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The evolution of inter-sectoral linkages in China's energy-related CO_2 emissions from 1997 to 2012

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ABSTRACT

Energy-related CO_2 emissions in China have been extensively investigated. However, the mechanisms of how energy-related emissions are driven by inter-sectoral linkages remains unexplored. In this paper, a subsystem input-output model was developed to investigate the temporal and sectoral changes of emissions in China from 1997 to 2012. We decomposed total emissions into internal, spillover, feedback, and direct components. Our results show that the equipment manufacturing, construction and services sectors are the main sources of emissions during the whole period, which have a larger spillover component, primarily through indirect upstream emissions in the heavy-manufacturing, transportation, and power sectors. The emissions from the power and transportation sectors are dominated by direct rather than the spillover emissions. The shares of the feedback and internal components in the heavy manufacturing sectors were significantly higher than those of other sectors. Our results suggest that further addressing carbon emissions along the supply chain of equipment manufacturing, construction and services sectors, and improving technologies in the heavy manufacturing and power sectors holds important future opportunities for curbing the rapid growth of carbon emissions in China.

1. Introduction

Accompanying extraordinarily rapid economic growth, China became the leading CO_2 emitter in the world in 2006. In 2014 Chinese emissions already accounted for 30% of the world total, twice as much as the second-largest, the United States, at 15% (Liu, 2015). In response, China has committed to cut emission intensity (kg CO2eq/Yuan) by 40–45% in 2020, and by 60–65% in 2030, both figures relative to a 2005 baseline (Xinhua net, 2009; NDRCC, 2015). Furthermore, the government has a goal to peak absolute CO_2 emissions by 2030 and increase the share of non-fossil fuel energy to 20% in the same year (CDNDRC, 2014). In order to meet these national goals in an efficient and cost-effective manner, specific policies targeting the economic sectors with more opportunities to reduce carbon emissions will have to be developed. As such, further information on sectoral emissions is of the utmost importance.

Several sectors already have their own reduction targets. For instance, the energy sector has a standing commitment to reduce coal consumption to 65% of total primary energy consumption by 2017 (The State Council, 2013). Within the Energy Development Strategy Action Plan (2014–2020), the installations of wind and solar power in 2020 are expected to reach 200GW and 100GW, respectively (The People's Republic of China, 2014; Yang et al., 2016). The refining, coking, non-metallic mineral, and chemical sectors have goals in terms of energy consumption per unit of value added (The State Council, 2011). The allocation of sectoral emission reduction targets has focused to a great extent on traditional, energy-intensive sectors. There is still a widespread under-appreciation of the importance of reductions in non-energy intensive sectors (Zhang et al., 2015). However, the achievement of national targets will depend on how emissions from each sector will interact with those from the rest of the economy (Zhao et al., 2016). Accordingly, understanding how embodied carbon emissions are driven throughout the economy is both important and urgent for developing differentiated and practical emission reduction targets.

Previous research has analyzed carbon emissions in China from both single-sectoral and multi-sectoral perspective. Single sector studies include, Li et al. (2016), focused on the cement sector and developed

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an integrated assessment model to estimate the reduction potentials through different carbon mitigation pathways. Lin and Zhang (2016), also focusing on cement, applied the logarithmic mean Divisia index (LMDI) method to examine carbon intensity, energy intensity, energy structure, sector scale, and labor productivity. In the mining sector, Shao et al. (2016) adopted the generalized Divisia index method (GDIM) to investigate drivers of CO_2 emissions changes, and conducted a scenario analysis to identify mitigation pathways. In the power sector, Khanna et al. (2016) used an energy end-use model to evaluate energy and carbon emissions reduction potential to 2050, and Su et al. (2016) calculated provincial CO_2 emissions considering the fuel mix of exported electricity. In the iron and steel sector, Xu et al. (2016b) developed a Material Flow Analysis to estimate the CO_2 emissions; Peng et al. (2016) used global, multi-regional input-output (MRIO) and structural path analysis to single out important supply chain paths; and, Lin and Wang (2015) used stochastic frontier analysis to evaluate CO_2 emission reduction potential. Finally, in the freight sector, Hao et al. (2015) established a bottom-up model to forecast trends of energy consumption and GHG emissions. Such single-sectoral analyses are very valuable in themselves but they do not take into account the possibility of synergistic effects, with emissions occurring elsewhere in the economic landscape, when a policy targets a specific sector.

Multi-sectoral studies have focused on cross-sectoral comparisons among various industries or sectors, usually with a continuous time series. For example, Yu et al. (2016) proposed a multivariable, environmental learning curve panel model to estimate the emission abatement potential of 43 sectors. There have been a number of studies employing the LMDI method to break down sectoral contributions to GHG emissions. For example, Wang and Zhao (2016) studied the changes of carbon emissions in high, mid, and low energy-consumption sectors for 1996–2012. Xu et al. (2016a) explored emissions during different periods and from different sectors. Liu et al. (2015a) extended the LMDI methodology to analyze the changes in carbon intensity in 12 sub-sectors in China's industrial sector. Yan and Fang (2015) investigated the impact of emissions in 42 sub-sectors of the Chinese manufacturing industry for 1993–2011. Xu et al. (2014) analyzed the variations in sectoral emissions from 1996 to 2012. Many studies have focused on CO_2 emissions in China's sectors, but previous work does not examine the inter-sectoral linkages of CO_2 emissions from the perspective of supply chains (Ouyang and Lin, 2015; Kang et al., 2014; Ren et al., 2014). Thus, they may over-estimate the responsibility of the energy-intensive sectors and under-estimate the responsibility of non-energy intensive sectors (e.g., services) when the full effect of their supply chain is considered. In other words, although significant efforts for emission reduction in the energy-intensive sectors has been made, the non-energy intensive sectors' demand for energy-intensive products may indirectly cause substantial CO_2 emissions in the upstream energy-intensive sectors. We therefore believe a complete analysis of sectoral CO_2 emissions propagating throughout the whole supply chain is required.

The trade linkages in different regions that influence China's emissions have been investigated. The regional linkage effect is divided into the spillover and feedback effect (Round, 2001). The spillover effect measures the indirect effect of final demand changes in a specific region on the CO_2 emissions of other regions. The feedback effect then measures the increase in emissions occurring in the original region resulting from spillovers from other regions. Some studies have examined spillover and feedback effects of carbon emissions occur in multiple regions of China (Zhang and Zhao, 2005; Meng et al., 2013; Tang et al., 2015), but we are not aware of any comparative analysis of spillover and feedback effects of Chinese sectoral emissions. It is then fruitful to examine sectoral linkages in China with more detail.

Several studies have applied a subsystem input-output methodology to investigate sectoral emissions, taking into account the structure and sectoral linkages of different national economies. Subsystem models consider an individual sector, or group of sectors, as a subsystem and then study its production relations with the rest of the economy, while remaining embedded in the fulal production system. Previous studies are focused on the carbon emissions embodied in a group of sectors (Alcantara and Padilla, 2009; Butnar and Llop, 2011; Rachel, 2014; Matias and Thomas, 2014; Yuan and Zhao, 2016; Yuan et al., 2017). Llop and Tol (2013) expanded the approach to sectoral based emissions for the whole Irish economy, but did not investigate feedback mechanisms of emissions in detail. Alcantara et al. (2017) extended the model in a different way to uncover the different components of total consumption-based emissions in the different sectors in Spain. They clarified the relationship between inter-sectoral spillover of CO_2 emissions and the whole supply chain and addressed inter-sectoral feedback of CO_2 emissions but only for a single year. Here, we use the method from Alcantara et al. (2017) and extend this approach to a time-series analysis.

Final consumption of one sector leads to both its own carbon emissions and to emissions in other sectors (Liu et al., 2012; Alcantara and Padilla, 2009) and, according to Alcantara et al. (2017), the sum of these emissions can be decomposed in four components: direct, internal, spillover and feedback, which we now briefly review. Direct emissions are the corresponding change in the emissions caused by a small, exogenous change in the final consumption. For example, an increase in the final consumption of chemical products will generate extra CO_2 emissions in the chemical sector simply because the increase causes a direct effect of the same amount on the output of the chemical sector. Internal emissions are defined as carbon emissions arising only from the intermediate consumption of own inputs for the final consumption itself. For example, to satisfy the final demand of chemical sector, the chemical sector buy its own inputs for intermediate consumption, which will generate new carbon emissions in the fabrication of chemicals. However, for the fabrication of chemicals, the chemical sector requires inputs from other sectors along a supply chain, leading to extra CO_2 emissions in the production processes of other sectors: these are inter-sectoral spillover effects. Spillover effects are defined as the indirect impacts of the final consumption of one sector on the emissions occurring in the production processes of other sectors arising from additional inputs requirements. If a specific sector has greater spillover effects than others, then this sector has a strong pulling effect on the total carbon emissions in China by stimulating production in other sectors and should therefore be taken into account when designing an emission reduction policy. Additionally, there might exist a loop in the economic network in which the chemical sector providing inputs to a sector further upstream in its own supply chain. If that is the case, there will be further CO_2 emissions taking place in the chemical sector: these are inter-sectoral feedback effects. Feedback effects are defined as further emissions generated in the intermediate consumption of one sector caused by an additional input stimulus arising in the other sectors. For example, if the chemical sector requires additional inputs from the other sectors, in turn, the additional production in the other sectors will be reflected in the intermediate consumption of the chemical sector through the further demand for additional inputs. Therefore, if a specific sector has greater feedback effects than others, then emission changes in this sector depend more strongly on its own demand.

Given the existence of a knowledge gap in the current understanding of inter-sectoral carbon linkages in the Chinese economy, and the importance this presents to policy making, here we use subsystem input-output modelling to conduct a time-series analysis (1997–2012) of multi-sectoral emissions in China. For the purpose of the study we investigate the four emission components outlined above: direct, internal, spillover, and feedback. Our study differs from those reviewed above as we explore how sectoral linkages of a given sector with the rest of the economy change over time, and compare the changes in inter-sectoral spillover and feedback emissions. Such analyses can not only clarify how emissions are created and distributed across sectors, but also reveal trends and disparities within sectors. We are thus able to obtain a thorough understanding of sectoral emissions features, singling out key emission sectors and providing new insights for allocating Chinese sectoral emission reductions.

The remainder of this paper is organized as follows: Section 2 introduces the subsystem input-output model of CO_2 emissions and data processing; Section 3 offers the empirical results of CO_2 emission multi-sectoral analysis; Section 4 discusses the policy implications of this work; and, finally we offer some conclusions.

2. Methodology and data

2.1. Subsystem input-output model

Sectoral carbon emissions are based on fossil fuel consumption using IPCC guidelines (IPCC, 2006). We do not include emissions from non-energy use and industrial processes. Carbon emissions (e) are calculated as

$$e = EF \times EC \tag{1}$$

where EF is the fossil fuel type specific equivalence CO_2 emission factor (based on 2006 IPCC Guidelines for National Greenhouse Gas Inventories) and $EC$is the physical amount of fossil fuel consumption (based on the energy statistics data).

The standard Leontief (1936) model is given by

$$x = Ax + y \tag{2}$$

where x is a $(n \times 1)$ vector of total output whose element x_i is the output of sector i, y is a $(n \times 1)$ vector of final demand whose element y_i is the final demand of sector i; and A is a $(n \times n)$ matrix of technical coefficients, where the characteristic element a_{ij} shows the consumption of inputs, in money terms, from sector i per unit of output, in money terms, of sector j. That is:

$$a_{ij} = \frac{x_{ij}}{x_j} \tag{3}$$

The solution of the system is then given by:

$$x = (I{-}A)^{-1}y \tag{4}$$

where $(I - A)^{-1}$ is the well-known Leontief inverse, and I is the identity matrix. To estimate CO_2 emissions, we introduce the carbon emission coefficients $c_i = e_i/x_i$ (i.e. CO_2 emissions per unit of economic output) for all economic sectors. Let c_i denote the carbon emission coefficient of sector i, then the CO_2 can be estimated as follows:

$$e = c'L\hat{y} \tag{5}$$

where e is a $(n \times 1)$ vector of total CO_2 emissions embodied in goods and services generated by final demand, c is a $(n \times 1)$ vector of carbon emission coefficient for all economic sectors, $(I - A)^{-1} = L = [l_{ij}]$ is the Leontief-inverse, $\hat{y} = diag(y)$ is the diagonal vector of y.

We define emissions embodied in the total output of sector i as output-induced emissions, which can be calculated as follows:

$$e_i = c_i l_{ii} y_i + \sum_{i \neq j} c_i l_{ij} y_j = e_{ii} + \sum_{i \neq j} e_{ij} \tag{6}$$

where e_i is emissions released from sector i driven by China's total final demand. By symmetry, the total emissions induced by the final demand of sector i is calculated as

$$e_i' = c_i l_{ii} y_i + \sum_{i \neq j} c_j l_{ji} y_i = e_{ii} + \sum_{i \neq j} e_{ji} \tag{7}$$

where e_i' is the amount of carbon emissions that all sectors have to produce to obtain the final demand of sector$i$. We define this as demand-induced emissions. Note that e_{ij} and e_{ji} both reflect inter-sectoral emission transfer, but they have different meanings. e_{ij} in Eq. (6) is the direct CO_2 emissions caused by sector j in sector i, which reflects the distribution of emissions in the demand chain of sector i. While e_{ji} in Eq. (7) is the embodied CO_2 emissions of sector j induced by the final demand of sector i, which reflects the distribution of emissions in the supply chain of sector i.

Next, we transform Eq. (7) to decompose demand-induced CO_2 emissions resulting from various effects. The first step is to decompose direct and indirect demand effects. Direct demand effects are those that occur within the sector and are directly caused by final demand. Indirect demand effects are total minus direct demand effects and can occur either in the sector itself, or further upstream along the supply chain:

$$e_i' = c_i y_i + \left(c_i l_{ii} + \sum_{i \neq j} c_j l_{ji} - c_i \right) y_i \tag{8}$$

where $c_i y_i$ shows the direct carbon emissions caused by the final demand of sector i and $(c_i l_{ii} + \sum_{i \neq j} c_j l_{ji} - c_i) y_i$ is the indirect carbon emissions caused by the final demand of sector i.

Indirect sectoral carbon emissions can be further decomposed into intra-sectoral indirect emissions (occurring in the same sector) and inter-sectoral spillover emissions (occurring in other sectors). The total demand-induced emissions occurring in sector i, denoted by e_i, can be decomposed as follows:

$$e_i' = c_i y_i + c_i (l_{ii}{-}1) y_i + \sum_{i \neq j} c_j l_{ji} y_i \tag{9}$$

where $c_i y_i$ reflects an additional growth of direct carbon emissions in the sector i when the final demand of sector i increases one unit (the direct effect identified above). The second term, $c_i(l_{ii} - 1)y_i$ shows the intra-sectoral indirect emissions generated in the production of intermediate inputs by the sector i required to satisfy its final demand (the intra-sectoral indirect emissions). The final term, $\sum_{i \neq j} c_j l_{ji} y_i$ shows the emissions occurring in sector i which result from inter-sectoral demands aimed at delivering final demand of sectors (spill-over effect).

Considering the matrix L is determined by $(I - A)$ and is the inverse of $(I - A)$, the elements of the main diagonal of the Leontief inverse can be expressed as follows:

$$l_{ii} = (1{-}a_{ii})^{-1} \left(1 + \sum_{i \neq j} a_{ij} l_{ji} \right) = (1{-}a_{ii})^{-1} + (1{-}a_{ii})^{-1} \sum_{i \neq j} a_{ij} l_{ji} \tag{10}$$

and $(l_{ii} - 1)$ can be transformed as follows:

$$\begin{aligned} l_{ii}{-}1 &= (1{-}a_{ii})^{-1} \left(1 + \sum_{i \neq j} a_{ij} l_{ji} \right) - 1 \\ &= \left[(1{-}a_{ii})^{-1} {-} 1 \right] + (1{-}a_{ii})^{-1} \sum_{i \neq j} a_{ij} l_{ji} \end{aligned} \tag{11}$$

Thus, the intra-sectoral indirect emissions can be further decomposed in two separate components, internal and feedback effects, according to the following equation:

$$c_i (l_{ii}{-}1) y_i = c_i \left[(1{-}a_{ii})^{-1} {-} 1 \right] y_i + c_i (1{-}a_{ii})^{-1} \sum_{i \neq j} a_{ij} l_{ji} y_i \tag{12}$$

where the first term, $c_i[(1 - a_{ii})^{-1} - 1] y_i$ shows the emissions generated in the own production of sector i through its internal inputs. The second term, $c_i(1 - a_{ii})^{-1} \sum_{i \neq j} a_{ij} l_{ji} y_i$ shows the emissions from sector i required for the production of inputs that it demands from other sectors, that is, the growth of emissions of sector *i* when an additional unit of final demand in sector *i* increases via sector *j*.

The total emissions associated with the components of sector *i* can be determined as:

$$e_i' = c_i\left[(1-a_{ii})^{-1}-1\right]y_i + c_i(1-a_{ii})^{-1}\sum_{i\neq j} a_{ij}l_{ji}y_i + \sum_{i\neq j} c_j l_{ji}y_i + c_i y_i \\ = INT_j + FEB_j + SPI_j + DIR_j \quad (13)$$

This final expression allows for the analysis of the emissions of each sector according to its relationship with the other sectors of the economy. The total emissions of sector *i* is decomposed into four components: internal component (*INT*), feedback component (*FEB*), spillover component (*SPI*) and direct component (*DIR*). The internal, feedback, and direct components maps all carbon emissions from production of sector *i*; these terms sum to total own emissions. The inter-sectoral transfer of embodied CO_2 emissions in the supply chain can then be determined based on sectoral spillover and feedback effects of carbon emissions.

2.2. Data

This paper utilizes Chinese input-output tables for 1997 (40 sub-sectors), 2002 (42 sub-sectors), 2007 (42 sub-sectors), and 2012 (42 sub-sectors) (NBS, 1999, 2006, 2009, 2015). The tables were harmonized across the years by aggregating to 26 sub-sectors (these sub-sectors are described in Table 1). For ease of analysis, we first perform all calculations at the level of 26 sectors, and then aggregate results to 9 sectors in which sub-sectors are included. Thus, the entire China economy was divided into 9 broader sectors: agriculture, mining, heavy manufacturing, light manufacturing, equipment manufacturing, power, construction, transportation, and services. Energy use in China was obtained from the final energy consumption data of China Energy Statistical Yearbooks (NBS, 1998, 2003, 2008, 2013). National Bureau of Statistics of China provides competitive I-O tables, however, the non-competitive I—O table has the advantage of giving more precise estimates of emissions considering domestic production technology matrix (United Nations, 1993; Su and Ang, 2013). Thus, in contrast to the previous measurement based on competitive I—O tables, the calculation in this paper is based on Chinese non-competitive import I—O tables.

Table 1
Sector classifications for the Chinese economy.

Sector	Code	Sub-sector
Agriculture	AGR	Agriculture
Mining	MC	Mining and Washing of Coal
	MPN	Extraction of Petroleum and Natural Gas
	MM	Mining and Processing of Metal Ores
	MO	Mining of Other Ores
Heavy manufacturing	PC	Petroleum Refining and Coking
	CHE	Chemical
	NMP	Non-metallic Mineral Products
	SPM	Smelting and Pressing of Metals
Light manufacturing	FD	Food
	TEX	Textile
	TR	Textile Related Products
	TF	Processing of Timber and Furniture
	PP	Paper and Paper Products
	OM	Other Manufacturing
Equipment manufacturing	MP	Metal Products
	GE	General Equipment
	TE	Transport Equipment
	EME	Electric Machinery and Equipment
	EE	Electronic Equipment
	IM	Instruments and Machinery of Cultural Activity and Office Work
Power	POW	Power
Construction	CON	Construction
Transportation	TRA	Transportation
Services	WRC	Wholesale, Retail Trade and Catering Service
	OS	Other Service

We use 16 kinds of fossil fuels for the economic sector to estimate carbon emissions, including: raw coal, cleaned coal, other washed coal, coke, coke oven gas, other gas, other coking products, crude oil, gasoline, kerosene, diesel oil, fuel oil, liquid petroleum gas, refinery gas, other petroleum products and natural gas. We refer to Zhang et al. (2015)'s method to estimate sectoral CO_2 emissions, in which the emissions from fuel combustion equals to the final use of energy plus energy inputs or losses during energy transformation processes. Therefore, energy inputs embodied in the transformation of thermal power and heating supply are allocated to energy consumption in the power sector. The net calorific value and CO_2 emission factor of the various fuels are listed in Table A1 of Appendix A.

3. Results

First, we present the general trends and sectoral contributions under the demand-induced accounting principle as compared with the output-induced accounting principle. Then we decompose the total sectoral emissions into the four components; internal, direct, feedback, and spillover. Finally, we analyze the evolution of inter-sectoral linkages in China's demand-induced carbon emissions by analyzing the ranking of spillover and feedback emission shares among 26 sub-sectors.

3.1. General trends and sectoral contributions

In the 15 years from 1997 to 2012, China's emissions rose 160%, from 3118 to 8090 million tons (Mt) (see Fig. 1). After 2002, China experienced a quick increase in total CO_2 emissions. Growth in emissions were, on average, 17.2% per year during 2002–2007, decreasing to 5.9% per year during 2007–2012. These trends mirror the evolution of the Chinese economy during this time period: growth of the Chinese economy accelerated, reaching an average GDP growth of over 10% per year between 2002 and 2007 (NBS, 2008). The high rate of economic growth led to a rise in carbon emissions as fast economic development provided consumers with more disposable income driving goods and services consumption, including energy. The emission growth rate dropped to 5.9% in 2012, largely due to the effects of the 2008–2009 global economic crisis, and an overall fall in final demand. Before moving to sectoral results we validate our total emission calculations against those from the Energy Information Administration (EIA, http://www.eia.gov/), Emission Database for Global Atmospheric Research (EDGAR, http://edgar.jrc.ec.europa.eu/), British Petroleum (BP, 2014), Carbon Dioxide Information Analysis Centre (CDICA, http://cdiac.ornl.gov/), and Liu et al. (2015b). These estimates vary as to the types of gas and processes that are included (see Fig. 1). Methodologically, our results are most similar to Liu et al. (2015b) because, like them, we estimate CO_2 emissions only, and do not include CH_4 and N_2O. Liu et al. (2015b) presented revised estimates of Chinese CO_2 emissions using two sets of new measurements of emission factors and find a revised estimate of CO_2 which is lower than estimates from other inventories. Our estimate of total emissions is still 9% lower than those of Liu et al. (2015b) in 2012. This is because we do not estimate emissions embodied in industrial processes, and cement process emissions accounted for about 9% of China's total CO_2 emissions over this period (Liu et al., 2015b).

As illustrated in Fig. 2 the carbon emissions of 1997 and 2012 show significant changes in the ranking of demand-induced carbon emissions among the 26 sub-sectors when compared to output-induced emissions. The output-induced emissions of power sector were largest, accounting for 40.1% and 49.3% of the total in 1997 and 2012 respectively. The second largest emitter was heavy manufacturing sector with 35.1% in 1997 and 32.5% in 2012. Comparing with output-induced accounting shows

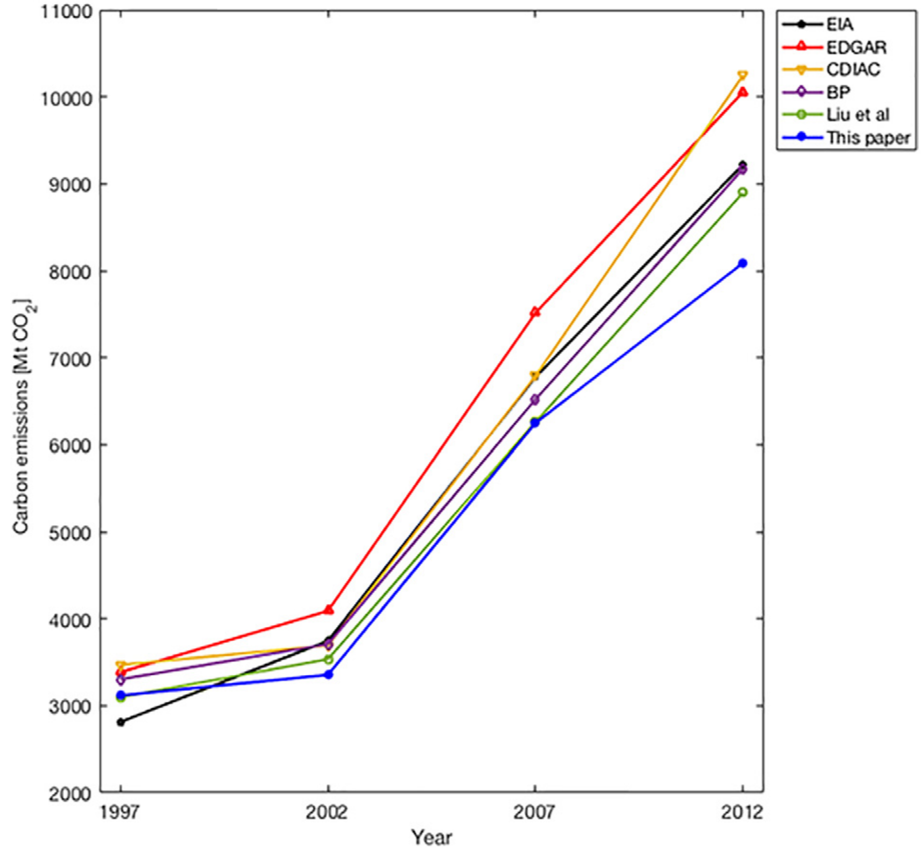

Fig. 1. The general trends of carbon emission from 1997 to 2012 based on different estimations.

that the construction sector was the largest demand-induced emitter, and equipment manufacturing ranked second.

Table 2 shows the significant changes over 1997–2012 in the emission shares of sub-sectors in the total emissions of China under demand-induced principle. The construction sector is a key emitter through all years, peaking at 28% of emissions in 2012. Emissions in equipment manufacturing sub-sectors grew quickly from 1997 to 2012. For example, general equipment grew from 6.5% in 1997 steadily to 8.6% of all emissions by 2012. This trend is repeated in the transport equipment sub-sector, growing from 3.7% to 6.6% by 2012. Other notable trends are the reduction in contributions from primary sectors such as agriculture (dropping 5.8% to 2.1% by 2012), along with some light manufacturing sub-sectors such as the food (FD). In 1997, the transportation sector accounted for around 1.8% of emissions, with an absolute increment of 255 Mt. in 2012. Other sectors such as the power sector show a consistent proportion over time. We note that demand-induced emissions in the mining sector present a decreasing trend, which can be explained by reductions in emission coefficients and the slow growth of final demand. We take Mining and Washing of Coal (MC) sub-sector as an example, CO_2 emissions per unit of economic output decreased from 1.04 tons in 2002 to 0.67 tons in 2012 due to technological improvement. Furthermore, the final demand for coal grew slowly between 2002 and 2012 due to an export reduction of 0.7 million yuan (NBS, 2013) and a great decrease in household

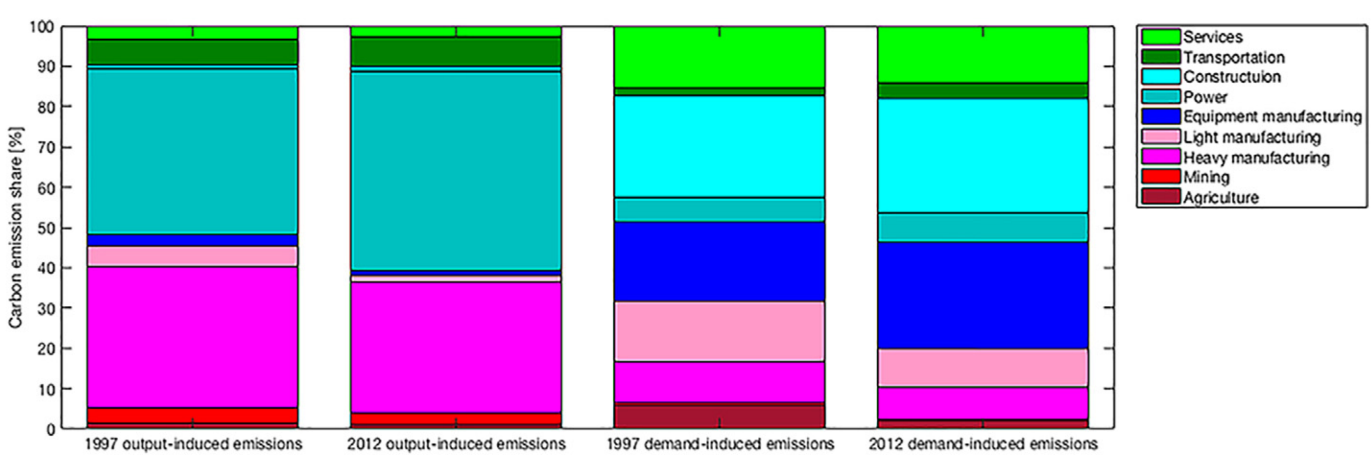

Fig. 2. Carbon emission share under the output-induced and demand-induced principles (1997 and 2012).

Table 2
Contributions of demand-induced emissions in sub-sectors from 1997 to 2012.

Sub-sectors	1997		2002		2007		2012	
	Mt CO_2	%	Mt CO_2	%	Mt CO_2	%	Mt CO_2	%
AGR	180.52	5.79	161.63	4.82	131.38	2.10	169.44	2.09
MC	9.73	0.31	18.16	0.54	12.44	0.20	10.11	0.12
MPN	9.14	0.29	5.11	0.15	5.51	0.09	7.17	0.09
MM	1.34	0.04	1.48	0.04	6.79	0.11	2.32	0.03
MO	4.58	0.15	4.98	0.15	3.73	0.06	0.92	0.01
PC	20.73	0.66	15.55	0.46	36.32	0.58	54.74	0.68
CHE	184.33	5.91	155.92	4.65	298.57	4.78	336.16	4.16
NMP	87.93	2.82	54.51	1.62	76.56	1.23	98.63	1.22
SPM	20.00	0.64	30.66	0.91	254.46	4.07	149.64	1.85
FD	198.76	6.37	138.19	4.12	224.25	3.59	304.58	3.76
TEX	71.55	2.29	78.54	2.34	154.03	2.47	70.13	0.87
TR	97.62	3.13	83.98	2.50	152.10	2.43	193.05	2.39
TF	27.54	0.88	25.82	0.77	70.81	1.13	75.86	0.94
PP	40.96	1.31	34.62	1.03	53.94	0.86	116.95	1.45
OM	29.27	0.94	20.26	0.60	45.17	0.72	9.11	0.11
MP	84.07	2.70	70.51	2.10	153.30	2.45	172.61	2.13
GE	203.27	6.52	223.05	6.65	501.31	8.02	696.11	8.60
TE	115.44	3.70	105.82	3.15	301.65	4.83	532.70	6.58
EME	120.60	3.87	103.28	3.08	318.34	5.10	397.61	4.91
EE	82.33	2.64	143.66	4.28	319.45	5.11	328.60	4.06
IM	16.79	0.54	36.72	1.09	61.07	0.98	32.71	0.40
POW	190.50	6.11	295.16	8.80	428.79	6.86	577.01	7.13
CON	784.76	25.17	796.23	23.73	1533.36	24.54	2308.11	28.53
TRA	57.38	1.84	128.07	3.82	257.05	4.11	311.85	3.85
WRC	100.16	3.21	146.17	4.36	204.81	3.28	201.96	2.50
OS	378.79	12.15	477.52	14.23	642.94	10.29	932.17	11.52
Total	3118	100	3356	100	6248	100	8090	100

consumption caused by a ban on the burning of coal for domestic heating in cities.

3.2. The decomposition of sectoral emissions

For ease of explanation, we aggregate results of 26 sector to 9 major sectors, and then report the results of each sector separately. Fig. 3 presents the decomposition of total emissions into internal, feedback, spillover, and direct components for the sectors outlined in Table 1. Figs. 4–7 show the disaggregate-level analysis for sectors with many sub-sectors.

Agricultural emissions were driven by spillover effects, accounting for 81.0% of total agricultural emissions by 2012. Agricultural emissions in the direct component grew rapidly from 11.4% in 1997 to 24.6% by 2007, before dropping significantly to 15.5% by 2012. These reductions reflected a shift from traditional agricultural activities to industrial activities. The proportion of the internal component increased from 2.1% in 1997 to 3.8% in 2010, then decreased to 2.3%. Given projected increases in Chinese population, direct demand will continue to increase carbon emissions in the agriculture sector, but spillover effects from agricultural demand are now a dominant issue.

In the mining sector, the spillover component was important over the period, and by 2012 was 68.0% of the total. The direct component was another major contribution, and by 2012 was 28.1% of the total. The internal component increased from 0.8% of the total in 1997 to 3.2% by 2012. The feedback component shows a stable share over time. Within the mining sector, the Mining and Washing of Coal (MC) sub-sector is the most active sub-sector, resulting from high levels of final demand (see Fig. 4). The emissions of the direct component accounted for above 30% of total emissions in the MC sub-sector from 1997 to 2012. The share of direct component in the MC sub-sector has fluctuated greatly with the share decreasing by 8% from 1997 to 2002. This is mainly due to increased intermediate inputs in the production processes of MC sub-sector, resulting in the growth of the spillover effect. While the spillover effect decreased by 12%, the share of the direct component increased by 6% from 2002 to 2012. Extraction of Petroleum and Natural Gas (MPN) is the second largest contributor to CO2 emissions in the mining sector, which is driven by the fact that China is now one of the most important producers of petroleum and natural gas in the world. From 1997 to 2007, emissions in MPN decreased nearly 44%. This can be explained by the drop in international oil prices which shrank total production. After 2002, MPN sub-sector grew at a slow pace as the economy expanded, representing an annual 4.1% increase. From 2002 to 2007, Mining and Processing of Metal Ores (MM) sub-sector grew 4 times, in step with increased demand due to the takeoff of the Chinese economy, particularly in infrastructure and

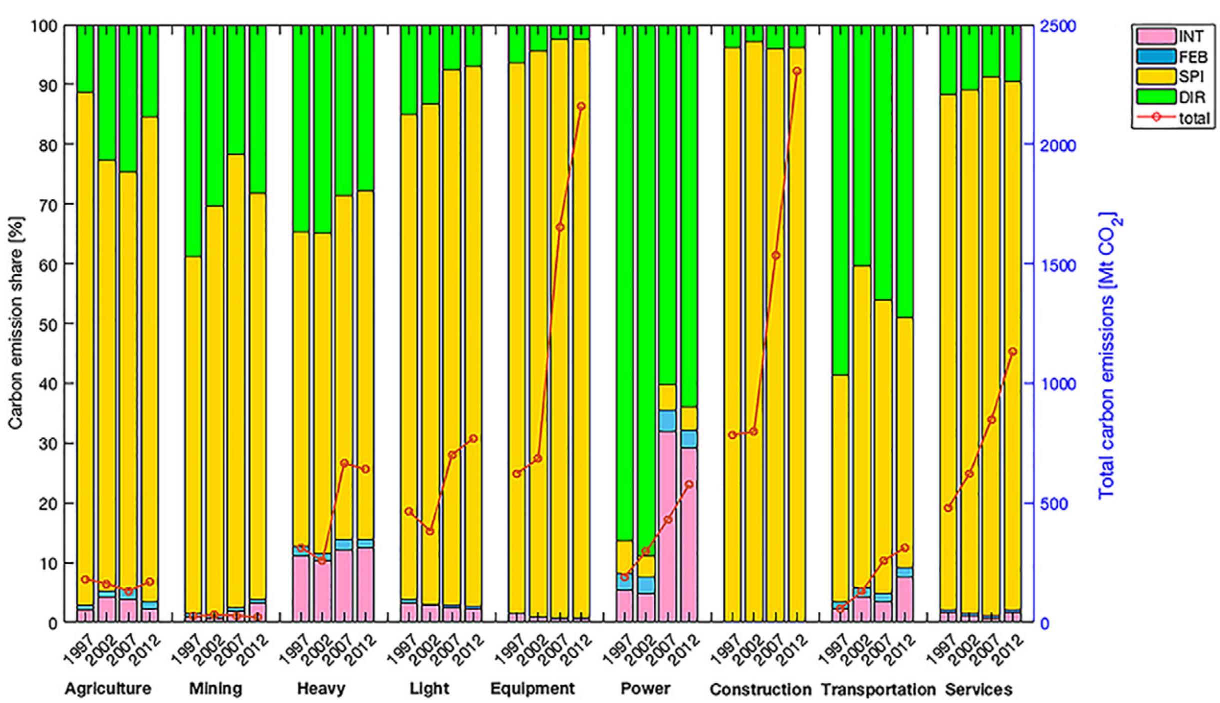

Fig. 3. Decomposition of demand-induced emissions from 1997 to 2012.

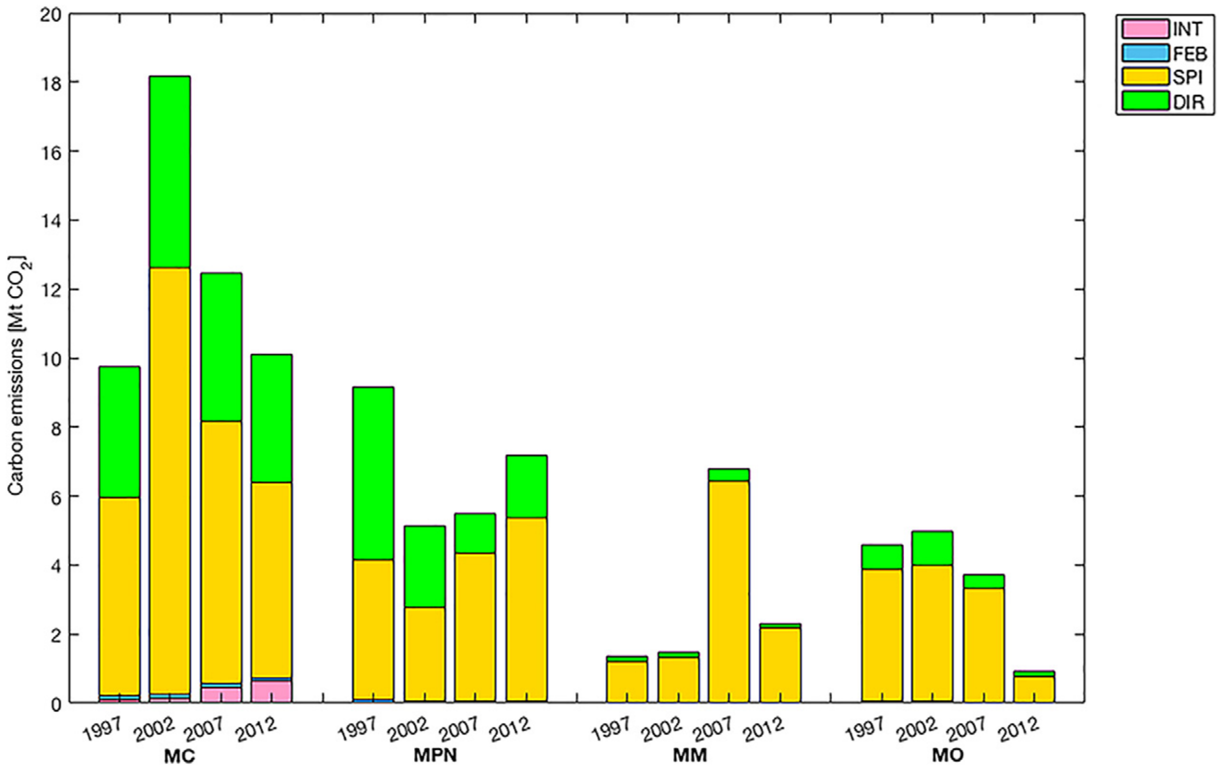

Fig. 4. Decomposition of demand-induced emissions in the mining sector from 1997 to 2012.

manufacturing. The slowdown in economic growth in 2012 has caused little economic incentive to increase CO_2 emissions in MM sub-sector. Similar trends occur in the Mining of Other Ores (MO) sub-sector.

Emissions in the heavy manufacturing sector grew 131%, from 257 Mt. in 2002 to 666 Mt. in 2007. In 2012, as the sector reaches maturity, we observe a small reduction in emissions which may be driven by government policies aimed at adjusting the Chinese economic structure. This is exemplified by the shifting of China's economic growth model from industry to services, which decreases the share of the heavy manufacturing sectors in China's value added output, and increases the proportion of labor and technology-intensive sectors. In the heavy manufacturing sector, the spillover component is a key factor,

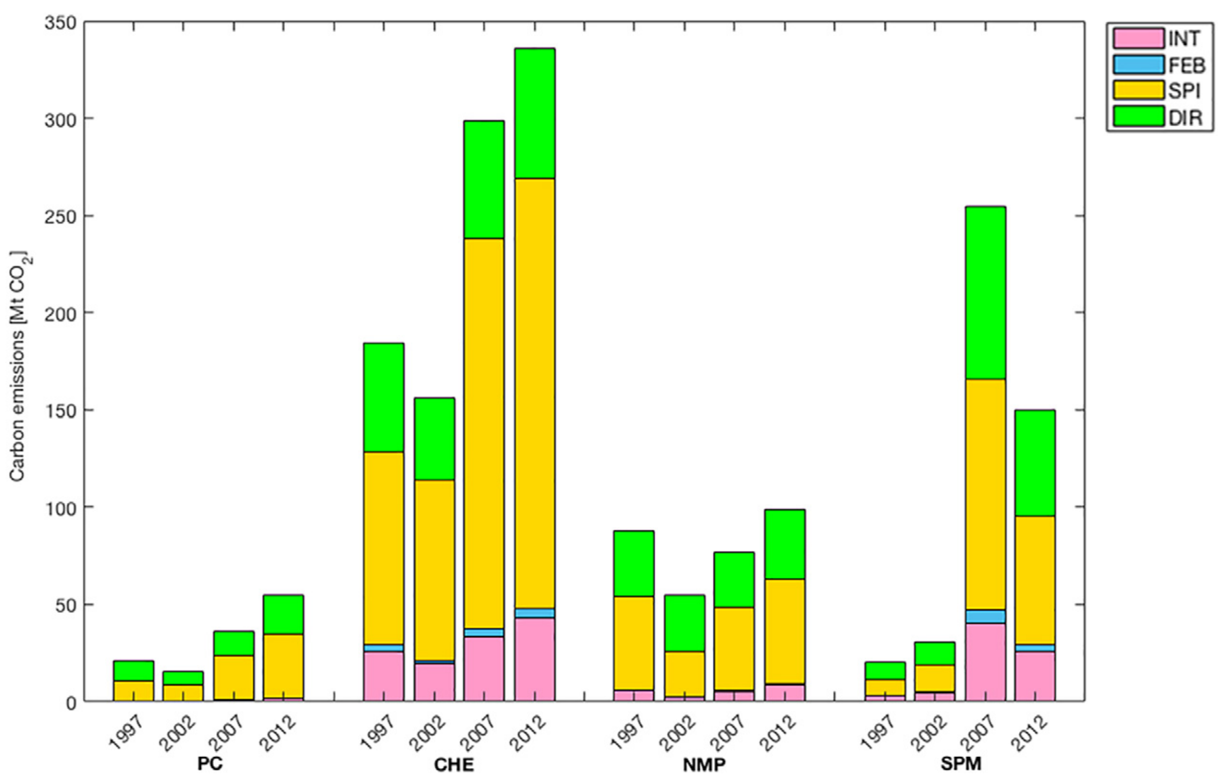

Fig. 5. Decomposition of demand-induced emissions in the heavy manufacturing sector from 1997 to 2012.

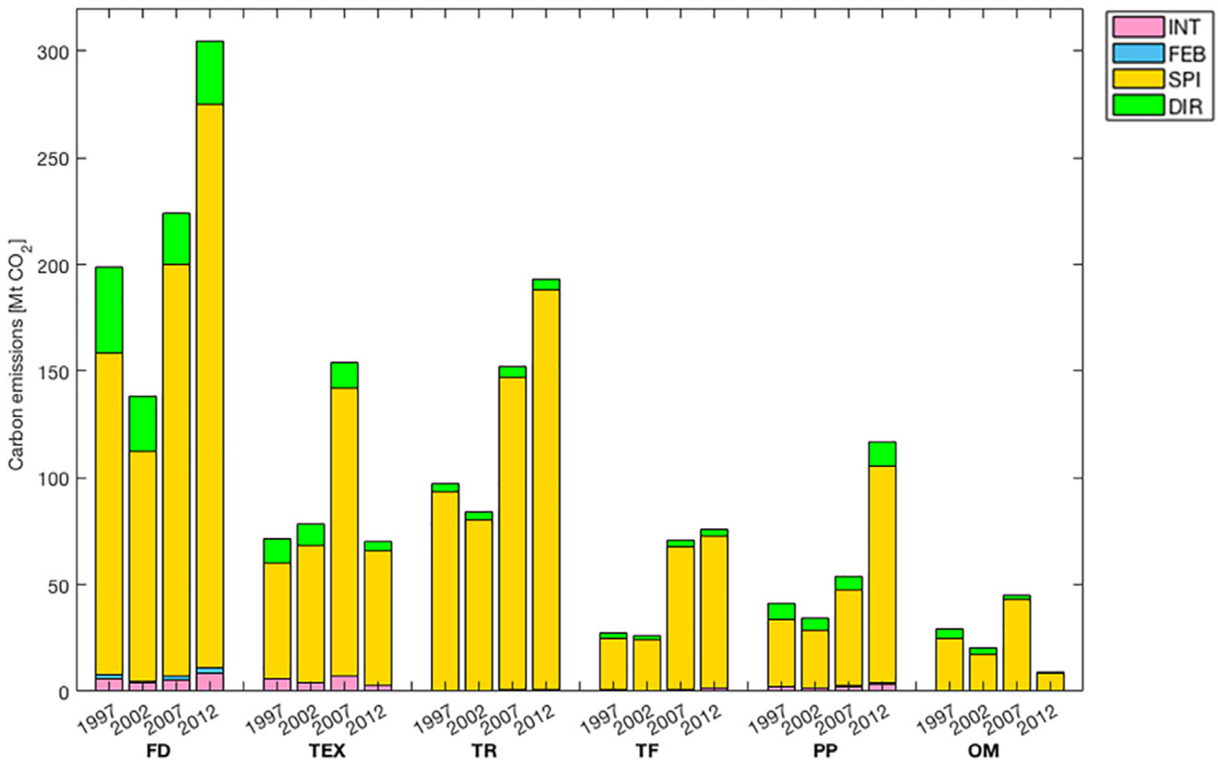

Fig. 6. Decomposition of demand-induced emissions in the light manufacturing sector from 1997 to 2012.

accounting for 58.5% of the total in 2012. 374 Mt. CO_2 emissions in other sectors were driven by the final demand for heavy manufacturing sector. Energy-intensive supply chains, related to the production of non-ferrous metals, chemical manufacturing, and metal products, may explain the largest effect of spillover component. Emissions in 1997 in the internal component comprise 11.1% of the total, and its share experienced a slight increase in the total carbon emissions (to 12.4% in 2012). Turning to the feedback share, the proportion grew gradually and eventually stabilized from 2007 to 2012 to 1.4% of the total. We present further sectoral decomposition results in Fig. 5. In 1997, the chemical emissions were dominated by spillover effects, accounting for 53.7% of the total. The spillover effect of the chemical sector showed a sharp upward trend between 1997 and 2007, with its share in 2007 accounting for 67.3% of the total emissions. In 2012, the spillover emission share fell slightly from 67.3% to 65.8%, while the internal component increased to 12.8%. Smelting and Pressing of Metals (SPM) had a rapid increase in the emissions between 1997 and 2007 due to a significant growth of the direct component, before reducing again by 2012. The direct component clearly demonstrates the direct demand effects of CHE and SPM subsectors on carbon emission. With fast economic development, China's chemical and metal consumption has increased rapidly, driven by massive infrastructure construction. For example, China has become the world's second largest consumer of basic chemical products. In addition, the largest growth in the internal component was from CHE and SPM sub-sectors, with their internal components in 2012 increasing by 17 Mt. and 8 Mt., respectively, compared to 1997. This suggests that improvements in the emission efficiency in the production of chemical materials and metal products

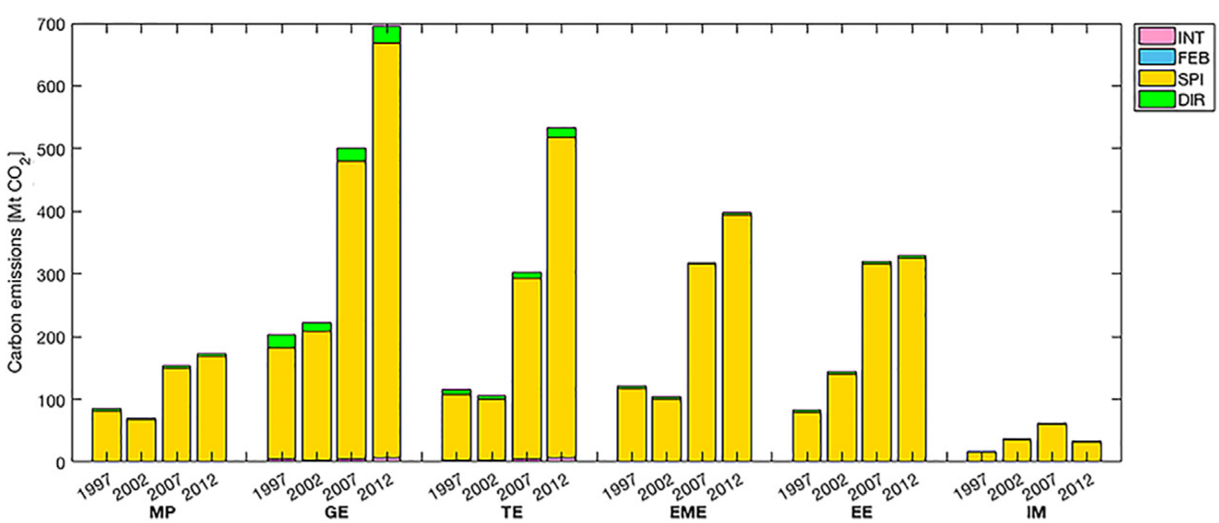

Fig. 7. Decomposition of demand-induced emissions in the equipment manufacturing sector from 1997 to 2012.

is limited. Advancements in technology and energy efficiency in the production process has not kept pace, resulting in much higher internal proportions than other heavy manufacturing sectors.

In the light manufacturing sector, the spillover component was a major driver between 1997 and 2012. The share of spillover emissions increased from 81.1% to 90.4% by 2012 due to the rapid growth of final demand-supporting extensive industrialization. Over the same period, the direct component was the second largest, but did decrease from 15.1% to 7.0% by 2012. The internal effect also shows a significant contribution to total emissions, with the share decreasing from 3.2% to 2.2% by 2012. Fig. 6 shows that the largest sub-sector with high spillover emissions was Food (FD). In 2012, the spillover component of FD sub-sector was 86.7% of the total, meaning that 86.7% of the emissions generated by the other sectors are incorporated into the final production of FD sub-sector. Meanwhile, the feedback component in FD sub-sector in 1997 was more than 1% reducing to 0.9% in 2012.

From 1997 to 2012, equipment manufacturing emissions increased almost 4-times. Between 1997 and 2002, China had a comparative advantage in light manufacturing sector such as food and beverages, textile, wood, paper. The comparative advantage of this sector declined in the twenty-first century. Equipment manufacturing began to boast a significant comparative advantage after 2002, especially for machinery and transport equipment. By producing and exporting more goods, carbon emissions in equipment manufacturing sector increased rapidly. This increase was dominated by spillover, which increased from 92.2% in 1997 to 96.8% in 2012. The carbon emissions induced by spillover for the equipment manufacturing sector are much higher than other sectors because of its role as processing sector, and the fact that its final product has a long life cycle. Therefore, the growth of its output is dependent on the other sectors and requires plenty of intermediate inputs. During this period, at sub-sectoral level, the General Equipment sub-sector (GE) was the fastest growing sector, followed by Transportation Equipment sub-sector (TE), both of which indicated a fast spillover component growth than industrial average (see Fig. 7). For instance, in 1997, 178 Mt. and 104 Mt. of carbon emissions were emitted in the spillover component in the general and transportation equipment manufacturing sub-sectors respectively. This accounted for 87.6% and 90.2% of the total emissions in these two sub-sectors respectively. By 2012, carbon emissions in the spillover component increased to 661 Mt. (94.9% of total) and 511 Mt. (96.0% of total) in the general and transportation equipment manufacturing sub-sectors respectively. The share of the spillover component for the Electric Machinery and Equipment (EME) and Electronic Equipment (EE) manufacturing sub-sectors are much larger than those of other equipment manufacturing sub-sectors. In the case of electric and electronic equipment manufacturing in 2012, the spillover effects amounted to 96.8% and 99.1% of the total emissions, respectively. The final demand of these sectors leads to a significant increase in emissions from the production of other sectors.

As shown in Fig. 3, the total emissions from the power sector increased rapidly between 1997 and 2007, reaching as much as 577.0 Mt. in 2012. The direct component, accounted for over 60% of the total emissions induced by the final demand of the power sector between 1997 and 2012. Emissions in the direct component increased from 164.6 Mt. to 257.8 Mt. in 2007 due to a rapid growth of electricity consumption by China's urban households. The total electricity consumption by China's urban households increased at an annual average rate of 10% between 1997 and 2007 (Akinobu et al., 2008). The internal component was another major contributor to total emissions, which was stable as a proportion, at around 5.5% and 4.8% in this early period, then increased dramatically from 4.8% in 2002 to 32.0% in 2007 before reducing again by 2012. This is because the share of input from its own sector in the total input (a_{ii}) increased to 0.35 in 2007 from 0.06 in 1997 (NBS, 1998, 2008). If we take into account the fact that the spillover component of power sector emissions amounted to 23.4 Mt. in the year 2012, then only 4.1% of emissions generated by other sectors were incorporated in the emission in power sector. This is likely due to the fact that the power sector is the primary provider of secondary energy carriers (electricity) for other sectors, and thus the power sector is dependent on the development of those sectors.

In the construction sector, emissions have risen significantly, with relatively rapid growth between 2002 and 2012, driven by uniform, rapid growth of final demand. This is predominantly driven by urbanization, industrialization, rising personal income levels, further population growth, and household growth driving a housing boom. The main source of carbon emissions in the construction sector depends, to a greater extent, on the spillover component from 1997 to 2012. This means that the construction sector has a strong pulling effect on the carbon emissions generated in the production processes of the rest of the economy. For example, the iron and steel sector is closely related to the construction sector. The construction sector has the potential to contribute to the output of iron and steel and to the growth of the carbon emissions in the production processes of iron and steel sector. The spillover component dominated in the early years and increased further, from 96.1% in 1997 to 97.1% in 2002. The direct component was also an important driver in the increase of emissions in the construction sector, with a share in the total emissions of 3.9% in 1997. In 2012, the spillover component and direct component contributed to 96.1% and 3.8% of the emissions in the construction sector, respectively, while the total emissions grew almost 3 times.

In transportation, emissions grew rapidly to 311 Mt. by 2012, with direct component as a major driver, since transportation is one of the main human activities in China. Nevertheless, there was obvious reduction tendency for the growth rate of total carbon emissions from 1997 to 2012, and the 21.3% emission growth between 2007 and 2012 was the lowest growth rate since 1997. This can be largely explained by changing consumer attitudes and macroeconomic headwinds. In 2012, the direct component of transportation sector was 153 Mt. (48.9%) higher than other components. The improved living standards of residents have stimulated both the demand for private cars and tourism, and thus carbon emissions in the direct component were four-times the amount of those of 1997. The spillover component was another primary factor from 1997 to 2012, peaking at 53.9% of emissions in 2002. This suggests that the transportation sector's emissions still have a great dependence on intermediate inputs from other sectors, since the sector consumes a large amount of energy-intensive materials and resource-consuming products from other sectors.

Emissions from the services sector also grew rapidly over the entire period, from 479 Mt. to 1134 Mt., with spillovers growing rapidly, accounting for 88.3% of total emissions by 2012. Most service emissions are upstream, occurring in material and energy production sectors due to the link between services and manufacturing. For instance, manufacturing creates products for much of the retail trade. From a direct component perspective, emissions from services grew from 56 Mt. in 1997 to 68 Mt. in 2002. Afterwards, emissions from the direct component increased at an annual rate between 1.8% and 9.3%. While the direct component's share decreased slowly in recent years, reaching 9.6% in 2012, it remains an important driver in emissions from services. This suggests that, although most services emissions still come from upstream emissions in non-service sectors, focusing on the decarbonization of the services sector directly would be worthwhile.

3.3. Comparisons of spillover and feedback emissions

The feedback and spillover effects outlined above provide a new method of studying inter-sectoral economic relationships and influences, but the results above show the share of feedback effects in the total sectoral emissions is small. Therefore, we further analyze the shares of the feedback and spillover components for different economic sectors.

Fig. 8 reflects feedback and spillover shares among the 26 sub-sectors in 1997 and 2012. Fig. 8 also presents the absolute emissions

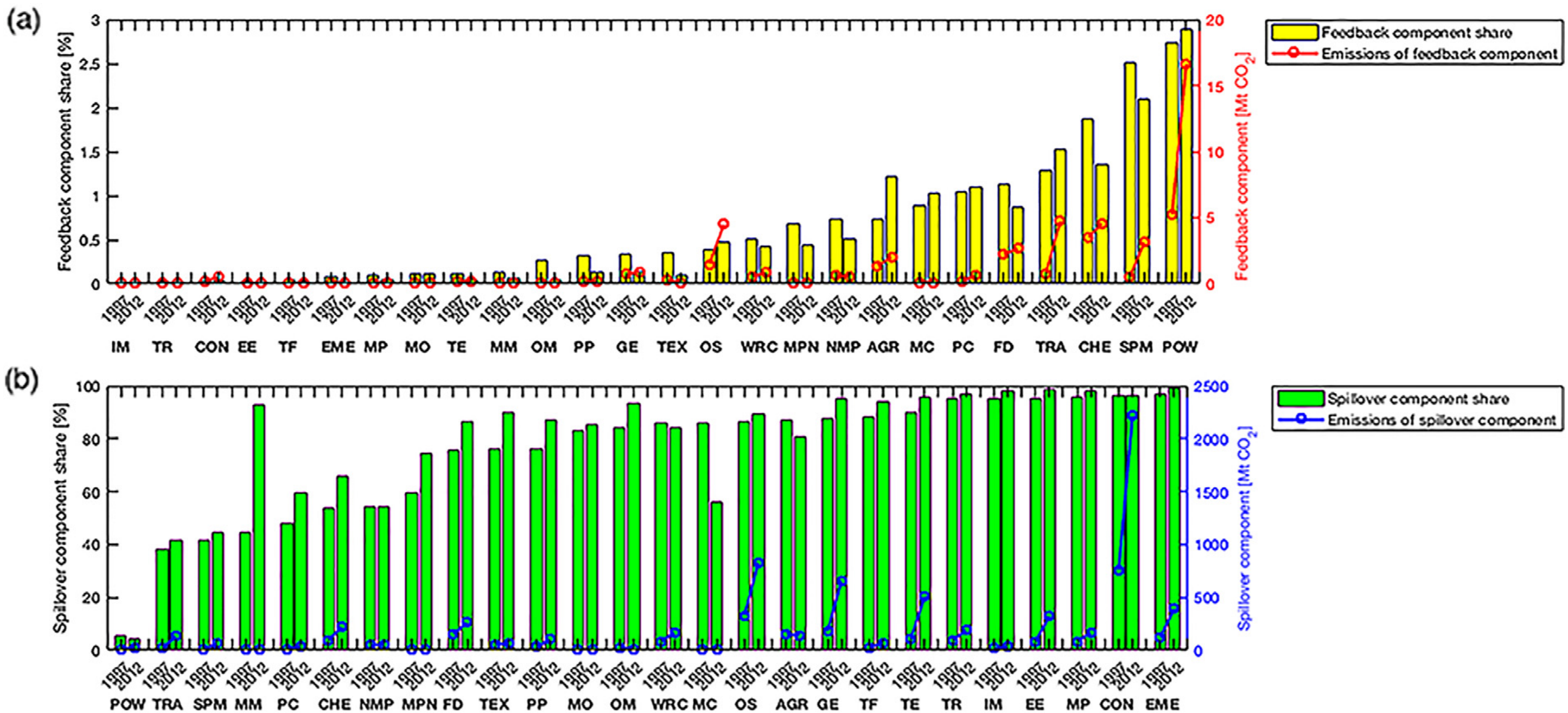

Fig. 8. Comparison of spillover and feedback emission share for different sub-sectors (1997 and 2012).

of feedback/spillover components in 1997 and 2012, which are similar to the results of feedback/spillover shares. This allows us to identify which sub-sectors have the higher feedback/spillover shares. In 1997, the feedback effect share in the Power (POW) sub-sector was significantly higher than that of other sub-sectors, with 2.7%. The second largest feedback share was in Smelting and Pressing of Metals (SPM), at 2.5%. The following five largest feedback shares were in Chemical (CHE), Transportation (TRA), and Food (FD) sub-sectors, ranging from 1.1 to 1.9%. In 2012, POW and SPM were the only two sub-sectors with feedback shares above 2%. Feedback in the agricultural sector grew the most from 1997 to 2012, approximately doubling in size. The feedback share in the transportation sector is also high, at 1.5%. This means that agriculture and transportation had a much closer relationship with other sectors. The feedback component shares of heavy manufacturing sub-sectors are relatively high compared to those of other sub-sectors, ranging from 0.5 to 2.1%. This implies that other sectors' output has important effects on carbon emissions from the production activities of heavy manufacturing. The feedback share of Mining and Washing of Coal (MC) presented a stable increasing trend from 0.7% in 1997 to 1.2% in 2012. During this period the feedback component in the food sub-sector decreased from 1.1% in 1997 to 0.9% in 2012.

The ranking of the spillover component reflects that, in 1997, the share of spillover emissions in the Electric Machinery and Equipment (EME) sub-sector was the largest, accounting for 96.8% of the total emissions in the EME sub-sector. The remaining sectors in the top five were in Construction (CON), Mental Products (MP), Electronic Equipment (EE), and Instruments and Machinery of Cultural Activity and Office Work (IM). In addition, most sectors with a higher spillover share have a lower feedback share. For example, the feedback shares in the EME and CON sub-sectors were significantly lower than those of other sub-sectors, accounting for 0.07% and 0.03% of the total, respectively. In 2012, the spillover effect share of Electric Machinery and Equipment (EME) remained the largest, with the Electronic Equipment (EE) sub-sector ranked second. The following four largest spillover effect shares were in Instruments and Machinery of Cultural Activity and Office Work (IM), Metal Products (MP), Textile Related Products (TR), and Construction (CON) with shares ranging from 99.1% to 96.1%. This means that the equipment manufacturing and construction sectors have caused large amounts of spill over emissions to other sectors. We note that more than 45% of the emissions in the heavy manufacturing sector are discharged in other sectors in 1997 and 2012, but their shares of spillover component are much smaller than those of other sectors.

3.4. The distribution of spillover emissions

Since spillover effects capture emissions embodied in the intermediate inputs of other sectors, these effects can reflect inter-sectoral embodied emission transfers, and describe how a sector's final demand affects CO_2 emissions in other sectors. We pick out light manufacturing, equipment manufacturing, construction, and services sectors (spillover shares are more than 80% during the whole studying period) to further analyze the distribution of spillover effects in the supply chain. For sectors with many sub-sectors, we choose a sub-sector with the largest demand-induced emissions as an example, thus, Food (FD), General Equipment (GE), and Other Services (OS) sub-sectors are considered. As final demand is considered as the driving force for emissions emitted in supply chains, we also identify how different final demand categories (rural household consumption, urban household consumption, government consumption, investment and exports) cause spillover effects. We incorporate government consumption into urban household consumption as this amount is small and structurally consistent (that is both categories are consumptive). Fig. 9 shows the five most important destinations of spillover effects for each selected sector in 1997 and 2012.

The distribution of spillover effects for food, general equipment, construction, other services sectors mainly concentrate on power, transportation and heavy manufacturing sectors. The final demand of the food sub-sector in 1997 drove 10 Mt. CO_2 of emissions in the agriculture sector, increasing to 21 Mt. by 2012. This can be explained by increased household consumption. In 1997, spillover effects of the food sub-sector were driven by rural household consumption (41.3%), while in 2012, spillover was dominated by urban household consumption (64.5%).

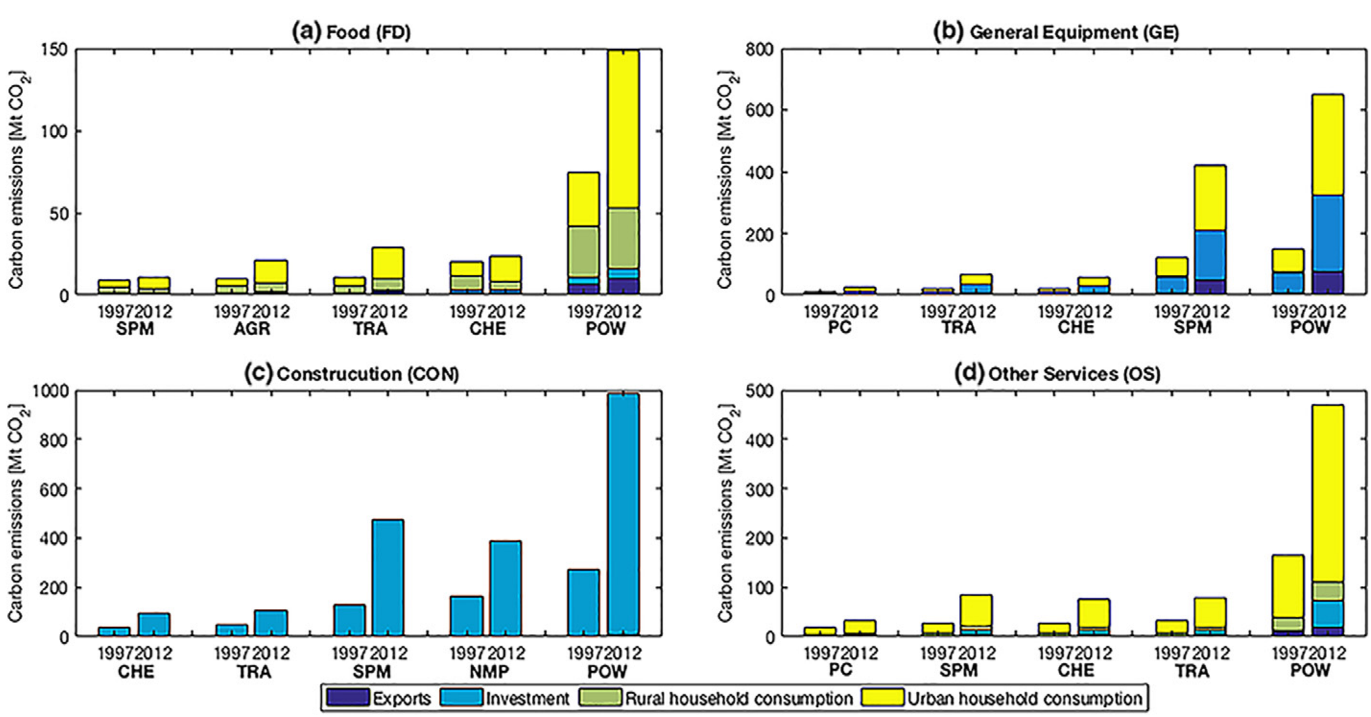

Fig. 9. The most important destinations of spillover emissions for sectors of food (a) general equipment (b) construction (c), other services (d) (1997 and 2012).

This is unsurprising given accelerated urbanization, leading to expansion of the food sub-sector and its CO_2 intensive supply chain. The rapid growth of emissions in the Smelting and Pressing of Metal (SPM) and power sectors from 1997 to 2012 were driven by capital investments in the general equipment and construction sectors. This is because China became a member of the World Trade Organization in 2001, which not only provided a more favorable environment for foreign investment in China, but also brought opportunities for both domestic and foreign companies to start contracting construction businesses. As a result, the final demand of equipment and construction sectors grew, and spillover effects increase simultaneously. Moreover, China's housing boom presented opportunities for investors in the construction sector, which led to an increase in the scale of construction, and growth of emissions. In 1997, the final demand of the Other Services (OS) sub-sector led to 166 Mt. CO_2 in the power sector, then rapidly increased to 360 Mt. in 2012. CO_2 emissions in the transportation sector induced by the Other Services (OS) sub-sector showed a 59 Mt. growth, reaching 86 Mt. in 2012. Urban household consumption played an important role in increasing the spillover effect of the Other Services (OS) sub-sector, accounting more than 70% of the total. The spillover emissions induced by services investment grew 10% from 1997 to 2012, as the economic structure was rebalanced from manufacturing to services. It is noteworthy that Fig. 9 shows little demand changes from exports. This contrasts with the results of Ou et al. (2017) and Huo et al. (2014) who identified exports as a major driver of China's carbon emissions. However, it should be noted that the sector with the largest contribution to total CO_2 emissions embodied in exports is the heavy manufacturing sector (Tang and Lin, 2017), which is not represented in Fig. 9. The sectors represented in Fig. 9 contribute little to total CO_2 emissions embodied in exports. Thus, the apparent conflict between our results and those found in the literature is explained by a different sectoral focus.

4. Discussion

Above, we report the results of our analysis, showing that, the relative importance of different components depends on the position of each sector in the supply chain. The direct, internal and feedback components reflect the CO_2 emissions produced in the production processes of sectors. The contribution of the three components for power sector is relatively larger, as it is not surprising that the electricity and fossil fuel are the top emitting sectors. The spillover component indicates the pulling effect of demand of a sector on CO_2 emissions produced in the rest of the economy. The contribution of spillover component is mainly responsible for the CO_2 emissions from construction and services sectors. In addition, the most important destinations of spillover emissions for construction and services sectors include heavy manufacturing, power and transportation sectors, as downstream sectors (e.g. services) have a considerable demand for the energy and raw materials of upstream sectors (e.g. power). Those mean that the embodied CO_2 emissions are mainly transferred from the basic industrial sectors to construction and services sectors via inter-sectoral trade.

When considering the relative role of feedback component relative to the spillover component, the share of feedback component for the power sector is the largest, followed by heavy manufacturing and transportation sectors. This means that, upstream sectors gain considerable feedback CO_2 emissions while lots of CO_2 emissions transfer to other sectors. Additionally, heterogeneous sectors, such as the agriculture sector including both crop and animal production sectors, have relatively high shares of feedback effects than more narrowly defined sectors (e.g. Non-metallic Mineral Products sub-sector).

Our analysis also shows that, during the period 1997–2012, the spillover share of agriculture is higher than 70%, and the spillover share of heavy manufacturing is around 50%. We now turn to specific phenomena within the results and attempt to explain them more generally.

Table 3
Destinations of agricultural spillover emissions from 1997 to 2012 (Mt CO_2).

Sub-sectors	1997	2002	2007	2012
MC	2.78	1.66	1.67	2.85
MPN	2.66	1.99	0.94	1.19
MM	0.20	0.10	0.05	0.08
MO	0.40	0.17	0.12	0.21
PC	7.41	6.09	3.88	5.93
CHE	30.79	15.99	12.64	20.97
NMP	4.05	3.18	1.53	1.65
SPM	8.47	5.36	4.67	5.09
FD	5.28	3.08	2.64	3.45
TEX	0.77	0.15	0.11	0.13
TR	0.03	0.02	0.02	0.02
TF	0.15	0.10	0.05	0.03
PP	1.00	0.59	0.44	0.32
OM	0.62	0.14	0.04	0.03
MP	0.31	0.20	0.09	0.07
GE	1.21	0.40	0.26	0.28
TE	0.37	0.24	0.11	0.08
EME	0.13	0.05	0.03	0.02
EE	0.04	0.02	0.01	0.01
IM	0.02	0.00	0.00	0.01
POW	74.56	67.97	55.19	83.25
CON	0.11	0.05	0.02	0.04
TRA	10.12	6.78	5.88	9.58
WRC	1.48	1.08	0.71	0.90
OS	1.81	1.17	0.64	1.05
Total	136	3	15	67

Our estimates for agricultural emissions may not exactly agree with those from the IPCC as those estimates include other GHG types such as CH_4 and N_2O. Although we do not report emissions from agricultural production process, we still obtain meaningful results from the view of inter-sectoral linkage. As shown in Table 3, the agricultural supply chain mainly induces indirect CO_2 emissions in power, transpiration and chemical sectors. In 1997, the agricultural final demand resulted in 75 Mt. CO_2 emissions emitted from the power sector via inter-regional linkage, accounting for 41.3% of the total agricultural emissions. The emissions in the chemical sector induced by the agricultural demand were 31 Mt., accounting for 17.1% of the total. The agricultural demand caused 10 Mt. emissions in the transportation sector, which contributed 5.6% of the total. In 2012, the CO_2 emissions in the chemical, transportation and power sectors induced by the agricultural demand increased to 21 Mt., 10 Mt. and 83 Mt. respectively due to the doubling of agricultural demand from 2007 to 2012 (NBS, 2008, 2013), while we find a 10 Mt. reduction of agricultural direct emissions (as shown in Fig. 3) during the same period due to the decreased agricultural emission coefficient. The difference between spillover and direct components highlights that, while the agricultural productivity has been improved in the recent years, low carbon agricultural supply chains are important to emission reductions.

The spillover share of heavy manufacturing seems like a large number (around 50% during period 1997–2002), as heavy manufacturing requires many intermediate inputs from other sectors to support its own final demand. Taking the chemical sector in 2012 as an example, the emissions in the power sector induced by the chemical demand were 165 Mt., accounting for 49.1% of the total chemical emissions (as shown in Table 4). The chemical demand stimulated 12 Mt. CO_2 emissions in the transportation sector, accounting for 3.6% of the total. This is because exports are the primary medium by which the chemical drives other sectors' emissions, resulting in expansion of bulk chemical shipping market and growth of emissions in the transportation sector. The chemical demand also induced 8 Mt. in Mining and Washing of Coal (MC), contributing 2.3% of the total, as coal is the raw material for transformation to a range of chemicals in China (Xie et al., 2010).

Table 4
Destinations of chemical spillover emissions by different demand categories in 2012 (Mt CO_2).

Sub-sectors	Urban household consumption	Rural household consumption	Capital investment	Export
AGR	0.11	0.51	0.02	1.04
MC	0.52	2.35	0.11	4.77
MPN	0.17	0.77	0.04	1.56
MM	0.01	0.07	0.00	0.13
MO	0.05	0.22	0.01	0.46
PC	0.74	3.34	0.16	6.76
NMP	0.26	1.16	0.05	2.36
SPM	0.74	3.31	0.16	6.71
FD	0.06	0.28	0.01	0.56
TEX	0.03	0.14	0.01	0.28
TR	0.00	0.01	0.00	0.02
TF	0.00	0.02	0.00	0.03
PP	0.04	0.17	0.01	0.34
OM	0.00	0.02	0.00	0.04
MP	0.01	0.04	0.00	0.09
GE	0.02	0.11	0.00	0.21
TE	0.01	0.02	0.00	0.05
EME	0.00	0.01	0.00	0.02
EE	0.00	0.00	0.00	0.01
IM	0.00	0.00	0.00	0.01
POW	11.13	50.08	2.36	101.53
CON	0.00	0.02	0.00	0.04
TRA	0.82	3.70	0.17	7.49
WRC	0.07	0.32	0.02	0.65
OS	0.10	0.43	0.02	0.87
Total	15	67	3	136

These finding provide further evidence for the view that unlike other upstream sectors (e.g. power), heavy manufacturing and agriculture sectors are two important conversion sectors that can explain shifts from direct to spillover emissions, as they consume lots of energy and resource-consuming products from power and transportation sectors, causing lots of CO_2 emissions to spill over to the other sectors, and at the same time, they are major input suppliers to the construction and services sectors.

5. Conclusions and policy implications

Even though existing studies analyzed some aspects of multi-sectoral carbon emissions in China, to our knowledge, none have analyzed multi-sectoral emissions from the perspective of inter-sectoral production networks including spillover and feedback effect emissions. We comprehensively identify the characteristics and patterns of sectoral emissions in China using an extended subsystem, IO-based, time-series decomposition.

Our results show that, equipment manufacturing, construction, and services sectors are the main sources of demand-induced emissions during the period, largely attributed to the spillover effect. Accordingly, these sectors generate carbon emissions primarily through indirect upstream emissions. Power and transportation sectors show a significant contribution of their direct component to their total CO_2 emissions. These findings indicate that the relative importance of spillover and direct emissions depends on the position in the supply chain. Sectors up in the supply chain (e.g. power) have a higher share of direct emissions while sectors at the end of the supply chain have higher spillover emissions (e.g. services). For the heavy manufacturing and relative heterogeneous sectors (e.g. agriculture), the feedback component should be highlighted. Finally, comparing the feedback component share with the spillover component share for each sub-sector in 1997 and 2012, results show that, in general, sectors with a higher spillover share have a lower feedback effect share. During the whole period, the power sector ranks top in the feedback component shares, while the top places for spillover component shares were occupied by equipment manufacturing, construction, and services sectors.

We also come up with the general patterns about a potential shift from direct toward spillover emissions by discussing the distribution and sources of spillover effects by different demand categories. We find that the distribution of spillover primarily influences power, transportation and heavy manufacturing sectors, as these are producers and suppliers of carbon-insensitive commodities. Construction and services sectors have a great demand for the basic industrial sectors (e.g. transportation and power sectors), thus, the embodied emissions are mainly transferred from basic industrial sectors to construction and services sectors. It should be mentioned that, although agriculture and heavy manufacturing sector spillover effects are much smaller than those of other sectors, they result in substantial CO_2 emissions in the power sector as electricity is a major intermediate input for both sectors.

Based on our empirical analysis, we argue that implementing appropriate mitigation policies for different sectors should consider inter-sectoral production linkages. Since the demand of downstream sectors such as services can induce emissions in heavy manufacturing, transportation, and power sectors, emission mitigation could be realized by developing a more sustainable demand structure. For example, emissions in the heavy manufacturing and power sectors induced by the capital investment of construction sector could be abated by promoting investments in green building technologies, and reducing unsustainable construction activities or unnecessary waste. Furthermore, as emissions in the transportation sector are mainly driven by the urban household consumption of services, policies focused on low carbon transportation modes could make large impacts. Moreover, it is very important to control energy consumption in the whole supply chain by improving life-cycle management. For example, since the greatest agricultural spillover emissions are in chemical, power and transportation sectors, improving management of agricultural supply chains can provide a major contribution toward emission reductions, such as improving fertilizer use efficiency, reducing electricity consumed per irrigation, and wasting losses in transport. Finally, the results demonstrate that policies to drive the construction of clean production is of strategic importance to reduce chemical CO_2 emissions, such as upgrading coal transformation technologies, improving recycling processes of coal-based chemicals, and promoting chemical sector's electricity conservation.

Appendix A

Table A1
Calorific values and CO_2 emission factors of 16 types of fuels.

Type of fuels	Net calorific value		CO_2 emission factor	
	Value	Unit	Value	Unit
Raw coal	20.91	GJ/t	1.8592	t/t
Cleaned coal	26.34	GJ/t	2.6409	t/t
Other washed coal	8.36	GJ/t	1.6331	t/t
Coke	28.44	GJ/t	2.8313	t/t
Coke oven gas	167.26	GJ/10^4 m^3	7.6220	t/10^4 m^3
Other gas	179.81	GJ/10^4 m^3	2.3235	t/10^4 m^3
Other coking products	28.44	GJ/t	3.0052	t/t
Crude oil	41.82	GJ/t	3.0680	t/t
Gasoline	43.07	GJ/t	2.9251	t/t
Kerosene	43.07	GJ/t	3.0334	t/t
Diesel oil	42.65	GJ/t	3.0959	t/t
Fuel oil	41.82	GJ/t	3.1705	t/t
LPG	50.18	GJ/t	3.1013	t/t
Refinery gas	46.00	GJ/t	2.5982	t/t
Other petroleum products	41.82	GJ/t	2.8563	t/t
Natural gas	389.31	GJ/10^4 m^3	21.6219	t/10^4 m^3

Data Source: IPCC (2006), NDRCC (2011).

Appendix B. Supplementary Data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.eneco.2017.11.022.

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