown in Table 1 have published 67 percent (100 of the 146 papers) of Chinese EE-IOA articles to date. Hoekstra's 2010 literature review identified *Ecological Economics* one of the most influential journals for publishing EE-IOA papers with *Energy Policy* and *Economic System Research*, similarly supporting the field, but to a lesser degree (Hoekstra 2010). As shown in Table 1, for Chinese EE-IOA literature, *Ecological Economics* provides a valuable outlet for publishing, though substantially less than *Energy Policy*. Similarly, the influence of *Journal of Industrial Ecology* is greater for publishing EE-IOA articles specific to China than in the general EE-IOA literature (Hoekstra 2010). As described in further detail below in Section 2.4 (Environmental Issues Analyzed), this broadly sketches the environmental topics that have dominated the published literature, with substantially greater focus placed on energy and carbon emissions than on other topics such as water, air pollutants, or solid waste.

Table 1. Top 10 Journals Publishing Chinese EE-IOA

Journal	Articles
Energy Policy	38
Ecological Economics	11
Journal of Industrial Ecology	10
Economic Systems Research	8
Energy	8
Environmental Science & Technology	6
Energy Economics	5
Journal of Cleaner Production	5
Natural Resources and Sustainable Development	5
Communications in Nonlinear Science and Numerical Simulation	4

Source: Author's calculation; Web of Science, 2014

2.3.2 Authors

Between Lin and Polenske publishing their first Chinese EE-IOA paper in 1995 and 2013, a total of 276 authors have contributed to the body of English-language journal publications with a total of 1998 citations. These citations do not include references in Chinese-language articles and reports, or non-peer reviewed materials. While many of these authors use EE-IOA to study China in addition to other countries, a substantial proportion have specialized in Chinese EE-IOA. Hoekstra identifies K. Hubacek in his 2010 review as publishing more than 10 papers in the general EE-IOA literature by 2009 (Hoekstra 2010). With additional papers published in 2012 and 2013, Hubacek leads the field of Chinese EE-IOA with 14 publications along with his frequent collaborator, D. Guan. Additionally, S. Liang, G.Q. Chen, and T.Z. Zhang have contributed more than 10 papers on Chinese EE-IOA. Table 2 lists authors who have published 5 or more Chinese EE-IOA articles.

Table 2. Authors with More Than 5 Chinese EE-IOA Published Papers

Author	# of Papers
D. Guan	14
K. Hubacek	14
S. Liang	13
G.Q. Chen	12
T.Z. Zhang	11
Z.M. Chen	9
B.W. Ang	7
K.S. Feng	7
B. Su	7
L. Shao	6
B. Zhang	6
J.E. Guo	5
H.T. Liu	5
G. Peters	5

Source: Author's calculation; Web of Science, 2014

As one of the earliest adopters of EE-IOA for studying China, Hubacek has amassed 644 citations for his papers; almost a third of all Chinese EE-IOA citations. Guan, working with Hubacek on many of these early papers, has 486 citations; nearly a quarter of the total Chinese EE-IOA citations (Web of Science, 2014). Table 3 lists the top 10 authors of Chinese EE-IOA papers by citations. Unsurprisingly, authors of older papers receive considerably more citations that those with newer papers, and authors on some seminal papers rank within the top 10 for only a single or few publications.

Table 3. Top 10 Authors of Chinese EE-IOA Papers by Citations

Author	# of Papers
K. Hubacek	644
D. Guan	486
G.P. Peters/C.L. Weber	378
K. Polenske	227
X. Lin	197
L.X. Sun	166
G.Q. Chen	165
K. Reiner	157
B.W. Ang/B. Su	144
B. Zhang	103

Source: Author's calculation; Web of Science, 2014

2.3.3 Research Impact

Reflecting the work of the authors above in Table 3 and including only references in English-language, peer-reviewed journals as described above, Lin and Polenske's initial foray into using EE-IOA for Chinese topics in 1995 is the most heavily cited paper in the body of literature (Lin and Polenske 1995). Hubacek's early land use paper with Sun and his later carbon dioxide and climate change articles with Guan, Peters, and Weber are all widely cited, as well. Table 4 lists the top 10 most cited studies in the body of literature along with the publishing journal and environmental topic addressed. The environmental topics addressed in the studies are categorized as described below in Section 2.4 (Environmental Issues Analyzed). Where multiple topics are addressed in a publication, this is denoted in the table. With 4 of the top 10 most-cited Chinese EE-IOA articles and the only journal to have more than one publication in the top 10, *Energy Policy* is one of the most influential journals for researchers using EE-IOA to study China. While the older papers shown below tend to exhibit more research impact, it is encouraging to note that more recent papers are also becoming well-cited.

Table 4. Top 10 Most-Cited Chinese EE-IOA Papers

Year	Author	Title	Journal	Env. Topic	Citations
1995	Lin, X. and Polenske, K.	Input–Output Anatomy of China's Energy Use Changes in the 1980s	Economic Systems Research	Energy	197
2008	Guan, D., Hubacek, K., Weber, C.L., Peters, G.P., and Reiner, D.M.	The drivers of Chinese CO2 emissions from 1980 to 2030	Global Environmental Change	CO_2	157
2001	Hubacek, K. and Sun, L.	A scenario analysis of China's land use and land cover change: incorporating biophysical information into input–output modeling	Structural Change and Economic Dynamics	Land	119
2008	Weber, C.L., Peters, G.P., Guan, D., and Hubacek, K.	The contribution of Chinese exports to climate change	Energy Policy	CO_2	113
2007	Peters, G.P., Weber, C.L., Guan, D., and Hubacek, K.	China's growing CO2 emissions - A race between increasing consumption and efficiency gains	Environmental Science & Technology	CO_2	106
1999	Garbaccio, R.F., Ho, M.S., and Jorgenson, D.W.	Why has the energy-output ratio fallen in China?	Energy Journal	Energy	74
2006	Shui, B. and Harriss, R.C.	The role of CO2 embodiment in US-China trade	Energy Policy	CO_2	72
2010	Su, B., Huang, H.C., Ang, B.W., and Zhou, P.	Input–output analysis of CO2 emissions embodied in trade: The effects of sector aggregation	Energy Economics	CO_2	69
2008	Li, Y. and Hewitt, C.N.	The effect of trade between China and the UK on national and global carbon dioxide emissions	Energy Policy	CO_2	54
2007	Liang, Q.M., Fan, Y., and Wei, Y.M.	Multi-regional input-output model for regional energy requirements and CO2 emissions in China	Energy Policy	Energy, CO_2	53

Source: Author's calculation; Web of Science, 2014

2.4 Environmental Issues Analyzed

The Chinese EE-IOA articles were categorized by the environmental issues addressed in the analysis into the following categories:

- Air pollutants (including discussions of emissions other than CO2 and greenhouse gases),
- CO2 (including analysis of greenhouse gases, carbon footprints, and carbon intensity),
- Energy (including embodied energy and energy intensity),

- Land use (including ecological footprints),
- Material flows (include natural resource use),
- Social impacts,
- Solid waste (including recycling), and
- Water (including water pollution, waste water, virtual water flows, and water footprints).

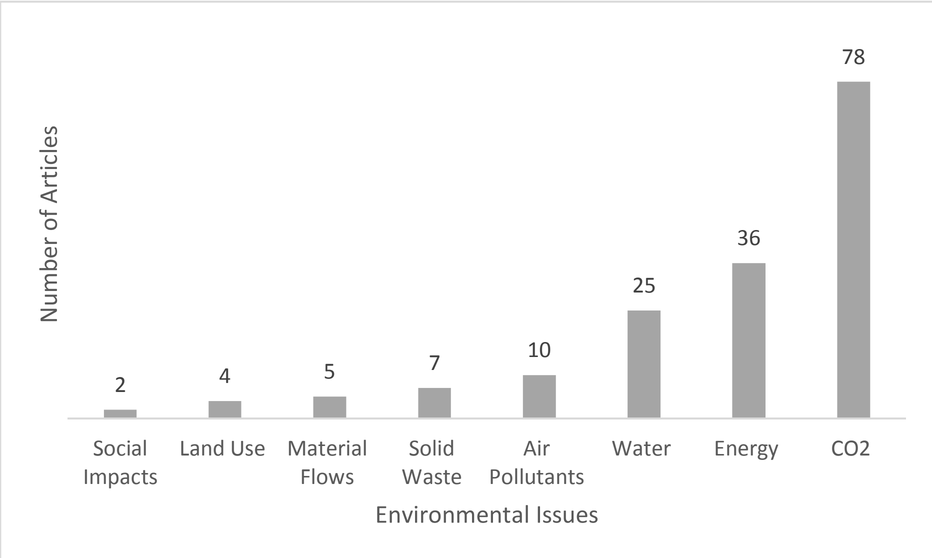

Figure 2. Number of Chinese EE-IOA articles by environmental issue area

While there are 146 total Chinese EE-IOA articles collected for this study, the categories shown reflect that 18 of the papers included research on multiple environmental issues. Hoekstra described in 2010 that EE-IOA articles, in general, from the 1970s to the early 1990s were "almost exclusively dedicated to the analysis of energy consumption", but that global warming has come to dominate research from 2005-2009. As Chinese EE-IOA articles only began being published in English-language journals in 1995, it is understandable how the numbers of issue areas analyzed reflect the transition of focus from energy to CO2. Research on energy has been a constant focus of papers from the earliest Chinese EE-IOA papers, but, mirroring the greater EE-IOA body of literature, the first Chinese CO2 EE-IOA study was published in 2006. Water research and air pollutants, similar to energy, were addressed in some of the earliest Chinese EE-IOA papers, but have continued to be published at lower levels. Studies on material flows, social impacts, and solid waste are relatively recent, but appear to be gaining interest and increasing. Land use and ecological footprints were among some of the earliest topics evaluated for China using EE-IOA, but only a handful of these studies have been published between 1995 and 2013.

As shown in Table 4, above, the top 10 most-cited studies show an almost complete dominance of the field by carbon dioxide and energy studies. This is reflected in the number of citations of Chinese carbon dioxide and energy publications in the greater body of literature. While land use articles comprise less than one-sixth of the total number of water articles, thanks in large part to Hubacek and Sun's early work in 2001, land use articles have three-quarters the number of the citations for water studies. Hubacek and Sun's 2001 paper using EE-IOA to study Chinese land use has 119 citations (Hubacek and Sun 2001). As one of only four papers addressing land use, this provides a disproportionately ratio of citations to papers for land use articles. By comparison, publications on air pollutants, solid waste, material flows, and social impacts all have relatively low numbers of citations and lower ratios of citations to papers.

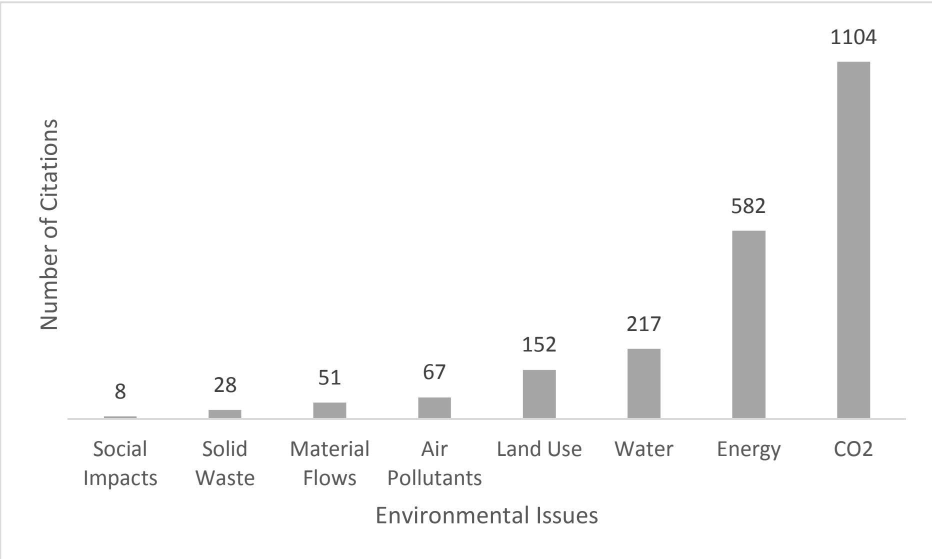

Figure 3. Number of citations by environmental issue area.

2.5 Trade, SRIOs, and MRIOs

In conjunction with examining the impact of the economy on specific environmental issue areas, researchers using EE-IOA for China utilize a variety of lenses through which these impacts can be viewed. A number of these lenses use specific analytical methodologies, such as using structural decomposition analysis (SDA) to identify the drivers affecting environmental impacts, or input-output life cycle assessment (IO-LCA) and hybrid life cycle assessment (hybrid LCA) to study system-wide effects, or scenario analysis to explore projections of different conditional states. While the studies associated with these methodological lenses will be described further below, as discussed here, the environmental effects of the Chinese economy with regard to trade is the most frequently used lens in the current body of literature.

The role of Chinese trade in environmental impacts is a popular perspective with which to use EE-IOA, largely for the following major reasons:

- Following the opening of the Chinese economy to trade in 1978, China has exhibited growth on a scale unparalleled by any other country in the same time period. As China's input-output data is available as far back as 1981, EE-IOA can and has been used to measure the effects of trade on growth and its associated environmental impacts nearly from the beginning of this period if economic expansion.
- Domestically, the economic and environmental landscape of Chinese provinces is highly heterogeneous with wide disparities between urban centers and rural areas as well as

within and between provinces. Trade between these regions drives much of the nation's economy and provincial/municipal input-output tables allows for analysis of resulting environmental impacts, particularly virtual water trade and embodied energy and carbon dioxide emissions.

- In its new place in the international community, China represents one of the top global importers of materials and goods. The demand by China's economy and reliance upon the global market for imports has massive environmental ramifications that use of EE-IOA can measure.
- Inextricably intertwined with Chinese imports is China's role as the largest global exporter, turning around the materials and goods from other nations, combining them with Chinese resources and manufacturing products to be exported across the globe. As with China's imports, the magnitude of environmental impacts associated with China's exports has global implications. With an increasing number of input-output tables being produced around the world, EE-IOA can be used to link China's international trade with both domestic and international environmental impacts.

With these motivations in mind, Chinese EE-IOA literature typically examines trade in one of two ways:

- Using a single-region input-output (SRIO) model and evaluating environmental impacts with respect to the import and/or export data columns of China's IO tables, or
- Using a multi-region input-output (MRIO) model to evaluate environmental impacts with respect to linked regional trade partners.

Although the majority of the overall body of Chinese EE-IOA literature uses SRIO models (105 out of 146 articles), of the 77 articles that examine trade, the majority of the research uses MRIO models (43 of 77 articles). Among the SRIO models used to analyse environmental impacts associated with trade, specifically exports, some authors remove imports from the matrix in order to capture only what is produced in China (Weber, Peters et al. 2008, Su and Ang 2010, Liang, Liu et al. 2013). Lin and Sun's 2010 evaluation of carbon dioxide in Chinese trade is an example of a SRIO masquerading as a MRIO analysis by utilizing the table's import and export data to represent trade with the rest of the world. Lin and Sun use only 15 sectors, but detailed emissions data are linked to these sectors in ways that seem incongruent with such a low level of resolution, raising questions as to the precision of their results (Lin and Sun 2010).

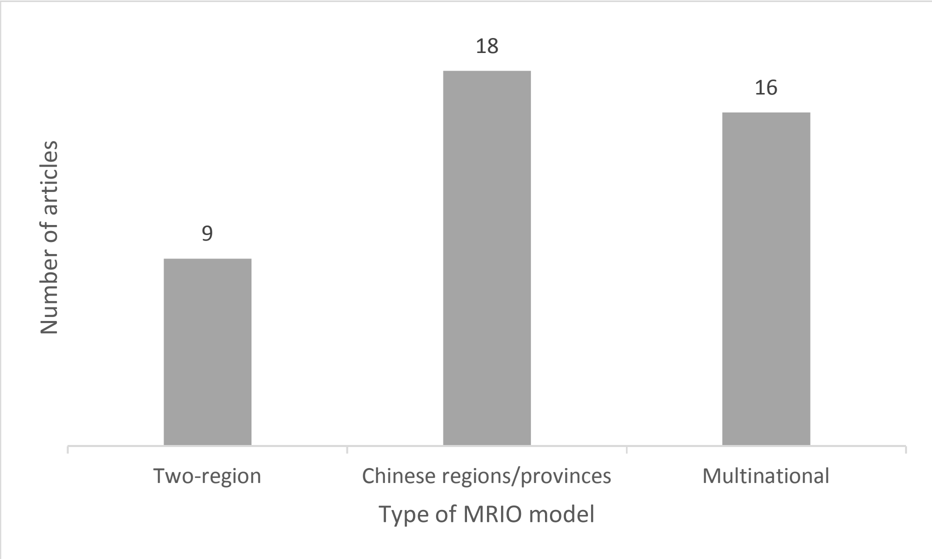

Figure 4. Number of types of MRIO models used in Chinese EE-IOA articles

As shown in Figure 4, of the 43 articles using MRIO models to analysis trade:

- 9 articles examined trade between China and another individual country, predominately between China and the United States and China and Japan,
- 18 articles used MRIOs specifically looking at trade within China between provinces, regional groupings of provinces, and/or large municipalities (Beijing, Tianjian, Shanghai, and Chongqing), and
- 16 articles analyzing trade between China and anywhere from 6 to 129 nations or regional groupings of nations.

While MRIO analyses could similarly be used to look at the specific effects of a Chinese industry or industries on other countries, most MRIO models made for China continue to look at the economy as a whole, much like the SRIO studies. As described above, many of the MRIO models currently developed for China have been sub-national constructs connecting individual provincial input-output tables into a larger system to observe the linkages between China's provinces or groupings of provinces. Hubacek and Sun's 2005 sub-national MRIO water use study was innovative as it was among the early Chinese water resource studies, and additionally, it was the first Chinese water resource MRIO to model water supply regions and then use the model to study a range of future water use scenarios (Hubacek and Sun 2005). A variety of subsequent Chinese sub-national water use MRIO studies have been conducted, each refining and building on Hubacek and Sun's methodology (Guan and Hubacek 2007, Guan and Hubacek 2008, Hubacek, Guan et al. 2009, Feng, Chapagain et al. 2011, Feng, Siu et al. 2012). These studies typically used 40-sector IO tables for their economic data, although Hubacek and Sun's 2005 study is particularly notable for its disaggregation of the agriculture sector to account for changes in diet (Hubacek and Sun 2005). Also notable is Feng, et al's 2013 Chinese CO_2 MRIO study of industry sectors and 30 Chinese sub-regions along with 107 individual countries. This study started off by using 42 industry sectors, but disaggregated the data to 57 sectors to accommodate the trade flow data and use of the global trade database version 8 published by the Global Trade Analysis Project (GTAP) (Feng, Davis et al. 2013). As the use of MRIO models becomes popular and prevalent and further data for other nations becomes available through institutions like GTAP, disaggregation of Chinese IO tables becomes all the more crucial to allow for straightforward use of these data resources.

2.6 Methodological Tools in Conjunction with EE-IOA

Much like in the greater EE-IOA literature, SDA, IO-LCA, hybrid LCA, and scenario analysis are frequently used in conjunction with published Chinese EE-IOA studies.

2.6.1 Structural Decomposition Analysis

SDA is used in input-output analysis to evaluate the drivers behind changes to economic outputs. These drivers are typically broken into changes in technology and final demand that can, in turn, be further broken down into technological change and product mix and the overall level of final demand and compositional change in final demand. These drivers can be broken down and categorized in a variety of other ways (Miller and Blair 2009). Lin and Polenske used EE-IOA to conduct the first environmentally-related SDA of the Chinese economy in 1995, finding increased energy efficiency to drive China's decline in energy intensity between 1981 and 1987. Lin and Polenske's study utilized eight final demand sectors and 18 industrial groups, noting that they would have preferred to use more industrial sectors, but that the energy consumption data for such a level of detail was unavailable (Lin and Polenske 1995). Lin and Polenske were the first of 39 studies to use SDA with Chinese EE-IOA to better identify the drivers in economic changes resulting in environmental impacts. The majority of these studies address important trends in Chinese resource use and pollution, but because of the high level of aggregation in the data used, largely serve as economic overviews.

Su and Ang, in contrast, have creatively used EE-IOA with SDA as much to compare differing methodologies as to report on embodied CO2 emissions in trade. Su and Ang used 110 sectors in their 2012 empirical study of China's CO_2 emissions with four different methods of SDA as well as with index decomposition analysis (Su and Ang 2012). Examining the level of detail used in previous studies, Su, et al's 2010 examination of sector aggregation with regard to SDA for CO_2 emissions found that 40 sectors appears sufficient to capture the results and that additional disaggregation would have little impact on values obtained in the analysis (Su, Huang et al. 2010). While this may be sufficient for exploratory evaluation of the entire economy, this level of sectoral aggregation limits the ability of researchers to delve more deeply into the specific effects associated with a single sector or grouping of sectors. At finer levels of analysis, however, and as acknowledged by Su, et al., the sufficiency of using only 40 sectors in an analysis is questionable (Su, Huang et al. 2010). These limitations due to sector aggregation will be further discussed below in Section 3.4 (Aggregation).

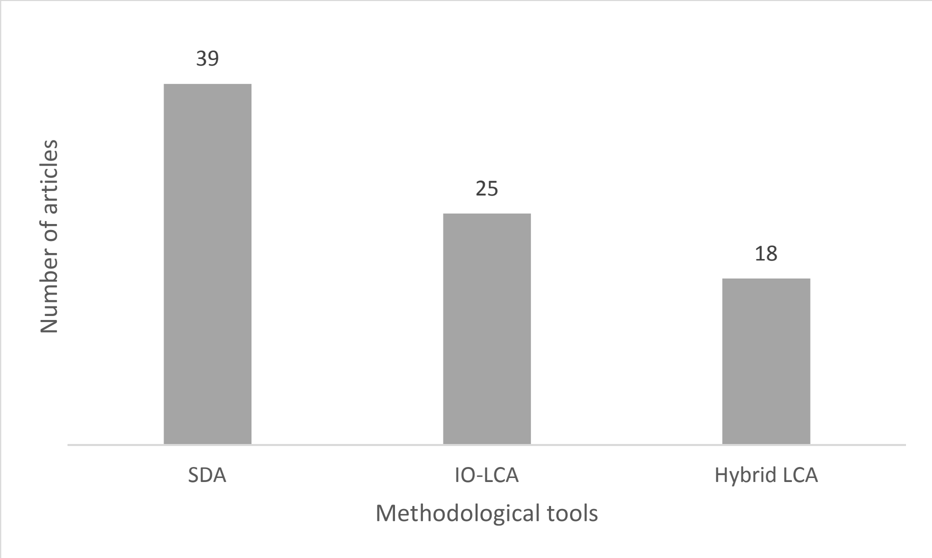

Figure 5. Number of articles utilizing SDA, IO-LCA, and hybrid LCA

2.6.2 Input-Output Life Cycle Assessment/Hybrid Life Cycle Assessment

Input-output life cycle assessment (IO-LCA) was developed in an attempt to provide a "system-wide view" for the study of means to reduce pollution and improve sustainability practices in manufacturing (Hendrickson, Lave et al. 2006). Due to the data intensive and bottom-up nature of traditional life cycle assessment (LCA), LCA can be excellent for measuring direct inputs, but it has difficulty accounting for indirect inputs. IO-LCA, by contrast, provides a top-down approach to life cycle analysis, having the advantage of accounting for both direct and indirect inputs (Wang, Zhang et al. 2012). In 2002, Polenske and McMichael published the first English-language Chinese EE-IOA using IO-LCA, using an input-output process model focusing specifically on the Chinese coke-making industry (Polenske and McMichael 2002). While this paper used a process model rather than an industry-by-industry input-output model more commonly used in recent Chinese IO-LCA papers, the study opened the door for expanded use of IO-LCA in the Chinese EE-IOA literature. In the period between 2002 and 2013, including Polenske and McMichael's paper, 25 Chinese IO-LCA papers have been published. While many of these IO-LCA papers have been used to examine economy-wide effects, articles have been published on specific products and industries ranging from straw-based energy (Liu, Polenske et al. 2010, Lu and Zhang 2010), to the tire and paper industries (Yang, Chen et al. 2010, Liang, Zhang et al. 2012), to building construction and tile manufacturing (Kuhtz, Zhou et al. 2010, Chang, Ries et al. 2013). Many of these, rather than using Chinese national, provincial, or municipal input-output tables are built on physical input-output tables developed using industry data. There remains an analytical gap, however, between these IO-LCAs using industry data and those using economy-scale data (Wang, Zhang et al. 2012).

Feng, et al's 2011 study compares top-down approaches like IO-LCAs with more highly-detailed, bottom-up LCA studies, and suggests that hybrid approaches are necessary to reconcile discrepancies between the two methodologies (Feng, Chapagain et al. 2011). Wang, et al's 2012 approach highlights how top-down and bottom-up methods can be hybridized by using process-based LCA to inform the direct inputs and IO-LCA to account for the indirect and embodied inputs (Wang, Zhang et al. 2012). As hybrid LCA and IO-LCA use overlapping methodologies in many ways, the distinction between the two is not always clear: some studies using IO-LCA may identify themselves as hybrid LCA and vice versa (Lindner 2013). Lu and Zhang's bioenergy study published in 2010 is the earliest self-identified Chinese EE-IOA hybrid LCA study (Lu and Zhang 2010). Between 2010 and 2013, a total of 18 hybrid LCA studies have been published on topics including energy and greenhouse gas emissions, bioenergy, wastewater, wind power, and building construction (Lu and Zhang 2010, Chang, Ries et al. 2011, Chen, Shao et al. 2011, Yang and Suh 2011, Chang, Ries et al. 2012, Li, Feng et al. 2012, Chang, Ries et al. 2013).

2.6.3 Scenario Analysis

Scenario analyses are used to assess how changes (most typically in the EE-IOA literature associated with supply and demand, policy, and/or technology) affect current or projected conditions. Hubacek and Sun published the first EE-IOA study to use scenario analysis with Chinese data in 2001 (Hubacek and Sun 2001). In addition to being the first among the few EE-IOA studies examining land use impacts, Hubacek and Sun projected future production functions using a combination of the RAS method (where "R" is the diagonal matrix of elements modifying rows, "A" is the coefficient matrix to be modified, and "S" is the diagonal matrix of column modifiers, thus "RAS") and case studies (Stone 1962, Bacharach 1970, Hubacek and Sun 2001, Miller and Blair 2009). Hubacek and Sun constructed six scenario projections to the year 2025 and evaluated land use changes based on these scenarios (Hubacek and Sun 2001).

Following variations on this initial model, 20 additional articles have been published through 2013 using scenario analysis. Most of the scenarios published develop projections between 2010 and 2025 (15 articles), with only a handful that extended scenarios out between 2030 and 2057 (5 articles).

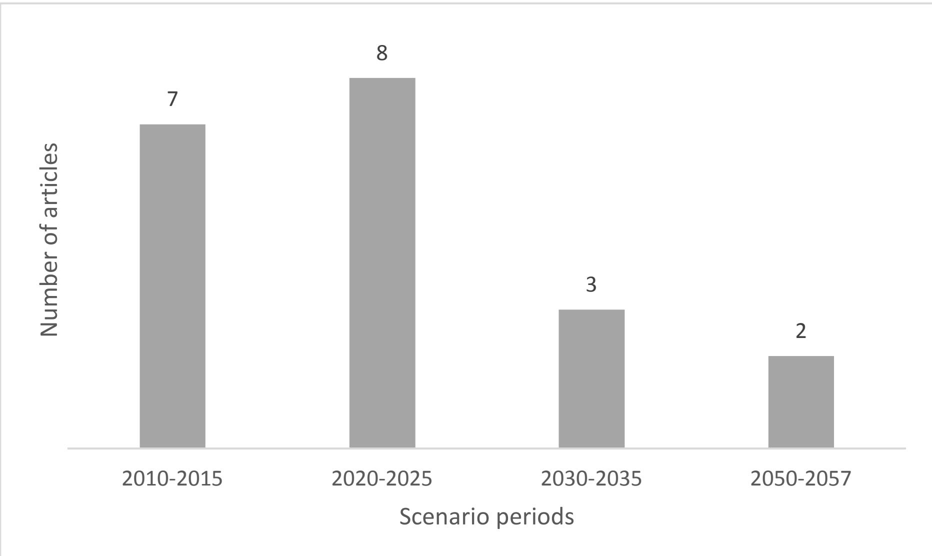

Figure 5. Number of articles using scenarios for the years 2010-2015, 2020-2025, 2030-2035, and 2050-2057

Additionally, four articles diverge from the model introduced by Hubacek and Sun by using scenario analysis without linking to time periods. Rather than looking at projections for time periods, two of these articles focus on alternative policy scenarios (Liu, Guo et al. 2009, He and Jim 2012) while the other two utilize physical input-output analyses to examine alternative processes and technologies (Qu, Zhang et al. 2013, Zhang, Wang et al. 2013).

2.7 Data Sets

China's National Bureau of Statistics started publishing trial IO tables in the late 1970's, and in 1991 produced their first national table with 117 sectors for the year 1987. Since then, China has produced detailed IO tables (110 industry sectors or more) every five years: 1987, 1992, 1997, 2002, and 2007. Additionally, China produces aggregated IO tables (less than 40 sectors) for the same years as the detailed tables as well as for interim years with the last digit being '0' or '5' (e.g. 1995, 2000, 2005, etc.). Simultaneously, China publishes 30 provincial input-output tables at the same time intervals and roughly similar levels of aggregation, including for the four largest municipal centers: Beijing, Chongqing, Shanghai, and Tianjian.

The vast majority of Chinese EE-IOA studies have utilized data directly from the National Bureau of Statistics (NBS), with 119 of 146 articles utilizing NBS input-output tables or data directly from these tables. Another 10 studies use data indirectly from the NBS, where the input-output tables have been compiled and repackaged by outside organizations including (IDE-JETRO 2003, IDE-JETRO 2006, GTAP 2007, OECD 2007):

- Institute of Developing Economies-Japan External Trade Organization (IDE-JETRO) (Kagawa and Inamura 2004, Dong, Ishikawa et al. 2010, Liu, Ishikawa et al. 2010, Su and Ang 2011);
- Global Trade Analysis Project (GTAP v.7 and v.8) (Weber, Peters et al. 2008, Chen, Chen et al. 2012, Yu, Feng et al. 2013); and
- Organisation for Economic Co-operation and Development (OECD) (Amador 2012, Bruckner, Giljum et al. 2012, Lopez, Arce et al. 2013).

Of the remaining articles, 6 used other countries' data with coefficients modified to represent Chinese data:

- Carnegie-Mellon's Green Design Initiative – modified United States data (Shui and Harriss 2006, Yan and Yang 2010, Mo, Zhang et al. 2012, Wang, Zhang et al. 2012); and
- United Kingdom Office for National Statistics Input-Output Analytical Tables – modified United Kingdom data (Li and Hewitt 2008, Tang, Snowden et al. 2013).

The remaining 13 articles either do not explicitly state the source of their input-output data or construct their own input-output tables based on specific industry data.

2.8 Sector Resolution

Ninety-one of Chinese EE-IOA studies use IO tables with 50 sectors or less. Only eight articles utilize China's detailed IO tables which have between 95 and 124 sectors. Most studies start by using a higher number of sectors than they ultimately use in the analysis and then aggregate sectors together either to match easily available environmental data. In many cases, the relatively low number of sectors allows for more complex manipulation of data, such as the development of scenarios based on historical IO tables (Hubacek, Guan et al. 2007, Guan, Hubacek et al. 2008, Zhang and Chen 2008, Hubacek, Guan et al. 2009). Only a small fraction of the published studies disaggregated sectors (11 of the 146 papers), though it is notable that disaggregation was used among the earliest Chinese EE-IOA studies. These early studies used disaggregation to examine specific industries or industry groupings within the context of the larger economy (Lin and Polenske 1995, Hubacek and Sun 2001, Hubacek and Sun 2005). Only in the last few years have authors disaggregated sectors in the detailed IO tables for higher resolution analysis, resulting in tables with up to 135 sectors (Yang and Suh 2011, Liang, Xu et al. 2013, Su and Ang 2013, Su, Ang et al. 2013, Vause, Gao et al. 2013).

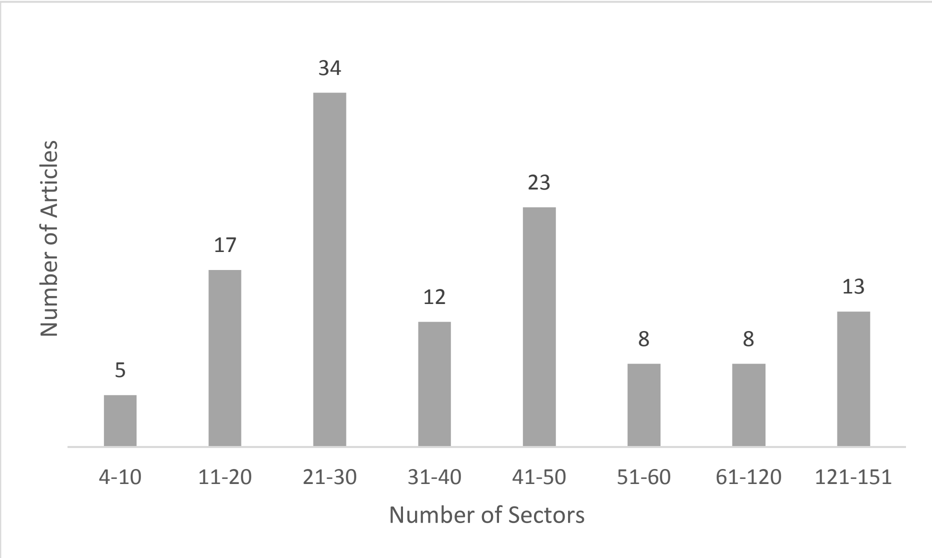

Figure 5. Number of sectors per Chinese EE-IOA study

The wide range of sectors used in articles raises the question as to what level of detail is needed for sector resolution. As most of the published studies have been designed to use IO models to explore the Chinese economy as a whole, it has been unclear how much of a difference the number of sectors analyzed has on the outcome of the model. Additionally, comparison of studies of similar topics is made difficult when the articles utilize differing levels of sector aggregation. Su, et al. demonstrated in their 2010 paper that around 40 sectors are sufficient to capture the effects of emissions embodied in trade and that additional disaggregation would contribute little to the observed results. The authors note that additional research is necessary to determine if these findings are more generally applicable outside the empirical study they performed (Su, Huang et al. 2010). At this point, little evidence outside of this has been published to show how the level of sector resolution affects study results.

3.0 Shortcomings in Chinese Data

Data published by China's National Bureau of Statistics has come under fire for its veracity for well over a decade. Garbaccio, et al's study specifically noted new product bias, deverticalization, and falsification of statistics as sources of error in Chinese EE-IOA in 1999 and was followed not long after by Rawski's influential 2001 *What is happening to China's GDP statistics?* which questioned the veracity of the National Bureau of Statistics data on a larger scale (Garbaccio, Ho et al. 1999, Rawski 2001). In the same year, Sinton's 2001 *Accuracy and reliability of China's energy statistics* raised questions specifically with regard to energy and emissions data (Sinton 2001). And while the Chinese government has worked to improve the reputation of its data, the validity of Chinese data continues to be questioned and disputed (Hsu 2013).

Considering the volume of data required for EE-IOA, special consideration should be given to potential sources of error, particularly in light of inconsistencies found Chinese data. The National Bureau of Statics and local statistical agencies are not established in a political vacuum and are often pressured by other agencies to provide statistics that conform to agency goals or policies (Guan, Liu et al. 2012). Most conspicuously, and directly related to questions over Chinese gross domestic product (GDP) figures, Chinese input-output tables are published with the inclusion of an "Others" or "Error" column. The "Others/Error" column is included with the final demand to ensure that the sum of the value added columns equals the GDP (Guan 2007). Finally, the quality of Chinese input-output data is limited by its level of resolution, as indicated by Guan most effectively with respect to spatial aggregation and Su and Ang with regard to sectoral aggregation (Su, Huang et al. 2010, Guan, Liu et al. 2012).

This section addresses the shortcomings in Chinese data used in EE-IOA from the most noticeable to the less-evident. This section offers qualitative discussion on the following:

- The ever-present "Others" column in Chinese input-output tables;
- The reliability of official sources for economic and environmental data; and
- Aggregation and the level of resolution in published data.

3.1 The "Others" Column

As outlined in the Supplemental Information for Peters, et al in 2007, the "Others" column is found in all Chinese input-output tables with the exception of the 1995 tables and represents the difference between the sectoral Gross Domestic Product (GDP) and the sectoral final demand. In other words, the GDP represented by the summed value added columns only agrees with the summed final demand when the "Others" column is included in the calculations. Peters, et al describes the Chinese National Bureau of Statistics treating the "Others" column as "an estimate of an error term representing different data sources" used to normalize the data (Peters, Weber et al. 2007). Peters, et al, Weber, et al, and Hubacek, et al similarly identify the "Others" column as a specific error term necessary to balance the Chinese input-output tables (Peters, Weber et al. 2007, Weber, Peters et al. 2008, Hubacek, Guan et al. 2009).

Peters, et al further identify in their Supplemental Information that while the "Others" column represents an error of less than 1 percent in aggregated GDP, that the "Others" figure can be up to 8 percent of output for individual sectors or can overwhelm the final demand figure (Peters, Weber et al. 2007). Hubacek, et al notes that the error for industry transactions is higher than the net-export figure for industrial goods (Hubacek, Guan et al. 2009). Chen and Zhang and Yang and Suh both point out the "Others" column in Chinese input-output tables and indicate that this source of error should not be ignored (Chen and Zhang 2010, Yang and Suh 2011). As described by Peters, et al, however, because of the magnitude of the figures in the "Others" column, there is no clear treatment that allows for the avoidance of the specious data (Peters, Weber et al. 2007).

While the explicit display and discussion of an error term by the Chinese National Bureau of Statistics is laudable, it raises troubling questions regarding the treatment of error in input-output tables for China as well as other countries' national accounts. Through the inclusion of the "Others" column in China's input-output tables by the National Bureau of Statistics, the Chinese government makes the error term in its data apparent and available for researchers to account for in their calculations. Lacking such a column to account for error, researchers using the input-output tables of other countries must make assumptions about implicit error within the data sets. In turn, however, this puts the eye of scrutiny back on China and its National Bureau of Statistics, causing researchers to question how much more error is implicit within Chinese input-output data in addition to the explicit error admitted to in the "Others" column.

3.2 Reliability of Official Data Sources

Garbaccio, et al, whose 1999 study was the second on China published using EE-IOA, address the questionability of official Chinese data with an entire section discussing the issue. The authors cite studies of Chinese GDP through the 1990s, identifying deverticalization, new product bias, and especially falsification of data as being well-documented problems in China (Garbaccio, Ho et al. 1999). In 2001, Rawski, whose earlier work was cited by Garbaccio, et al in 1999, published bold assertions that China's National Bureau of Statistics was producing substantially exaggerated GDP figures. Rawski found the National Bureau of Statistics blaming fabrication and overestimation on low-level statistical agencies. Rawski contends that the result of these data errors could potentially aggregate to Chinese GDP growth being only one-third or less of officially released statistics (Rawski 2001). Subsequently in 2001, Sinton addressed the issue of official Chinese data reliability with respect to energy statistics. Sinton identified misreporting, non-reporting, and unreliable data collection as being primarily responsible for inaccurate Chinese energy data (Sinton 2001).

Guan, et al (2012) and Hsu (2013) pursue the motivation behind data falsification for energy and environmental statistics. Guan, et al caution that statistics departments are not independent of politics and are embedded in a greater matrix of the agendas and motivations of other agencies. The authors argue that local and regional agencies have it in their best interest to overestimate GDP figures while underestimating energy consumption data (Guan, Liu et al. 2012). Hsu looked specifically at data collection and verification at the local and regional levels, interviewing many officials and finding a desire for improved accuracy in data collection, but motivation for the falsification and distortion of data and a mistrust for third-party verification of data (Hsu 2013). Hsu cites Liu and Yang describing the phenomenon of "numbers make leaders, and leaders make numbers" to characterize the incentives to adjust data to suit the needs of officials (Liu and Yang 2009, Hsu 2013).

Many researchers, however, take the potential errors from the National Bureau of Statistics in stride. Liu and Zhang acknowledge the error inherent in the government statistics due to the transformations and manipulation the data undergoes before being published, but accede that the government statistics are authoritative because they are the most widely used (Liang and Zhang 2011). Similarly, Fang, et al acquiesce the issue of questionable official data by ratifying their results as being reasonable in comparison to similar previous work in China (Fang, Wei et al. 2012). Does this make Chinese economic research a case of social relativism, however, with authors and their conclusions beholden to the National Bureau of Statistics? Liu, et al conclude that while the official statistics are the only open published data source available for China and that further manipulation of the statistics to improve them is currently impossible, improvements in statistics must come from other data sources (Liu, Geng et al. 2012). As comparing results based on poor data to other studies based on poor data can only lead to confirmation of inaccuracy, using official Chinese data in conjunction with other sources is essential to ensure the veracity and robustness of research conclusions.

3.3 Aggregation

Data aggregation has long been seen as a source of error in EE-IOA. As opposed to other forms of questionable data, however, where there is little to be done to correct or treat suspect data, disaggregation techniques have been developed to resolve some of error associated with aggregation as well as overcome some of the limitations of input-output analysis. Treloar, in 1997, identifies these limitations, arguing that EE-IOA is unreliable due to “assumptions regarding tariffs and the homogeneity and proportionality of sectors.” Treloar adds, however, “More highly disaggregated input-output tables similarly would resolve some, but not all of the errors relating to the homogeneity assumption” (Treloar 1997). Many of the authors of Chinese EE-IOA studies describe the uncertainty introduced into their analysis as a result of aggregation and encourage the efforts of other researchers to disaggregate data for improved results (Su and Ang 2010, Su, Huang et al. 2010, Zhao, Yang et al. 2010, Du, Guo et al. 2011, Zhang, Shi et al. 2011, Bruckner, Giljum et al. 2012, Guo, Zhang et al. 2012, Liu, Geng et al. 2012). Fewer studies actually take up the mantle of disaggregating their data to improve the resolution of their research (Lin and Polenske 1995, Hubacek and Sun 2005, Su and Ang 2010, Su, Huang et al. 2010, Su and Ang 2011, Yang and Suh 2011, Lindner, Legault et al. 2013).

While temporal aggregation has received limited attention, and primarily in the context of SDA (Su and Ang 2012), aggregation in the Chinese EE-IOA literature has mainly been discussed with regard to spatial aggregation and sectoral aggregation. Spatial aggregation addresses the geographical level of resolution for which data is published. With the input-output tables produced by the Chinese National Bureau of Statistics, the most common scales of resolution are the national and provincial levels of data. Su, et al and Guan, et al show data discrepancies between these two levels and demonstrate how these differences affect study results (Su, Huang et al. 2010, Guan, Liu et al. 2012). Sector aggregation, on the other hand, is the level of detail by which industries in an input-output table are divided. As described above in Section 2.8 (Sector Resolution), Chinese EE-IOA studies use a huge variety of levels of aggregation in their research. As implied by Su, et al (2010), with such variations in sector aggregation, researchers using the same data set for the same year may not yield consistent results.

Lenzen's advocacy for disaggregation has been influential in the general body of EE-IOA literature, and Su and Ang and Su, et al, drawing on Lenzen's example, have championed the benefits of disaggregation in Chinese EE-IOA literature (Su, Huang et al. 2010, Lenzen 2011, Su and Ang 2012, Su and Ang 2013). Sectoral aggregation has received considerably more attention within the Chinese EE-IOA literature, with researchers viewing data disaggregation as a means to overcome the questionable quality of official published data (Liu, Geng et al. 2012).

Su, et al (2010) and Zhang, et al (2011) describe that the primary challenge of using disaggregated data is finding appropriate matches between detailed economic and trade data and environmental and emissions data. Data availability plays a large role in this as industry and environmental data are only published at more aggregated levels (Zhao, Ma et al. 2010). Consequently, it is often up to the researcher to disaggregate the data on their own, using the RAS or more recently developed random-walk methods to break aggregated data into higher resolution (Hubacek and Sun 2005, Dietzenbacher, Pei et al. 2012, Lindner, Legault et al. 2012, Lindner, Legault et al. 2013). Su, et al argue for the use of multiple scales of aggregation in research for the sake of robustness when the data is available, however, this is often not the case (Su, Huang et al. 2010).

In a landscape where the official published data is suspect and the magnitude of data necessary for EE-IOA is massive, little can be done to independently verify the data collected. Disaggregation of published data allows researchers to observe higher levels of detail while corroborating official Chinese input-output tables against other sources of data collected from industry or other organizations. While this requires a substantial amount of effort, studies produced using these techniques emerge more technically robust and better able to withstand critique. Section 4.3 (Disaggregation of Data), below, describes in greater detail the techniques available to bolster Chinese EE-IOA by disaggregating official data to a higher resolution.

4.0 Room for Expansion

As described above in Section 2.0 (Literature Review), there are a handful of environmental issue areas and methodologies that have been explored and used extensively in the body of Chinese EE-IOA research. The lack of publications about other environmental issues, however, has much to do with the limitations of analytical techniques and data. This section describes the following:

- High-profile environmental issue areas that are under-analyzed with EE-IOA, but are in the Chinese public spotlight;
- Available, but underutilized methodologies used in conjunction with EE-IOA and how they can be used with Chinese data; and
- Disaggregation techniques to overcome the limitations and unreliability of Chinese data sets.

4.1 Environmental Issue Areas

Section 2.4 (Environmental Issues Analyzed), above, showed that the predominance of Chinese EE-IOA research has been focused on energy, CO_2, air pollutants, and water issues. In recent years, the Chinese government has shown greater awareness of energy use and both air and water pollution, making the volume of studies on these topics particularly cogent to current stated government policies. Additionally, however, Chinese officials are speaking at greater frequency regarding the issues of land use and solid waste, which have not seen as many published EE-IOA papers. Erosion and restoration of arable land for farming, however, has increased interest in Chinese land use (Naylor, Steinfeid et al. 2005). With the implementation of sweeping food waste reduction policies by the Chinese government, however, a great amount of media attention is on solid waste and material flows (Magistad 2013, Vermeulen 2014).

Hoekstra notes that in the greater body of EE-IOA literature that studies of land uses, and particularly ecological footprints, have increased rapidly (Hoekstra 2010). While there have been a handful of Chinese EE-IOA papers published about land use and ecological footprints, including Hubacek and Sun's 2001 article laying out the groundwork for linking biophysical information in EE-IOA, Chinese EE-IOA has not seen the increases in studies found in the international literature (Hubacek and Sun 2001). Hubacek returns to the topic of land use with Yu, et al (2013) to demonstrate how the use of EE-IOA to study land uses has changed with increased global data and the use of MRIOs. The authors note the continued challenges with compiling consistent land use data, but found enough data from national government agencies to be sufficient for the model (Yu, Feng et al. 2013). With improvements in satellite imagery, land use mapping, computing power, new MRIOs, and accessibility to geographic information systems software, research on Chinese land use and ecological footprints may soon experience the rapid growth seen for other nations in the greater body of EE-IOA literature.

All of the seven Chinese EE-IOA articles on the topics of solid waste and material flows were published in 2012 and 2013, demonstrating substantial interest and growth in these areas. He, et al (2013) cite recent improvements in data availability, treatment of uncertainties, and the development of software and applications have made EE-IOA easier for Chinese studies. Liang and Zhang (2013), Qu, et al (2013), Liang and Zhang (2012), and Liang, et al (2012) describe improvements in modeling that allow for improved analysis and discussion of solid waste and material flows in China. As with improvements for land use data, it is anticipated that these continued improvements in waste data availability and software will attract increasing numbers of researchers to publish on the subject.

4.2 Methodologies

As described above in Section 2.6 (Methodological Tools in Conjunction with EE-IOA), IO-LCA and Hybrid LCA are utilized in only a small portion of the 146 Chinese EE-IOA papers published through 2013. Hoekstra identifies IO-LCA in the general literature as one of the strains of EE-IOA with a high impact factor and notes significant increases in the number of studies published using IO-LCA (Hoekstra 2010). With the exception of two early IO-LCA papers in 2002 and 2006, all other papers using IO-LCA and Hybrid LCA have been published since 2010, with the majority published in 2012 and 2013.

Articles using IO-LCA and Hybrid LCA reflects that of the body of Chinese EE-IOA literature: largely similar to the topics in the overall Chinese EE-IOA literature, but with a greater proportion of publications examining solid waste and material flow issues. As addressed by Chang, et al (2010), IO-LCA is useful for observing the supply chain of a product and the energy consumption and environmental impacts of each life-cycle phase, but is often unsuitable for specific case studies. Hybrid LCA, on the other hand, proves particularly capable for the analysis of case studies through the examination of main processes in detail while estimating far upstream flows (Dong, Geng et al. 2013). The range of studies using both IO-LCA and Hybrid LCA indicate, however, that while these methods can be used to study tightly focused environmental questions, with a great enough set of data, they can be used to examine larger-scale environmental issues.

4.3 Disaggregation of Data

Disaggregation has been recognized as an important issue for furthering the development of input-output analysis, in general, and EE-IOA, specifically, for decades (Fei 1956, Wolsky 1984, Treloar 1997, Wiedmann, Wilting et al. 2011). Disaggregation of data in EE-IOA provides for greater levels of distinction in the analysis of industrial sectors, processes and products, and environmental impacts (Su, Huang et al. 2010, Wiedmann, Wilting et al. 2011). Not surprisingly, methods for disaggregating input-output sectors have similarly been sought for decades (Wolsky 1984, Treloar 1997).

The widely-utilized RAS approach was developed by Richard Stone in the 1960s as an iterative proportional method or biproportional method of modifying the input coefficients in an input-output table (Stone 1962, Polenske 1997). While the technique is most commonly used to update input-output tables, it can also be used to disaggregate data within an input-output table, including environmental data associated with industry sectors or processes (Miller and Blair 2009, Fan and Xia 2012, Su and Ang 2012, Feng, Davis et al. 2013).

The RAS technique generates modified input coefficients using three pieces of information for each sector in the economy:

- Total gross outputs,
- Total intermediate sales, by sector, and
- Total intermediate purchases, by sector (Miller and Blair 2009).

Using this information for the target year (be it an update to make the matrix consistent with current economic data or a projection of data to a target future year), RAS iteratively scales column and then row elements by prorating to column totals and row totals until the matrix satisfies the target year row and column totals. RAS can be further improved with the inclusion of accurate exogenous information, and these variants are used by the United States Bureau of the Economic Analysis and European Union Eurostat agencies to update input-output tables for non-benchmark years (Miller and Blair 2009).

Disaggregation using RAS follows a similar iterative procedure, and requiring the three pieces of information described above for all of the target subsectors the aggregated industry sector will be divided into. Starting with common intermediate input coefficients for subindustries, the column and row elements are progressively scaled until the matrix satisfies the target subindustry row and column totals (Timmer 2012).

In the Chinese EE-IOA literature, RAS is used extensively for updating input-output matrices (Hubacek and Sun 2001, Liang, Fan et al. 2007, Hubacek, Guan et al. 2009, Fan and Xia 2012, Wang, Zhang et al. 2013) and many of the published papers specify that the authors have disaggregated their data (Lin and Polenske 1995, Hubacek and Sun 2005, Yang and Suh 2011, Zhang, Beck et al. 2013), but only one paper, by Su and Ang (2010), explicitly states that they used RAS to disaggregate the data for their analysis. While it is unclear as to how often RAS is the approach researchers take to disaggregate data for Chinese EE-IOA, as ubiquitously as RAS is used to update data, it seems likely that this is the largely unnamed authors are using as their primary disaggregation technique.

Lindner, et al (2012) argue that the proportionality assumption upon which RAS is based, may not best reflect existing conditions. Marriot (2007) and, in turn, Lindner, et al (2012) assert that the estimates of coefficients developed through the iterative RAS process do not represent the disaggregated input-output matrix, but instead one of many possible disaggregated input-output matrices. Lindner, et al (2012, 2013) extend Wolsky's ideas of disaggregation (1984) by using a random-walk algorithm to fully explore the range of values differentiating the disaggregated input-output table from the initial estimate. Lindner, et al's case study finds that while the overall results from using a random-walk algorithm to disaggregate the data do not substantially differ from the initial estimate, the results for individual sectors can be striking (Lindner, Legault et al. 2012, Lindner, Legault et al. 2013). These results are promising for research focused on examining the effects of specific industries rather than overall effects.

5.0 Conclusion

Although EE-IOA as an analytical tool has been in use since 1969, the use of EE-IOA in the research of environmental economic impacts in China has exploded in only the last four years, with the greatest expansion occurring in 2012 and 2013. This time lag can largely be attributed to a lack of data for many years and lack of easy access to the data for many more. It should be noted again, that the body of literature surveyed here includes only English-language, peer-reviewed journal articles, and consequently, the conclusions drawn herewith are specific to the sample and cannot be extended to the Chinese or other non-English-language literature. The environmental issues in Chinese EE-IOA papers reflected that of the greater body of EE-IOA literature, with a major focus on energy and CO2 emissions, but with articles about land use and water receiving disproportionately large numbers of citations relative to other issue areas. While this is in part due to the age of the land use and water papers, it speaks to the methodological influence these papers have had on Chinese EE-IOA studies, in general. In conjunction with Chinese EE-IOA being used to evaluate a range of environmental issue areas, there are thematic lenses through which environmental impacts are viewed. Some of these are analytical methodologies, such as the use of SDA, IO-LCA, Hybrid LCA, and scenario analysis.

Others are topical lenses, such as trade impacts being analyzed through the use of both SRIOs and MRIOs.

All of these analyses, however, are limited by the data available to the researchers. Although the amount of data available is growing and becoming more reliable, researchers continue to struggle with uncertainty in Chinese input-output datasets, the vast majority of which are directly from or based on statistics published by the Chinese government. Some of the uncertainty authors must contend with is explicit and unapologetic in its nature, such as the Chinese government's use of the input-output table's "Others" column as an error term. Other uncertainty comes from the shortcomings in Chinese data collection, namely from the veracity of data sources and the level to which the data is aggregated. And while authors continue to search for the means to reduce uncertainty through data verification and disaggregation, most authors agree that coping with unreliable data is one of the costs of using Chinese EE-IOA.

The quest for improved data, or at least the use of methodologies to limit uncertainty in the data or minimize its influence on outcomes, is demonstrated in the efforts of researchers focusing their studies on previously underrepresented environmental areas. In the case of issues like solid waste and material flows, these topics are getting a boost from the advancement of IO-LCA and Hybrid LCA techniques. The data intensive nature of these techniques, however, requires a greater resolution of data. The disaggregation of data within economic input-output tables and their associated environmental satellite tables is becoming more common while authors wait for higher resolution and higher quality data from the Chinese government. These disaggregation techniques are proving valuable not only for IO-LCA and Hybrid LCA techniques being used to study solid waste, but also for the larger scale topics of energy and CO2, allowing for a deeper focus within what have often been sprawling scopes of study.

In the foreword to the 2008 Journal of Economic Systems Research special issue on China's Growing Pains, guest editor, Christian DeBresson, posited that research on China's development dealt largely only on macroeconomic issues and that IO analysis would "provide more in-depth insights into the inner workings of the Chinese economy" (Debresson 2008). It is true that EE-IOA has given researchers the tools to probe the interconnections between the facets of China's economy and identify their impacts to the environment. The majority of these studies, however, have continued to look at China's economy as a whole. In their discussions, many may highlight the effects or drivers of a handful of economic sectors relative to the others, but only a select few studies offer a perspective on specific sectors. There is optimism, though, that with the advancements in techniques to improve and better use available data, DeBresson's vision of delving deeper into the interiors of China's economy can be achieved.

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Appendix A

The following table lists all of the EE-IOA papers addressing Chinese issues published between 1995 and 2013. Each listing includes the year; authors; citations; environmental issues addressed (as categorized in Section 2.4, Environmental Issues Analyzed); if the article discusses trade and whether it uses a SRIO or a MRIO to do so; whether the article uses SDA, IO-LCA, or Hybrid LCA; if the article uses scenario analysis and for what time period; the years of the data sets used; and the number of sectors used for the analysis.

Publication			Env. Issue	Trade			Methodological Tools			Data	
Year	Author	# of Cites?		Trade?	SRIO	MRIO	SDA?	IO-LCA/ Hybrid	Scenarios	Sets	# of Sectors
1995	Lin and Polenske [1]	197	Energy		X		X			1981, 1987	18
1999	Garbaccio et al. [2]	74	Energy		X		X			1987, 1992	29
2001	Hubacek and Sun [3]	119	Land Use			X			2025	1992	11
2002	Polenske and McMichael [4]	23	Energy		X			IO-LCA		*	*
2004	Kagawa and Inamura [5]	35	Energy	X		X	X			1985, 1990	45
2005	Hubacek and Sun [6]	43	Water			X				1992	*
2006	Okadera et al. [7]	16	Water			X		IO-LCA		2001	28
2006	Shui and Harriss [8]	72	CO2	X		X		IO-LCA		*	*
2007	Guan and Hubacek [9]	40	Water	X		X				1997	40
2007	Li et al. [10]	24	Energy	X	X					1997	20
2007	Liang et al. [11]	53	Energy, CO2	X		X			2010, 2020	1997	4
2007	Peters et al. [12]	106	CO2	X	X		X			1992, 1997, 2002	95
2008	Guan and Hubacek [13]	14	Water			X				1997	40
2008	Guan et al. [14]	157	CO2		X		X		2030	1997, 2000, 2002	18
2008	Li and Hewitt [15]	54	CO2	X		X				2003	46
2008	Weber et al. [16]	113	CO2	X		X				1987-2002, 2005	36
2009	Chai et al. [17]	16	Energy		X		X			1992, 1997, 2002, 2004	30
2009	Hubacek et al. [18]	31	Land Use, Water		X				2020	1997	40
2009	Liu et al. [19]	33	Energy		X				X	1992, 1997, 2002, 2005	52
2009	Zhang [20]	22	CO2		X		X			1992-2006	26
2010	Arvesen et al. [21]	3	CO2, Air Pollutants		X					2007	*
2010	Cao et al. [22]	19	Energy		X		X	IO-LCA		1978-2004	*
2010	Chang et al. [23]	26	Energy, CO2, Air Pollutants		X			IO-LCA	2015	2002	24

Publication			Env. Issue	Trade			Methodological Tools			Data	
Year	Author	# of Cites?		Trade?	SRIO	MRIO	SDA?	IO-LCA/ Hybrid	Scenarios	Sets	# of Sectors
2010	Chen and Chen [24]	35	CO2, Material Flows	X	X					2007	135
2010	Chen and Zhang [25]	39	CO2	X	X					2007	26
2010	Dong et al. [26]	6	CO2	X		X	X			1995, 2000	24
2010	Guo et al. [27]	15	CO2	X		X				2005	13
2010	Kuhtz et al. [28]	7	Energy		X			IO-LCA		*	5
2010	Lin and Sun [29]	38	CO2	X	X					2005	15
2010	Liu, Polenske et al. [30]	7	CO2		X			IO-LCA		2007	135
2010	Liu, Xi et al. [31]	15	Energy	X	X		X			1992, 1997, 2002, 2005	52
2010	Liu, Ishikawa et al. [32]	30	CO2	X		X				1990	76
2010	Lu and Zhang [33]	13	Energy		X			Hybrid LCA		*	*
2010	Peters et al. [34]	2	CO2		X					*	*
2010	Su and Ang [35]	47	CO2	X		X				1997	30
2010	Su et al. [36]	69	CO2	X	X		X			2002	122, 42
2010	Yan and Yang [37]	29	CO2	X	X		X	IO-LCA		1997	98
2010	Yang et al. [38]	3	Solid Waste		X			IO-LCA		2005	*
2010	Yuan et al. [39]	11	Energy	X	X					2005	15
2010	Zhang and Chen [40]	21	Air Pollutants	X	X					2007	26
2010	Zhang [41]	14	CO2	X	X		X			1992, 2002, 2005	26
2010	Zhao et al. [42]	16	Water		X					1997, 2000, 2002	14
2011	Chang et al. [43]	4	Energy, Air Pollutants, Social Impacts		X			IO-LCA		2002, 2005, 2007	44
2011	Chen, Chen et al. [44]	26	CO2	X	X			IO-LCA		*	40
2011	Chen, Shao et al. [45]	16	CO2		X			Hybrid LCA		2007	135
2011	Chen, Yang et al. [46]	15	CO2		X			Hybrid LCA		*	151
2011	Du et al. [47]	1	CO2	X		X	X			2002, 2005, 2007	28
2011	Feng et al. [48]	6	Water	X		X		IO-LCA/ Hybrid LCA		2010	113
2011	He et al. [49]	3	Energy		X		X		2010	1997, 2002	31
2011	Liang et al. [50]	8	Water		X			IO-LCA	2015	2007	8
2011a	Liang and Zhang [51]	12	CO2	X	X		X			1997, 2002, 2007	26

Publication			Env. Issue	Trade			Methodological Tools			Data	
Year	**Author**	**# of Cites?**		**Trade?**	**SRIO**	**MRIO**	**SDA?**	**IO-LCA/ Hybrid**	**Scenarios**	**Sets**	**# of Sectors**
2011b	Liang and Zhang [52]	8	Energy, CO2, Water		X				2020	2007	28
2011	Su and Ang [53]	13	CO2	X		X				2000	24
2011	Wei et al. [54]	1	CO2	X	X					2002, 2007	27
2011	Xu et al. [55]	11	CO2	X	X		X			2002, 2007	45
2011	Yang and Suh [56]	3	Air Pollutants, Water	X	X		X			2002	122
2011	Zhang and Qi [57]	0	CO2	X	X		X			1992, 1997, 2002	21
2011	Zhang, Shi et al. [58]	4	Water	X		X				2002, 2007	20
2011	Zhang, Yang et al. [59]	10	Water	X		X				2002	33
2011	Zhou and Inamura [60]	2	Land Use	X		X	X			1997	30
2012	Amador [61]	0	Energy		X		X			1995, 2000, 2005	17
2012	Bruckner et al. [62]	8	Material Flows	X		X				1995, 2000, 2005	48
2012	Cao et al. [63]	0	CO2	X	X			IO-LCA		*	*
2012	Chang et al. [64]	2	Energy, Air Pollutants	X	X			Hybrid LCA		2007	135
2012	Chen et al. [65]	3	Water	X		X				2004	44
2012	Dai et al. [66]	4	Energy, Social Impacts		X					2007	7
2012	Dietzenbacher et al. [67]	3	CO2	X		X				2002	28
2012	Fan et al. [68]	2	CO2	X	X					2005	*
2012	Fan and Xia [69]	4	Energy		X		X	Hybrid LCA	2020	1987, 1992, 1997, 2002, 2005, 2007	44
2012	Fang et al. [70]	0	CO2	X	X					2007	27
2012a	Feng, Siu et al. [71]	5	CO2	X		X	X			2002, 2007	73
2012b	Feng, Siu et al. [72]	8	Water	X		X				2007	48
2012	Fu and Li [73]	0	CO2	X		X				*	*
2012	Gao et al. [74]	0	CO2		X					2007	26
2012	Guo, Zhang et al. [75]	5	CO2	X		X				2002	28
2012	Guo, Liu et al. [76]	1	CO2	X	X					2007	42
2012	He and Jim [77]	1	Energy		X				X	1980-2009	*
2012	Lan et al. [78]	1	CO2		X			IO-LCA		1992, 1997, 2002, 2005	33
2012	Li et al. [79]	0	CO2, Water		X			Hybrid LCA	2020, 2030, 2050	2007	44
2012	Liang and Zhang [80]	13	Solid Waste		X			IO-LCA	2015	2005	15

Publication			Env. Issue	Trade			Methodological Tools			Data	
Year	Author	# of Cites?		Trade?	SRIO	MRIO	SDA?	IO-LCA/ Hybrid	Scenarios	Sets	# of Sectors
2012	Liang, Zhang, Wang, et al. [81]	7	Air pollutants		X					2005	15
2012	Liang, Zhang et al. [82]	8	Solid Waste		X			IO-LCA		2005	36
2012	Lin et al. [83]	1	Water			X				2000	*
2012	Lindner et al. [84]	4	CO2		X					2007	14
2012	Liu, Xi et al. [85]	0	Energy		X		X	Hybrid LCA		1992, 1997, 2002, 2007	*
2012	Liu, Geng et al. [86]	1	Energy		X					2007	29
2012	Mo et al. [87]	0	Energy		X			IO-LCA		2002	*
2012a	Su and Ang [88]	10	CO2		X		X			2002, 2007	110
2012b	Su and Ang [89]	4	CO2		X		X			1997, 2000, 2002, 2005, 2007	38, 104
2012	Tian et al. [90]	2	CO2			X				2002	17
2012	Wang, Zhang et al. [91]	1	CO2		X			Hybrid LCA		2007	135
2012	Wang and Wang [92]	0	CO2	X	X			IO-LCA		2007	*
2012	Wang, Wang et al. [93]	0	Air Pollutants, Solid Waste		X			IO-LCA		2007	*
2012	Wiebe et al. [94]	5	CO2	X		X				1995-2005	48
2012	Xia et al. [95]	0	Energy		X		X			1987, 1992, 1997, 2002, 2007	44
2012	Xia [96]	0	CO2		X					2007	*
2012	Yuan [97]	0	CO2		X		X			2002, 2007	29
2012	Zhang, Liu et al. [98]	1	CO2		X					2007	*
2012	Zhang and Huang [99]	1	CO2		X					1997, 2000, 2002, 2005, 2007	42
2012	Zhang [100]	2	CO2	X	X		X			1987, 1990, 1992, 1995, 1997, 2002, 2005, 2007	26
2012	Zhang, Shi et al. [101]	1	Water	X	X		X			1997, 2002, 2007	30
2012	Zhu et al. [102]	1	CO2		X		X			1992, 1997, 2002, 2005	14
2013	Bergmann [103]	0	CO2	X		X				2004	57
2013	Chang et al. [104]	0	Energy		X			Hybrid LCA	2020, 2057	2007	42
2013	Chen, Guo et al. [105]	2	CO2	X	X					2007	42
2013a	Chen and Chen [106]	3	Energy	X		X			2035	2007	57

Publication			Env. Issue	Trade			Methodological Tools			Data	
Year	**Author**	**# of Cites?**		**Trade?**	**SRIO**	**MRIO**	**SDA?**	**IO-LCA/ Hybrid**	**Scenarios**	**Sets**	**# of Sectors**
2013b	Chen and Chen [107]	2	Water	X		X				2004	44
2013	Chen, Chen et al. [108]	2	CO2	X		X				2004	57
2013	Dong, Mao et al. [109]	0	CO2		X		X	Hybrid LCA		1997-2007	*
2013	Dong, Geng, Sarkis et al. [110]	1	Water	X	X		X			2007	28
2013	Dong, Geng et al. [111]	0	CO2		X			Hybrid LCA		2007	17
2013	Feng et al. [112]	4	CO2	X		X				2007	30
2013	Fu et al. [113]	0	Energy		X		X			1992, 1997, 2002, 2007	6
2013	Geng et al. [114]	0	CO2	X	X		X			1997-2007	28
2013	Guo et al. [115]	0	Energy	X	X					*	*
2013	He et al. [116]	1	Energy, Water, Air Pollutants, Solid Waste		X			Hybrid LCA	2015	2007	42
2013	Hong et al. [117]	3	Energy		X					2007	42
2013	Karstensen et al. [118]	0	CO2	X		X				2007	57
2013	Kunimitsu et al. [119]	0	CO2	X		X				2004	*
2013	Li and Liu [120]	0	Energy	X	X		X			2009	*
2013	Liang, Xu, Suh et al. [121]	0	Material Flows		X			IO-LCA		2007	135
2013	Liang, Xu et al. [122]	7	Material Flows		X			IO-LCA		*	*
2013	Liang and Zhang [123]	3	Solid Waste		X			IO-LCA/Hybrid LCA		2005	21
2013	Liang, Zhang et al. [124]	4	Material Flows		X			Hybrid LCA		2007	28
2013	Lindner et al. [125]	0	CO2		X					2007	50
2013	Liu and Wu [126]	0	CO2, Air Pollutants, Water		X				2015	2007	*
2013	Liu et al. [127]	0	Water	X						2010	*
2013	Lopez et al. [128]	0	CO2	X		X				2005	23
2013	Meng et al. [129]	1	CO2	X		X				2002, 2007	17
2013	Qu, Zeng et al. [130]	0	CO2	X	X					2007	*
2013	Qu, Zhang et al. [131]	0	Solid Waste		X		X	IO-LCA	X	2005	*
2013	Shao et al. [132]	1	Energy, Water		X			Hybrid LCA		2007	135

Publication			Env. Issue	Trade			Methodological Tools			Data	
Year	Author	# of Cites?		Trade?	SRIO	MRIO	SDA?	IO-LCA/ Hybrid	Scenarios	Sets	# of Sectors
2013	Su and Ang [133]	1	CO2	X	X					1997, 2000, 2002, 2005, 2007	
2013	Su et al. [134]	0	CO2	X	X		X			1997, 2002	104
2013	Tang, Shi et al. [135]	1	Energy	X	X					2002, 2005, 2007	25
2013	Tang, Snowden et al. [136]	0	Energy	X		X				2005	*
2013	Vause et al. [137]	0	CO2	X	X					2007	135
2013	Wang, Wang et al. [138]	0	CO2		X					2007	21
2013	Wang and Liang [139]	2	CO2		X			Hybrid LCA	2020	2007	58
2013	Wang, Zhao et al. [140]	0	CO2	X	X		X			1997, 2000, 2002, 2005, 2007, 2010	28
2013	Wang, Huang et al. [141]	0	Water	X	X					2002, 2007	21
2013	Yang and Wang [142]	0	CO2		X			IO-LCA		2010	*
2013	Yu et al. [143]	0	Land Use	X		X				2007	57
2013	Zhang, Beck et al. [144]	0	Water, Air Pollutants, Solid Waste	X	X					1997, 2002, 2007	45
2013	Zhang, Wang et al. [145]	1	CO2		X			Hybrid LCA	X	2007	135
2013	Zhang [146]	0	CO2		X					1987, 1992, 1997, 2000, 2002, 2005, 2007	26

* This information regarding the data set or number of sectors was not provided in the published article.

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