Developing the Chinese Environmentally Extended Input-Output (CEEIO) Database

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Summary

Environmentally extended input-output (EEIO) databases are increasingly used to examine environmental footprints of economic activities. Studies focusing on China have independently, repeatedly developed EEIO databases for China. These databases are usually not publicly available, leading to repeated efforts, inconsistent with one another using different approaches, of limited environmental accounts, and lacking transparency, preventing continuous updating. We developed a transparent, comprehensive, and consistent Chinese EEIO database covering a wide period of time (currently 1992, 1997, 2002, and 2007 for which benchmark input-output tables [IOTs] are available), sector classifications (original sector classifications in benchmark IOTs, a 45-sector classification commonly used in China's environmental and energy statistics, and a 91-sector classification with maximized sector resolution ensuring temporal consistence), and environmental satellite accounts for 256 types of resources and 30 types of pollutants in this study. Moreover, the environmental satellite accounts cover households in addition to sectors, allowing developing closed models. We make this database publicly available with open access for broader dissemination (www.ceeio.com). We demonstrate the database by evaluating environmental pressures of Chinese products in 2007. Comparisons of our database with previous studies validate its rationality and reliability.

Introduction

China's rapid economic growth in the past few decades has led to severe environmental challenges (Liu and Diamond 2005). For example, China has the largest material footprint in the world (Wiedmann et al. 2015), is currently the world's top carbon dioxide (CO_2) emitter (Gregg et al. 2008), and is one of the top atmospheric mercury emitters (Pacyna et al. 2010; Liang et al. 2013d, 2014b, 2015b). Given that many environmental problems are driven by economic activities (Arrow et al. 1995; Raupach et al. 2007), measuring environmental pressures attributed to specific economic activities can hence guide environmental policy making to decouple economic growth and environmental pressures in China (Eurostat 2001).

Environmentally extended input-output (EEIO) databases characterize environmental pressures associated with the exchanges of goods and services between economic sectors (Miller and Blair 2009). They are increasingly used to measure environmental pressures driven by the production and consumption of particular goods and services. Many studies have been conducted to use EEIO databases to examine China's various environmental problems, including water resources (Guan et al. 2014), energy consumption (Peters et al. 2006; Zeng et al. 2014), CO_2 emissions (Guan et al. 2008, 2009; Peters et al. 2006, 2007; Zhang et al. 2014; Wang and Liang 2013; Minx et al. 2011), atmospheric mercury emissions (Liang et al. 2013d, 2014b), and material flows (Liang et al. 2013a, 2013c, 2014a; Yang and Suh 2011). Despite the increasing popularity of EEIO analysis for China, there exist several challenges for developing and utilizing Chinese EEIO (CEEIO) databases.

First, EEIO databases for China developed in previous studies are not always publicly available, except for the 2002 EEIO

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database developed by the Green Design Institute of Carnegie Mellon University (CMU) (CMU 2015). EEIO databases are repeatedly constructed by researchers for individual studies. For example, several studies have independently developed EEIO databases for China's CO_2 emission in 2007 (Minx et al. 2011; Wang and Liang 2013) and energy use in 1997 and 2002 (Peters et al. 2006; Zeng et al. 2014). There exists an urgent need to develop a common EEIO database with public availability to facilitate the widespread EEIO analysis for China and help avoid repeated efforts of database development.

Second, data sources and estimation methods for the construction of existing Chinese EEIO databases are different from one another. For example, China's coal consumption is found to be underestimated during 1996–2003 (Akimoto et al. 2006). Some studies scale up coal consumption data and related air emissions for this period (Liang et al. 2013d, 2014a; Minx et al. 2011; Peters et al. 2007; Yang and Suh 2011), whereas others do not (Zeng et al. 2014; Zhang et al. 2014). The lack of a common framework makes it difficult to compare results of studies using independently developed EEIO databases.

Third, existing EEIO databases for China usually focus on specific environmental pressures and specific years. A comprehensive EEIO database covering popular resources and pollutants in multiple years can thus help save efforts in constructing specific EEIO databases. Moreover, considering multiple environmental pressures helps identify cobenefits and unintended consequences of environmental policies (Liang et al. 2012a, 2013c, 2014a; Yang et al. 2012). A comprehensive EEIO database covering multiple environmental pressures enables such studies.

Fourth, lack of transparency in the development of existing CEEIO databases makes it difficult, if not impossible, to construct comparable time-series EEIO databases with newly available data.

In this study, we address these challenges by developing a comprehensive, transparent, and consistent CEEIO database. CEEIO currently covers a wide period of time (currently 1992, 1997, 2002, and 2007 for which benchmark input-output [I-O] tables [IOTs] are available), sector classifications (original sector classifications in benchmark IOTs, a 45-sector classification commonly used in China's environmental and energy statistics, and a 91-sector classification with maximized sector resolution ensuring temporal consistence), and environmental satellite accounts for 256 types of resources and 30 types of pollutants associated with sector outputs and household consumption. We make it publically available to facilitate broader applications (www.ceeio.com).

Database Development

The CEEIO database comprises two parts: benchmark IOTs and environmental satellite accounts including environmental pressures for not only sectors, but also rural and urban household consumption. We only use sources that regularly publish time-series data with public availability (mostly government statistics) to ensure that the CEEIO database can be updated in the future transparently and consistently. We describe data sources and methods in detail in the following sections.

Benchmark Input-Output Tables

The CEEIO database includes all available benchmark IOTs for China since 1990 (1992, 1997, 2002, and 2007) from China's National Bureau of Statistics (NBS) (NBS 1996, 1999, 2006, 2009). Sector classifications of these benchmark IOTs are 118 sectors in 1992, 124 sectors in 1997, 122 sectors in 2002, and 135 sectors in 2007. In particular, there are two columns respectively representing exports and imports in 1997, 2002, and 2007 IOTs, whereas only one column represents net exports in the 1992 IOT.

Total output and total input for the *Grain and oil business* sector are negative in the 1992 IOT. Such an issue is attributed to four entries in final demand and value added with negative values for this sector: rural household consumption; urban household consumption; net taxes on production; and net operating surplus. Mirror transition is used to adjust these negative values. We first set two negative values in rural and urban household consumption as zeros and then add the sum of their absolute values to employee compensation in value added of the *Grain and oil business* sector. Negative values in net taxes on production and net operating surplus mean that government subsidy exceeded taxes on production and operating surplus. We first set two negative values in net taxes on production and net operating surplus as zeros and then add the sum of their absolute values to net export in final demand of the *Grain and oil business* sector.

Environmental Satellite Accounts

The environmental satellite accounts include 256 types of resources and 30 types of pollutants, listed in supporting information S1 available on the Journal's website. Many environmental data from Chinese statistics are in 45-sector format. We first compile the environmental satellite accounts in 45-sector format and then disaggregate to match original sector classifications of benchmark IOTs following Weber (2008).

Data for the environmental satellite accounts are mainly from two sources: annually published environmental statistics, for example, *China Agriculture Yearbooks* (Cai and He 1993; Fu and Liang 2003; Shen and Chen 1998; Zhang and Liu 2008), *China Mining Yearbooks* (Chen 2004 [in Chinese], 2009 [in Chinese]), *China Energy Statistical Yearbooks* (NBS 1990–2012), *China Environment Yearbooks* (MEP 1993 [in Chinese], 1998 [in Chinese], 2003 [in Chinese]), and *Annual Statistic Reports on Environment in China* (MEP 2008 [in Chinese], 2011 [in Chinese]), and benchmark environmental statistics or studies for selected years, for example, the first national survey of pollution sources in 2007 (MEP/NBS 2011; MEP/NBS/MA 2010) and Chinese physical IOT in 2005 (Liang and Zhang 2013; Liang et al. 2012b). In particular, several annual environmental statistics are available only after 2000 (e.g., *China Mining Yearbooks*) or after 2005 (e.g., *Annual Statistic Report on Environment in China*).

Resource Satellite Accounts

Resource use can be allocated to either sectors directly extracting resources from the Earth (Xu et al. 2008; Wang et al. 2014) or sectors using resources after the extraction (Liang et al. 2013c, 2014a; Guan et al. 2014; Zhang and Anadon 2013, 2014). We compare these two allocation methods in supporting information S2 on the Web. We find that they are equivalent if the latter method includes the use of resources in the final demand sectors. We use the first approach because the second one needs additional data that are not available for all resources.

In particular, resource sectors are highly aggregated in China's benchmark IOTs. Taking the 2007 benchmark IOT, for example, 40 types of crops are linked to a single sector: *Crop cultivation*. Future applications of our EEIO database in resource analyses can disaggregate resource sectors according to practical needs. For possible disaggregation methods, one can refer to previous work (Lindner et al. 2012; Lenzen 2011; Lenzen et al. 2012).

Resource satellite accounts in our EEIO database cover biomasses, primary energy sources, mineral ores, and freshwater. In particular, we currently use freshwater use indicator in the CEEIO database, instead of freshwater extraction indicator, mainly due to data constraints.

Biomasses, primary energy, and mineral ores

Biomasses in the CEEIO database include agricultural products, forestry products, and fishery products, from *China Agriculture Yearbooks* (Cai and He 1993; Fu and Liang 2003; Shen and Chen 1998; Zhang and Liu 2008). Data for primary energy sources including fossil fuels (i.e., raw coal, crude petroleum, and natural gas), hydropower, and nuclear power are from *China Energy Statistical Yearbooks* (NBS 1990–2012). Mineral ores include ferrous metal ores, nonferrous metal ores, nonmetallic mineral ores, and salt mines. Data for extractions of specific mineral ores in 1992 and 1997 are unavailable, except that data for six types of mineral ores in 1992 are obtained from China's 1992 physical IOT (NBS 1996 [in Chinese]). We also include an aggregated amount of extracted mineral ores in 1992 and 1997 from the literature (NBS 1996 [in Chinese]; Xu and Zhang 2007). China has been publishing annual extraction data for mineral ores since 2000. We obtained data for the extraction of specific mineral ores in 2002 and 2007 from *China Mining Yearbooks* (Chen 2004 [in Chinese], 2009 [in Chinese]), which can also be used to construct future environmental satellite accounts for mineral ores.

Freshwater consumption

Data on freshwater use by agriculture and industrial sectors are from *China Environment Yearbooks* (MEP 1993 [in Chinese], 1998 [in Chinese], 2003 [in Chinese]) and *Annual Statistic Report on Environment in China* (MEP 2008 [in Chinese]). In particular, freshwater use by manufacturing and construction sectors is aggregated together. We then get freshwater use of construction sector by deducting the sum of freshwater uses of industrial sectors from the aggregated freshwater use of industry and construction sectors.

In addition, freshwater use by service sectors and households is also aggregated together. We use the following methods to estimate freshwater uses by specific service sectors and households.

First, we calculate freshwater use of the transportation sector by equation (1):

$$t = x_t f_t \tag{1}$$

where t represents freshwater use by the transportation sector, x_t represents total output of the transportation sector (in 2005 constant price), and f_t is a ratio of freshwater use by unitary output of the transportation sector (in 2005 constant price). We derive f_t from China's 2005 physical IOT (Liang and Zhang 2013; Liang et al. 2012b). In particular, data in constant prices are calculated based on data from the benchmark IOTs in current prices (NBS 1996, 1999, 2006, 2009) and sectoral producer price indices from *China Statistical Yearbooks* (NBS 1993–2011).

Freshwater use by all other service sectors, rural households, and urban households is calculated by equations (2), (3), and (4), respectively.

$$o = df + e - t \tag{2}$$

$$h_r = d(1 - f)\frac{w_r}{w_r + w_u} \tag{3}$$

$$h_u = d(1 - f)\frac{w_u}{w_r + w_u} \tag{4}$$

The notations o, h_r, and h_u indicate freshwater use by all other service sectors, rural households, and urban households, respectively; d represents domestic water use from China's environmental statistics (MEP 1998 [in Chinese], 2003 [in Chinese], 2008 [in Chinese]); f represents the portion of freshwater use by all service sectors in domestic water use, which is set as 0.55 in this study (Wang et al. 2008); e indicates ecological freshwater use from China's annual environmental statistics, which indicates artificial water replenishment to rivers and lakes and freshwater use by urban environmental management (MEP 1998 [in Chinese], 2003 [in Chinese], 2008 [in Chinese]); and w_r and w_u, respectively, represent freshwater uses by rural and urban households in monetary units from IOTs.

In particular, freshwater usage data in 1992 are unavailable from existing environmental statistics. We estimate using relevant information (e.g., each sector's freshwater to wastewater ratio, and per capita freshwater use by services and households) for the nearest years. Freshwater use by service sectors and households is then estimated by equations (1) to (4). Details on estimating sector-level freshwater use in 1992 can be found in our previous study (Liang et al. 2014a).

Pollutant Satellite Accounts

Water pollutants

China's annual environmental statistics (MEP 1993 [in Chinese], 1998 [in Chinese], 2003 [in Chinese], 2008 [in Chinese]) only contain water pollutant discharges for industrial sectors and households, excluding agricultural, construction, and service sectors. We obtain water pollutant discharges for agricultural, construction, and service sectors by equation (5):

$$w_{i,j} = x_i f_{i,j} \tag{5}$$

where $w_{i,j}$ represents the j^{th} type of water pollutants for sector i, x_i represents total output of sector i (in 2007 constant price) from IOTs, and $f_{i,j}$ is the emission of the j^{th} type of water pollutants by unitary output in sector i (in 2007 constant price). China conducted a national survey of pollution sources in 2007 (MEP/NBS 2011; MEP/NBS/MA 2010). This was the first time to comprehensively cover a wide range of pollutants for all economic sectors and households. It is regarded as an important baseline of Chinese environmental statistics. We derive emission factors $f_{i,j}$ in this study by dividing the amounts of pollutants from a national survey of pollution sources in 2007 (MEP/NBS 2011; MEP/NBS/MA 2010) by each sector's total output in the 2007 IOT.

China's environmental statistics in 1992 and 1997 do not have data on ammonia nitrogen discharge. We estimate using equations (6) and (7), respectively.

$$a_i = x_i f_i \tag{6}$$

$$a_h = p_h f_p \tag{7}$$

The notations a_i and a_h indicate ammonia nitrogen discharge by sector i and households, respectively; x_i represents total output of sector i (in 2002 constant price) from IOTs; f_i represents ammonia nitrogen discharge by unitary output of sector i (in 2002 constant price) calculated using 2002 sectoral ammonia nitrogen discharge data and the 2002 IOT; p_h indicates population from *China Statistical Yearbook* (NBS 2012); and f_p represents per capita ammonia nitrogen discharge calculated using 2002 data in this study.

Water pollutant discharges from rural and urban households in China's environmental statistics are usually aggregated together. We disaggregate by rural and urban households using equations (8) and (9).

$$w_{r,i} = w_{h,i} \frac{c_r}{c_r + c_u} \tag{8}$$

$$w_{u,i} = w_{h,i} \frac{c_u}{c_r + c_u} \tag{9}$$

Notations $w_{r,i}$ and $w_{u,i}$ represent the amounts of water pollutant i discharged by rural and urban households, respectively; $w_{h,i}$ indicates the amount of water pollutant i discharged by both rural and urban households; and c_r and c_u represent total rural household consumption and total urban household consumption from IOTs, respectively.

Air emissions

Three types of air emissions (sulfur dioxide, soot, and dust) for industrial sectors and households are available from China's annual environmental statistics (MEP 1993 [in Chinese], 1998 [in Chinese], 2003 [in Chinese], 2008 [in Chinese]). Air emissions for rural and urban households in China's annual environmental statistics are usually aggregated together. We disaggregate by rural and urban households using equations (8) and (9). China began to publish annual nitrogen oxides emission data for industrial sectors after 2005. Thus, for the year of 2007 and potential future updates, emissions of nitrogen oxides for industrial sectors are available.

For sectors (i.e., agricultural sectors, construction, and service sectors), households, and years (i.e., nitrogen oxides emissions in 1992, 1997, and 2002) in which air emission data are unavailable from China's annual environmental statistics, we estimate using equation (10) including air emissions from both fuel combustion and industrial processes:

$$r_i = \sum_{j=1}^{k} m_{i,j} f_{i,j} + p_i f_i \tag{10}$$

where r_i indicates specific air emissions by sector i, $m_{i,j}$ represents the use of the j^{th} type of energy source by sector i, $f_{i,j}$ is the emission factor for the j^{th} type of energy source in sector i, p_i represents product yield of sector i, and f_i is the emission factor for the industrial process of sector i. Emission factors of nitrogen oxides from fuel combustion and industrial processes in China are from Hao and colleagues (2002), whereas emission factors of sulfur dioxide, soot, and dust are derived from China's 2005 physical IOT (emissions per unit of each sector's fuel usage) (Liang and Zhang 2013; Liang et al. 2012b).

Greenhouse gases (GHGs) and atmospheric heavy metal emissions are not covered by China's current environmental statistics. We estimate using equation (10). GHGs in this study include CO_2, methane, and nitrous oxide. GHG emission factors from fuel combustion and industrial processes are from the Intergovernmental Panel on Climate Change (IPCC) (IPCC 2006). Atmospheric heavy metals in this study include atmospheric mercury, arsenic, and selenium emissions, estimated using emission factors from literature (Liang et al. 2013c, 2013d, 2014a, 2014b; Tian et al. 2010). Nineteen types of fuel sources are considered, including raw coal, washed coal, other washed coal, briquettes, crude petroleum, natural gas, coke, other coking products, gasoline, kerosene, diesel oil, fuel oil, other petroleum products, electricity, heat, coke oven gas, other gas, liquefied petroleum gas, and refinery gas. In particular, previous studies found that China's coal consumption during 1996–2003 was under-reported (Akimoto et al. 2006; Peters et al. 2007). We scaled up each sector's coal consumption data and related emissions in 1997 and 2002 using empirical correlation methods during 1953–2010 (i.e., scaled up to 1.065 and 1.193 times of primary data in 1997 and 2002, respectively) (Liang et al. 2013d, 2014a), according to methods of previous studies (Peters et al. 2007; Yang and Suh 2011). Industrial processes generating GHG emissions include the production of 30 types of industrial products covered by the IPCC (IPCC 2006). Industrial processes for atmospheric mercury emissions include agricultural residue burning, grassland/savanna burning, forest burning, coal mines spontaneous burning, household waste burning, and the production of caustic soda, cement, pig iron, zinc, copper, lead, gold, mercury, batteries, and fluorescent lamps. Data for product yields are from *China Statistical Yearbooks* (NBS 1993–2011–2011). Atmospheric arsenic and selenium emissions from industrial processes are currently not considered because of the unavailability of emission factors, but can be easily estimated once emission factors become available.

Solid wastes

China's annual environmental statistics (MEP 1993 [in Chinese], 1998 [in Chinese], 2003 [in Chinese], 2008 [in Chinese]) contain data for solid waste generation by specific industrial sectors and urban households (i.e., municipal domestic solid wastes). Solid waste generation from rural households is calculated by multiplying rural population (NBS 1993–2011) with a generation factor that is set as 0.86 kg/(capita*day) (Yao et al. 2009) in this study. Household waste in this study only includes solid wastes from private households and does not include business waste. In particular, industrial solid waste generation from the *Water production and supply* sector comprises two separately recorded parts: industrial solid wastes (excluding sludge) and sludge. Sludge is not covered by China's annual environmental statistics until the year of 2005. We first derive a sludge generation factor for unitary output of the *Water production and supply* sector using data from China's national survey of pollution sources in 2007 (MEP/NBS 2011; MEP/NBS/MA 2010). We then calculate the amount of sludge for years before 2005 (i.e., 1992, 1997, and 2002) by multiplying the total output of the *Water production and supply* sector (in 2007 constant price) by the emission factor.

Solid waste generation from agricultural sectors includes plastic film, crop straws, and animal manure, calculated by equations (11), (12), and (13), respectively.

$$e_p = u_p w_p r_p \tag{11}$$

$$e_c = \sum_{i=1}^{k} p_i g_i f_i \tag{12}$$

$$e_m = \sum_{j=1}^{m} n_j c_j q_j \tag{13}$$

Notations e_p, e_c, and e_m represent the amounts of plastic film, crop straws, and animal manure, respectively; u_p indicates the amount of plastic film used in farmlands from *China Rural Statistical Yearbooks* (NBS 1993, 1998, 2003, 2008); w_p and r_p are scrap rate (0.58) and emission rate (0.20) of plastic film, respectively, from China's national survey of pollution sources in 2007 (MEP/NBS 2011; MEP/NBS/MA 2010); p_i represents the yield of crop i from *China Agriculture Yearbooks* (Cai and He 1993; Fu and Liang 2003; Shen and Chen 1998; Zhang and Liu 2008), g_i and f_i indicate harvest factor (Lu and Zhang 2010) and emission rate (0.294) (NDRC 2011) of crop straws for crop i, respectively; n_j represents the number of animal j from *China Statistical Yearbooks* (NBS 1993–2011–2011); c_j and q_j indicate generation rate (Lu 2010) and emission rate (0.55) (Lu 2010) of animal manure for animal j, respectively; and k and m indicate specific types of crops and animals, respectively.

Solid wastes from the service sector are medical wastes, which are not covered by China's annual environmental statistics. Medical wastes are calculated by multiplying total output of the *Health services* sector from IOTs with emission factor of medical wastes (MEP/NBS 2011; MEP/NBS/MA 2010).

Disaggregation and Aggregation Methods

Sector classification of environmental data is inconsistent with that of IOTs. The CEEIO database offers three types of sector classifications for the convenience of practical applications: original sector classifications from benchmark IOTs; a 45-sector classification commonly used in China's environmental and energy statistics; and a 91-sector classification with temporal consistence and maximized sector resolution.

Many environmental data from Chinese statistics are in 45-sector format, whereas China's benchmark IOTs are in the resolution of over 100 sectors. Disaggregating environmental data to match sector resolution of IOTs can fully use the information contained in IOTs and give better results (Bouwmeester and Oosterhaven 2013; de Koning et al. 2015; Su and Ang 2012; Su et al. 2010; Lenzen 2011). Thus, we disaggregate these 45-sector environmental flows to match original sector classifications of benchmark IOTs as shown in equation (14) (Weber 2008):

$$\begin{aligned} \mathrm{E}_{\mathrm{original}} &= \mathrm{E}_{45}(\mathrm{diag}(\mathrm{C}_{45\text{-}original} x_{original}))^{-1} \\ &\quad \times \mathrm{C}_{45\text{-}original}\mathrm{diag}(x_{original}) \end{aligned} \tag{14}$$

where matrices $\mathrm{E}_{\mathrm{original}}$ and E_{45} represent environmental satellite accounts in original sector classifications and in 45-sector classification, respectively, binary matrix $\mathrm{C}_{45\text{-original}}$ is the concordance between 45-sector classification and original sector classifications, and column vector $x_{original}$ indicates sectoral total outputs in original sector classifications.

We also aggregate China's benchmark IOTs to the 45-sector format to match with energy and environmental statistics. In addition, we construct a 91-sector classification with temporal consistence and maximized sector resolution. Aggregation methods are shown in equations (15) to (19).

$$\mathrm{Z}_{\mathrm{target}} = \mathrm{C}_{\mathrm{target\text{-}original}} \mathrm{Z}_{\mathrm{original}} (\mathrm{C}_{\mathrm{target\text{-}original}})^{\mathrm{T}} \tag{15}$$

$$x_{target} = \mathrm{C}_{\mathrm{target\text{-}original}} x_{original} \tag{16}$$

$$\mathrm{Y}_{\mathrm{target}} = \mathrm{C}_{\mathrm{target\text{-}original}} \mathrm{Y}_{\mathrm{original}} \tag{17}$$

$$\mathrm{V}_{\mathrm{target}} = \mathrm{V}_{\mathrm{original}} (\mathrm{C}_{\mathrm{target\text{-}original}})^{\mathrm{T}} \tag{18}$$

$$\mathrm{E}_{\mathrm{target}} = \mathrm{E}_{\mathrm{original}} (\mathrm{C}_{\mathrm{target\text{-}original}})^{\mathrm{T}} \tag{19}$$

In particular, $\mathrm{Z}_{\mathrm{target}}$, x_{target}, $\mathrm{Y}_{\mathrm{target}}$, $\mathrm{V}_{\mathrm{target}}$, and $\mathrm{E}_{\mathrm{target}}$ represent intermediate flows matrix, sectoral total outputs vector, final demand matrix, value added matrix, and environmental satellite accounts in target sector classifications (i.e., 45 or 91 sectors), respectively, whereas $\mathrm{Z}_{\mathrm{original}}$, x_{original}, $\mathrm{Y}_{\mathrm{original}}$, $\mathrm{V}_{\mathrm{original}}$, and $\mathrm{E}_{\mathrm{original}}$ represent ones in original sector classifications. The binary concordance matrix $\mathrm{C}_{\mathrm{target\text{-}original}}$ shows

Table 1 Selected environmental pressures of Chinese construction sector in 2007

No.	Environmental accounts	Units	Direct intensity (per million U.S. dollars)	Total intensity (per million U.S. dollars)	Production-based accounting	Consumption-based accounting
1	Food crops	kg	0	26,259	0	20,701,341,657,074
2	Woods	cubic meter	0	18	0	14,520,919,697
3	Raw coal	tonne	0	909	0	716,675,173,781
4	Ferrous metal ores	tonne	0	237	0	186,513,172,005
5	Freshwater	tonne	96,627	145,919	78,705,960,000,000	115,033,661,768,881
6	Carbon dioxide	kg	80,769	3,556,731	65,788,879,193,605	2,803,914,221,393,480
7	Sulfur dioxide	kg	513	8,040	417,745,130,491	6,338,017,512,548
8	Nitrogen oxides	kg	149	5,648	121,630,891,342	4,452,895,164,228
9	Chemical oxygen demand	kg	0	1,260	0	993,615,274,334
10	Ammonia nitrogen	kg	0	149	0	117,529,039,154
11	Industrial solid wastes	kg	0	4,109	0	3,238,897,006,853

Note: Chinese RMB is changed to U.S. dollar by the average exchange rate (7.6075325 Chinese RMB per U.S. dollar) in 2007 (*World Bank* 2015). Results for all types of environmental pressures are listed in supporting information S1 on the Web.
kg = kilogram; RMB = renminbi.

correspondences between target sector classifications and original sector classifications. The notation "^{T}" transposes a matrix.

Results and Comparisons

We demonstrate the use of the CEEIO database by examining sectoral environmental pressures using production- and consumption-based accounting (Peters 2008). *Production-based* environmental pressure of Chinese sectors (denoted as P) is just the environmental satellite accounts. *Consumption-based* environmental pressure of Chinese sectors (denoted as C) is calculated by equations (20) to (22).

$$C = F(I - A)^{-1}\hat{y} \quad (20)$$

$$F = P(\hat{x})^{-1} \quad (21)$$

$$A = Z(\hat{x})^{-1} \quad (22)$$

The notation F indicates the *direct intensity* of environmental pressures for unitary output of sectors; I is the identity matrix; A is the direct requirement coefficient matrix in which element a_{ij} indicates direct inputs from sector i to satisfy unitary output in sector j (Miller and Blair 2009); $(I\text{-}A)^{-1}$ is the Leontief inverse (Miller and Blair 2009); $F(I\text{-}A)^{-1}$ is the *total intensity* (direct and indirect) of environmental pressures of unitary output of sectors along supply chains; column vectors y and x represent sectoral final demand and total output, respectively; and matrix Z represents intermediate consumption of sectors.

Imports are endogenous in China's IOTs, that is, the import matrix is combined together with domestic intersectoral transaction matrix. For the following case study and comparisons, in order to avoid errors caused by the assumption that imports are produced by domestic technologies (Weber et al. 2008; Su and Ang 2013), we remove imports from China's IOTs. We also remove the "others" column in the final demand matrix, which is regarded as statistical errors (Liang et al. 2013c, 2014a; Peters et al. 2007). IOTs are rebalanced to derive new x vector and A matrix.

Environmental Pressures of Chinese Sectors in 2007

We use the CEEIO database to calculate direct intensity, total intensity, and environmental pressures in production- and consumption-based accounting for Chinese sectors in 2007. Full results are shown in the Supporting Information on the Web. From the viewpoint of production-based accounting, extraction sectors and pollutant-intensive sectors are major contributors to China's environmental pressures. From the viewpoint of consumption-based accounting, however, sectors producing finished products (e.g., equipment, machinery, and construction) and service sectors emerge as major contributors. Table 1 shows that the construction sector does not directly extract resources (except for freshwater) and directly discharges limited types of pollutants by production-based accounting. However, the construction sector is a major destination of products from many resource- and pollutant-intensive sectors (e.g., mineral ores mining, metals production, cement production, and chemicals production sectors), which drives significant amounts of embodied resources and emissions upstream the supply chain. Thus, from the viewpoint of consumption-based accounting, the construction sector is the driver of significant amounts of resource extraction and pollutant discharges.

Table 2 Sectors ranked within top 12 by consumption-based emissions of five typical pollutants in China in 2007

Rank	*Carbon dioxide*	*Sulfur dioxide*	*Nitrogen oxides*	*Chemical oxygen demand*	*Ammonia nitrogen*
1	Construction	Construction	Construction	Livestock and livestock products	Livestock and livestock products
2	Electricity and heat production and supply	Electricity and heat production and supply	Electricity and heat production and supply	Slaughtering and meat processing	Crop cultivation
3	Steel processing	Public administration and social organization	Water transport	Construction	Construction
4	Motor vehicles	Motor vehicles	Wholesale and retail trade	Leather, furs, down, and related products	Public administration and social organization
5	Metal products	Health services	Motor vehicles	Eating and drinking places	Eating and drinking places
6	Public administration and social organization	Education services	Public administration and social organization	Health services	Health services
7	Health services	Wholesale and retail trade	Education services	Public administration and social organization	Wholesale and retail trade
8	Education services	Metal products	Health services	Wearing apparel	Slaughtering and meat processing
9	Other special equipment	Wearing apparel	Highway transport	Education services	Education services
10	Wholesale and retail trade	Steel processing	Wearing apparel	Liquid milk and dairy products	Wearing apparel
11	Wearing apparel	Knitted mills	Metal products	Wholesale and retail trade	Leather, furs, down, and related products
12	Household appliances	Electronic computer	Air transport	Arts and crafts products and other manufacturing products	Real estate

Note: Full results are listed in supporting information S1 on the Web.

Taking five types of emissions that are regulated in China's current 5-year plans (i.e., CO_2, sulfur dioxide, nitrogen oxides, chemical oxygen demand, and ammonia nitrogen), for example, table 2 lists sectors ranked within the top 12 by consumption-based emissions in 2007. *Construction*, *public administration and social organization*, *health services*, *education services*, *wholesale and retail trade*, and *wearing apparel* sectors are major contributors to China's five regulated emissions in 2007. China's policy should pay special attention to these six sectors, such as promoting consumption behavior changes to reduce the demand on products from these sectors (Liang et al. 2015b, 2015c) and improving production efficiency of these sectors to reduce upstream emissions (Liang et al. 2015a, 2015b, 2015c).

Comparisons with Previous Studies

We calculate total intensity and consumption-based accounting of CO_2 emissions for China's sectors in 2002 to compare with Yang and Suh (2011). In particular, imports and the "others" column are not removed from the IOT of Yang and Suh (2011). In order to avoid the influence of different I-O data treatments on comparison results, we use the same 2002 Chinese IOT, with imports and the "others" column removed, to calculate results in this section. Table 3 lists the top 20 sectors in total intensity of CO_2 emissions. Full results for all sectors in 2002 are shown in the Supporting Information on the Web. The top 20 sectors identified using the CEEIO database and Yang and Suh's are generally consistent.

Table 3 Top 20 sectors in total intensity of CO_2 emissions in 2002

	This study		*Yang and Suh (2011)*	
Rank	*Sectors*	*Total intensity ($g\ CO_2$/U.S. dollars)*	*Sectors*	*Total intensity ($g\ CO_2$/U.S. dollars)*
1	Electricity and heat production and supply	21,356	Cement, lime, plaster, and related products	23,007
2	Other nonmetallic mineral products	14,426	Electricity and heat production and supply	20,987
3	Cement, lime, plaster, and related products	14,314	Iron smelting	16,656
4	Glass and glass products	13,635	Steel smelting	9,919
5	Fireproof products	13,628	Chemical fertilizers	9,448
6	Ceramic products	13,270	Other nonmetallic mineral products	7,112
7	Steel processing	13,151	Steel processing	6,867
8	Steel smelting	12,122	Iron alloy smelting	6,571
9	Iron alloy smelting	11,944	Raw chemical materials	6,362
10	Iron smelting	11,098	Coking	5,738
11	Raw chemical materials	8,249	Fireproof products	5,351
12	Coking	6,556	Pipeline transport	5,199
13	Chemical fertilizers	6,308	Glass and glass products	4,941
14	Synthetic chemicals	6,291	Gas production and supply	4,653
15	Chemicals for special usages	6,265	Ferrous metal ore mining	4,441
16	Chemical pesticides	5,956	Ceramic products	4,367
17	Chemicals for painting, dyeing, and others	5,871	Nonferrous metal smelting	4,335
18	Metal products	5,416	Water production and supply	4,334
19	Gas production and supply	5,405	Metal products	4,050
20	Petroleum refining and nuclear fuel	5,383	Sugar refining	3,975

Note: Chinese RMB is changed to U.S. dollar by the average exchange rate (8.2769575 Chinese RMB per U.S. dollar) in 2002 (*World Bank* 2015). Results for all sectors are listed in supporting information S1 on the Web.
CO_2 = carbon dioxide; g = grams; RMB = renminbi.

Regarding the difference between the two sets of results, six chemical sectors rank as top 20 using the CEEIO database, whereas only two chemical sectors do in Yang and Suh (2011). This can be mainly explained from two aspects. First, data for CO_2 emissions from Yang and Suh (2011) come from Peters and colleagues (2006) covering two chemical processes (ammonia production and soda ash use). CO_2 emissions from the CEEIO database are estimated for 11 industrial processes. Second, CO_2 emission factors used in Peters and colleagues are from the IPCC's 1996 guidelines (Peters et al. 2006), whereas CO_2 emission factors that used the CEEIO database are from the IPCC's 2006 guidelines (IPCC 2006).

Figure 1 shows the Kendall correlation analysis of all sectors based on two sets of results. Two sets of results are generally consistent with each other, except for some outliers caused by two reasons discussed above. The correlation coefficient for total intensity of CO_2 emissions is 0.79, with the p value of 1.17×10^{-37} indicating that the two sets of results highly correlate with each other ($p < .01$). Moreover, the correlation coefficient for consumption-based accounting of CO_2 emissions is .88, with the p value of 2.41×10^{-46} also indicating that the two sets of results highly correlate with each other ($p < .01$).

We also compared our results for the total intensity of CO_2 emissions and coal extraction in 2007 with the study of Chen and Chen (2010) in 2007, as shown in figure 2. The Kendall correlation analysis of all sectors shows that two sets of results are generally consistent with each other, except for some outliers. The correlation coefficient for total intensity of CO_2 emissions is .75, with the p value of 2.10×10^{-38} indicating that the two sets of results highly correlate with each other ($p < 0.01$). Moreover, the correlation coefficient for total intensity of coal extraction is .86, with the p value of 2.45×10^{-49} also indicating the two sets of results highly correlate with each other ($p < 0.01$). Differences between these two sets of results are mainly caused by different data treatments. We removed imports and the "others" column from China's 2007 IOT, whereas Chen and Chen (2010) did not.

Discussion

The CEEIO database is a transparent, comprehensive, and consistent EEIO database for China covering a wide range of years, sector classifications, and environmental accounts in this study. We make it publicly available with open access. Its system boundary is consistent for multiple years, making temporal comparison possible.

In addition to the CEEIO database itself, the framework of developing the CEEIO relies mostly on publically available data sources with regular updating. As a result, updating the CEEIO database in the future is relatively easy. In addition, factors and coefficients used in various estimations are also

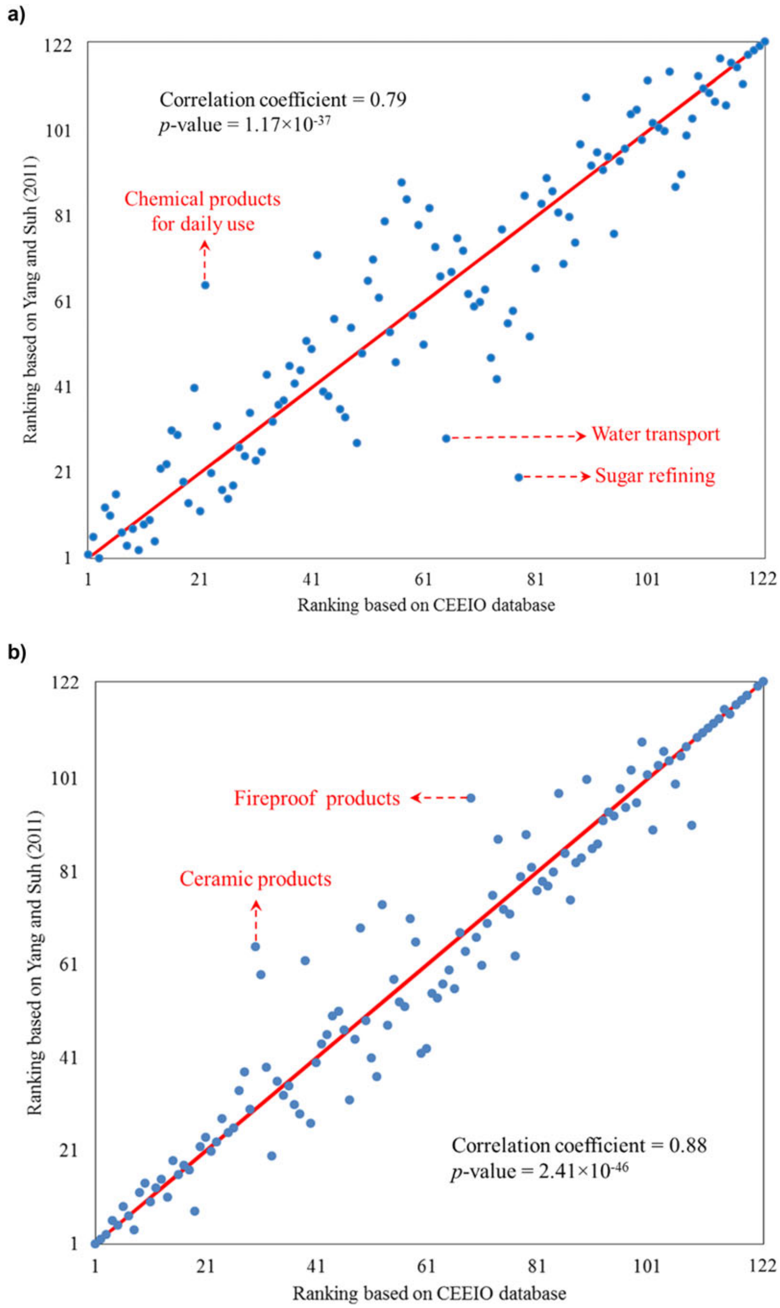

Figure 1 Kendall correlation analysis of (a) all 122 sectors in total intensity and (b) consumption-based accounting of CO_2 emissions in 2002 using CEEIO and data from (Yang and Suh 2011). Quantitative results for all sectors are listed in supporting information S1 on the Web. CEEIO = Chinese environmentally extended input-output; CO_2 = carbon dioxide.

regularly updated, such as the IPCC's GHG emission factors and China's atmospheric mercury emission factors. Moreover, we only construct environmental pressure indicators for years when benchmark IOTs are available. Future studies can also construct those indicators for other years based on methods in this study.

We find that environmental statistics in China became more comprehensive after 2005. However, this does not undermine the reliability of our database before 2005, for which we use widely accepted estimation methods, as validated by the comparisons with previous studies. To make it easy for users to use the CEEIO database, we classify the data by their reliability in the CEEIO database.

The CEEIO database can be applied in multiple ways. For example, one can combine it with life cycle assessment to evaluate life cycle environmental pressures of particular products, processes, or sectors (Hendrickson et al. 1998; Hawkins et al. 2007; Suh et al. 2004; Liang et al. 2012a, 2012b, 2013b, 2013c). It can be integrated with structural decomposition analysis to evaluate relative contributions of social and economic factors to the changes of environmental pressures in China over a certain

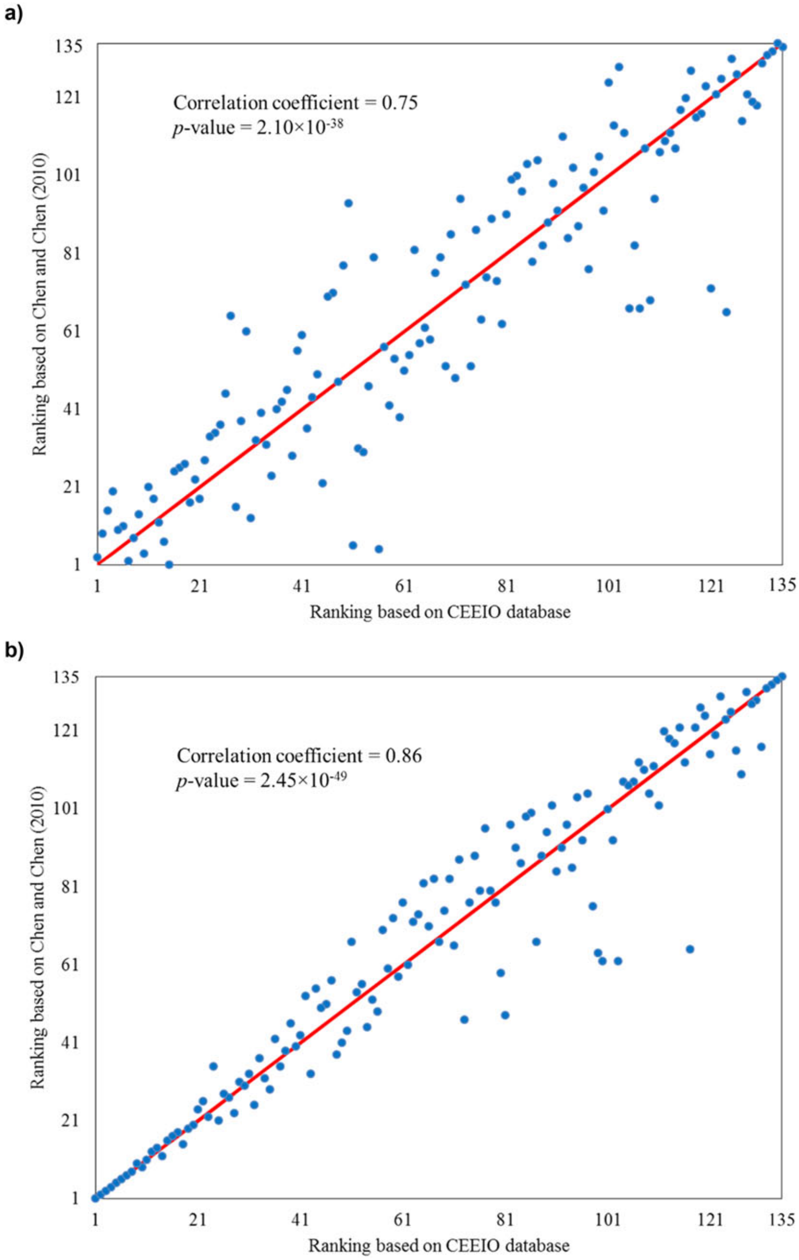

Figure 2 Kendall correlation analysis of (a) all 135 sectors in total intensity of CO_2 emissions and (b) coal extraction in 2007 using CEEIO and data from (Chen and Chen 2010). CEEIO = Chinese environmentally extended input-output; CO_2 = carbon dioxide.

period of time (Rose and Casler 1996; Dietzenbacher and Los 1998; Liang et al. 2013d, 2014a). Structural path analysis can also be conducted based on CEEIO to investigate individual supply-chain paths causing environmental pressures in China (Lenzen 2007; Peters and Hertwich 2006; Liang et al. 2015c). Moreover, integrating the CEEIO database with network analysis tools can help reveal the structure of China's environmental-economic systems (Blöchl et al. 2011; Liang et al. 2015a; Xu et al. 2011; Kagawa et al. 2013a, 2013b).

We keep imports and the "others" column for IOTs in the CEEIO database. Users can decide by themselves on whether and how the imports and the "others" column should be removed in practical applications. Moreover, exports of a country include processing exports and normal exports (Dietzenbacher et al. 2012; Su et al. 2013). Processing exports import intermediate inputs (e.g., raw materials, parts, and packaging materials) free of duty, process or assemble them domestically, and then re-export finished products. Normal exports are ordinary exports, also distinguished as nonprocessing exports. Processing exports have different input structure from normal exports. Currently, most I-O-based studies are based on the uniform export assumption, that is, assuming input structure of processing exports is the same as that of normal exports (Dietzenbacher et al. 2012; Su et al. 2013), which can bring about uncertainties for estimations of environmental pressures embodied in exports. Future applications of the CEEIO database to estimate environmental pressures embodied in exports should pay attention to this issue.

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Supporting Information

Supporting information is linked to this article on the *JIE* website:

Supporting Information S1: This supporting information S1 provides full results for environmental pressures of Chinese products in 2007 and the total intensity and consumption-based accounting of CO_2 emissions for Chinese products in 2002. The whole CEEIO database can be downloaded at: http://www.ceeio.com.

Supporting Information S2: This supporting information S2 compares two methods for allocating extracted resources to sectors using a two-sector case.