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Carbon footprints of urban transition: Tracking circular economy promotions in Guiyang, China

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Abstract: Promoting urban transition is critical, particularly for China's rapid urbanization. Circular economy strategy is widely recognized as an effective way to achieve a low-carbon transition of cities through improved waste recycling and industrial symbiosis. However, the evidence of low-carbon benefit is less reported. While the carbon footprint (CFP) represents a mature tool responding to climate change concerns, limited studies have made use of CFP as a proxy for the performance of urban circular economy promotion. The aim of this paper is to investigate the CFP with a ten years span (2002-2012) of Guiyang, so as to understand how its circular economy practices have led to low-carbon benefits. Guiyang, one of China's national pilots of the Circular Economy (CE) City, the Low-Carbon City, as well as the Ecological Civilization City, has offered an ideal laboratory where the opportunities and challenges for a low-carbon urban transition can be explicitly discussed. A hybrid model that integrates an input-output (IO) approach and process-based inventory analysis is developed to distinguish between direct carbon emissions of sectors from energy consumption, and indirect carbon emissions related to upstream and downstream flows both from production and consumption perspectives. The CFP of Guiyang in 2002, 2007 (after becoming the circular economy pilot) and 2012 (with implementation of urban industrial symbiosis) are analyzed by taking the 2002 as year of business as usual (BAU) scenario. Particularly, we identify scenarios related to proposed urban industrial symbiosis. Results imply that dramatic resource saving and CFP reductions could be achieved simultaneously. Changes to the CFP in 2002, 2007 and 2012 provide critical insights into the role of circular economy in speeding up urban transition towards a low-carbon society. Finally, policy recommendations to tackle the barriers to regional low-carbon transition are proposed. We believe that this study is informative for policy makers of urban planning by shedding a light on innovative eco-industrial development and urban transition in China.

Keywords: Carbon footprint; Circular economy ;Urban transition ;Urban industrial symbiosis ;China

1. Introduction

Mitigating global warming through reduction of carbon emissions has received top priority in global environmental policy agenda (Fang and Heijungs, 2015). Therefore, the Paris Agreement reached in December 2015 is committed to keeping warming below 2°C and even below 1.5°C above pre-industrial levels (UNFCCC, 2015). In response to the fight on climate change, cities are taking a critical role in addressing mitigation actions and policies (Bruestle, 1993; Hamin and Gurran, 2009; Xu et al., 2012), as urbanization has become a main driver for socioeconomic development as well as resource consumption and waste generation, accounting for about three quarters of global energy consumption and greenhouse gas (GHG) emissions (Liu et al., 2012). Therefore, low-carbon promotion in urban level requires intensive academic attention (Dong et al., 2013a; Dong et al., 2014b).

Urban transition provides innovative pathway for cities to realize sustainable development and address the challenges for climate change. Fig.1 illustrates the urban transition stage model proposed by (Bai and Imura, 2001), which highlights different stages for urban development, including the poverty stage, production stage, consumption stage, and finally to a pursuit of eco-city stage. Among these challenges, how to coordinate the relationship of industry, urban, and rural area harmoniously is the most critical one.

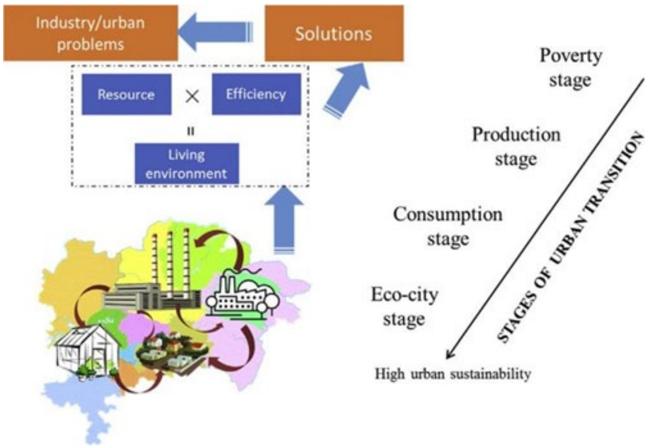


Fig.1: Coordination of industry and urban to enhance the efficiency Source: revised by the authors based on(Bai and Imura, 2001)

Circular economy strategies can contribute to above transition. Via system-wide innovation, it aims to redefine products and services in order to enhance resource efficiency and to design waste out, while minimizing negative impacts (Dong et al., 2013a, 2014b, 2016a). It includes but not limited to "3R" (reduce, reuse and recycling), urban industrial symbiosis (resource and waste exchange among industries and between cities and industries) as well as green supply chains, offers one critical approach to boosting urban transition (Dong et al., 2016b; Li et al., 2015). By enhancing resource efficiency (via 3R and waste utilization) and coordinating the industries and cities (via urban industrial symbiosis), circular economy could strongly support sustainable urban resource management and sustainability transition. Globally, various related approaches and policies forwarding the transition are promoted, including but not limited to: a. Cleaner production, which as micro and micro level (in company and industrial park level) environmental protection initiative, effectively minimized waste and emissions via process optimization (Meng et al., 2017; Zou et al., 2017); b. 3R promotion in Germany and Japan, with focuses on building material sound and recycling type society 1997 (Moriguchi, 2000); c. eco-industrial parks (EIPs), which is a practice of industrial symbiosis, very field their resource efficiency and low-carbon effects in Europe (Denmark) (Chertow, 2000; Jacobsen, 2006); South Korea (Behera et al., 2012; Park et al., 2008); Kwinnana and Gladstone, Australia (van Beers et al., 2007); and China(Bai et al., 2014; Tian et al., 2014; Zhang et al., 2010); d. National industrial symbiosis project in United Kingdom (Costa et al., 2010; Mirata, 2004), focusing on regional waste recycling and exchanges; and e. Eco-town and “zero emission” practice in Japan (Hashimoto et al., 2010; Van Berkel, 2010), in which, urban industrial symbiosis and recycling industries promotion was core. Among all these promotions, urban industrial symbiosis was one key part, as it optimized the urban and industrial metabolism, and particularly, its promotion significantly reduced the carbon emissions at industrial cluster (Hashimoto et al., 2010; Van Berkel, 2010) and city level (Geng et al., 2010; Jacobsen, 2006). With this concerns, accounting the carbon emissions and discussing on the related environmental responsibilities had become hot topic and emerging study provided enlightening information, e.g. the boundary setting, carbon emissions accounting for entities presented in (Kim et al., 2017).

With the rapid and intertwined urbanization (illustrated in Fig.2)and industrialization, China makes it possible to trace the urban transition and the urban GHGs mitigation via circular economy promotion. By 2010, the urban population in China has increased to more than 660 million, with an urbanization rate of about 50%.

These numbers are expected to further up to 850 million and 60% in the coming years, respectively (Chen et al., 2013; NBS, 2011; UN, 2012). In response to the growing challenges of resource depletion and climate change, the Chinese government does have promoted a series of policies to support sustainable urban development with more concerns on environmental protection and eco-civilization construction. The important policy initiatives includes, but is not limited to: the "Circular Economy" strategy in the city level, the "Eco-City" project (Liu et al., 2014a; Nan et al., 2012; Wu, 2012), and the "Low-Carbon City" project (Su et al., 2012; Yang and Li, 2013). In all the projects, circular economy remains the key in view of its considerable effectiveness on the enhancement of resource efficiency and reduction in waste generation

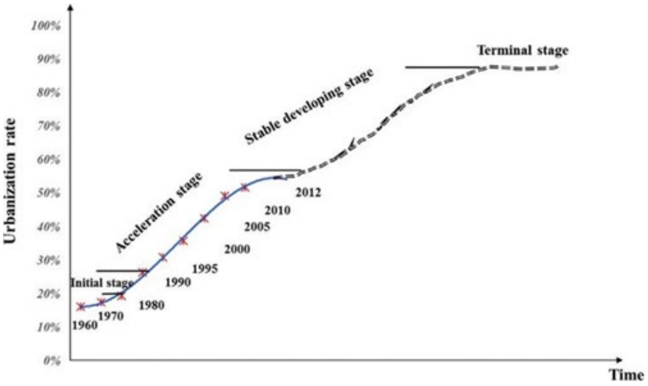


Fig.2: China's urbanization process.

As the biggest carbon dioxide (CO_2) emitter in the world, China has made a remarkable contribution to the negotiation of the Paris Agreement by setting its ambitious carbon emissions reduction target towards 2030 (Zhao et al., 2017) and speeding up the development of circular economy (Jiao and Boons, 2017). China is also one of the countries that make "circular economy" as national strategy (Dong et al., 2013b). A number of related projects have been promoted nationally and regionally, such as the “National Eco- Industrial Park” project by the Ministry of Environment (MEP) and “Circular Economy Pilots Projects” by the National Development and Reform Commission (NDRC) (Dong et al., 2016b; Dong et al., 2014b). However, the evidence on low-carbon benefit of circular economy is less reported in China, particularly at the urban level. While the carbon footprint (CFP) serves as a mature tool responding to climate change concerns, limited studies have made use of CFP as a proxy for the performance of urban circular economy promotion (Dong et al., 2016a, 2014a). Besides, the quantitative evidence on how the circular economy practices lead to reductions in CO2 emissions is less reported, especially at the city level.

CFP, which is a fundamental member of the footprint family (Fang et al., 2016), offers the opportunity scientifically to account for the direct and indirect carbon emissions associated with human activities, normally subject to a consumption-based accounting. It has attracted tremendous interest from academia, the public, organizations and governments as an approach to inform efforts towards low-carbon societies (Kanemoto et.al., 2016;Wiedmann, 2009). The CFP of a city can be defined as the amount of CO2-equivalent emissions caused directly and indirectly by human activities within the urban system boundaries. To provide an over- all picture of the state-of-the-art in CFP studies, a word cloud has been drawn to give a visual representation of frequency of papers keyword within relevant fields of research (Fig. 3). As illustrated, the more commonly the word appears in scientific publications, the larger the word in the figure would be. There are 2545 publications with keywords "carbon footprint"; "carbon footprints" or "carbon foot-printing" in terms of topic search tools in Science Citation Index Expanded (SCIE) during 2007–2016. Those words that have the same or similar meaning have been grouped into one word. For example; life cycle assessment; life cycle analysis; LCA; life- cycle assessment; life-cycle assessment and life-cycle-assessment are all classified as "life cycle assessment". Apparently the most prominent words highlighted are "carbon footprint" in itself. This is followed by the words of "life cycle assessment" and "green-house gas (GHG) emissions". It shows that "sustainability"; "climate change"; "CO_2 emissions"; "energy efficiency" and "industrial ecology" are also booming with high frequency of emergence for no less than 60 times.

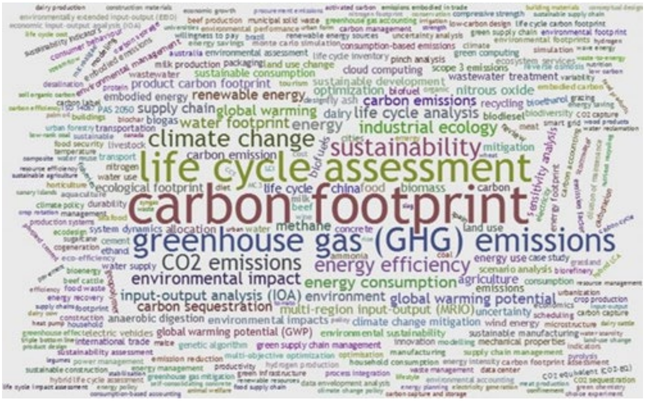


Fig. 3: Word cloud of carbon footprint research.

Note: The publications were gathered through the Science Citation Index Expanded (SCIE) of Web of Science Core Collection in the Thomson Reuters on March 11, 2017.

Broadly speaking, there are three major methods to accounting for CFP, including accounting based on Intergovernmental Panel on Climate Change (IPCC) recommended emission inventory and factors (hereafter IPCC method), life cycle assessment (LCA), and input-output analysis (IOA). The IPCC method is the mostly applied one to account for the direct emissions caused by energy and land use, primarily appropriate for use in macro entities (e.g. nations). When being applied to micro entities such as products and enterprises, the accuracy of the IPCC method may not be satisfactory (Liu et al., 2015). While LCA and IOA both can be used to calculate direct and indirect emissions, the former concentrates on micro entities such as products (Baldini et al., 2017), consumers (Jukka et al., 2013) and enterprises (Liu et al., 2017). Although the result figured out by LCA method is more detailed, it still faces some limitations such as uncertainty and, data unavailability, etc. By contrast, IOA is mainly used to measure the emissions of macro entities such as nations (Barrett et al., 2013), regions (Feng et al., 2013) and industries (Tidy et al., 2016), which is likely to be able to overcome the shortcoming of truncation error while needing input–output tables (IOTs) in which extensive aggregation of sectors may lead to inaccuracy. In keeping with continuous development and refinement of IOA and basic datasets (Minx et al., 2009), nowadays more researches are attempting to employ IOA to analyze micro entities and, in some cases, even micro entities in combination with LCA (e.g., hybrid LCA). Nevertheless, it has been observed that the results of hybrid LCA is not necessarily more accurate than those of traditional process-based LCA, unless the IO-based LCA and process-based LCA have the same level of details (Yang et al., 2017). Besides, given the limited coverage of hybrid LCA accounts (typically including food, water, fuels and cements), the estimation may not be adequately informative since many other materials are produced out of the cities but consumed within them (Ramaswami et al., 2008).

Despite the increasing studies on the CFP accounting of nations and regions by means of IOA, studies on the CFP accounting of cities remain largely unexplored, with a few exceptions such as extended territorial carbon emissions in UK's cities (Jan et al., 2013), Melbourne's carbon map (Wiedmann et al., 2016) and consumption based carbon emissions of China's 13 cities (Mi et al., 2016), probably because of the lack of IOTs of cities and the mismatching between financial and physical flows (Ramaswami et al., 2011). The first application of IOA at the city level was to Denver City for which IPCC method has been found incapable of addressing indirect carbon emissions embodied in traded goods. Nowadays there have been a growing number of cities releasing their urban GHG emission inventories, but most of these overlook indirect emissions embodied in imports and exports (Ramaswami et al., 2008). Only few urban inventories include some items related to indirect carbon emissions, such as those of Aspen and Seattle (Hillman and Ramaswami, 2010).

With this circumstance, this paper aims to investigate the CFP from 2002 to 2012 in Guiyang City in China. Guiyang is highlighted as an ideal laboratory to test the effects of circular economy promotion engaged in a number of related national pilots project, including: a. China's Circular Economy City pilot (since 2005) by NDRC; b. Low-Carbon City pilot (since 2011) by NDRC; c. Ecological Civilization City pilot (since 2014) by MEP. It hence offers a good case to verify our developed approach and to seek for the follow-up implications. To support this analysis, a hybrid model integrating input-output (IO) approach and process-based inventory analysis is developed to investigate the urban CFP and the impacts of various circular economy scenarios (the year of 2002-business as usual scenario, 2007-initially applied the circular economy strategy since the pilot in 2005 and 2012-circular economy promotion enhanced after years' practice). However, given the lack of IOTs of Guiyang City, we are about to combine the IOTs of Guizhou Province with fiscal data of Guiyang City with the same aggregation of the details, which could minimize the deviation of calculation and depict the direct and indirect carbon emissions explicitly in comparison to the IPCC method. Furthermore, IOA method will allow us to disclose the nexus between direct and indirect sector carbon emissions both from production and consumption perspectives, thus pointing to the hot-spot industries of a region in a walk. Particularly, we identify scenarios related to proposed urban industrial symbiosis. Analytical results are expected to provide critical insights into the role of circular economy in speeding up urban transition towards a low-carbon society. Policy recommendations aimed to tackle the barriers to regional de-carbonization are also proposed in support of wise decision making. We believe that this study will be informative for policy makers of urban planning by shedding a light on innovative eco-industrial development and urban transition in China.

The remainder of this paper is organized as follows: Section 2 describes the methodology and data; Section 3 overviews the case area; Section 4 presents the analytical results and discussion; and finally, Section5 draws the conclusions and implications.

2. Methodology and data

2.1Hybrid model integrating IOA and inventories analysis

As stated, we take the input-output analysis (IOA) to measure the direct and indirect emissions associated with anthropogenic activities. IOA is a typical top-down approach that reflects the relationship of initial, intermediate and total inputs, as well as the outputs of the intermediate, final and total. This approach was first proposed by Leontief in 1936 and was proven successful in predicting the USA's demand for steel in 1950 (Leontief, 1936).

When choosing IOA for the city-wide CFP accounting, we must adjust the common pattern of this method compared to macro-level cases mostly due to the lack of sound IO data. Three components can be identified in urban CFP accounting. Simply put, the environmental coefficient matrix quantifies the carbon emissions per unit, the production structure matrix represented by IOTs reveals the productive relationship between all sectors provided in the IOTs, and the final demand matrix denotes the final consumption including imports while excluding the exports in the market (Fig. 4).

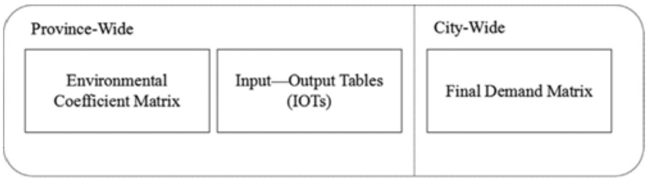


Fig.4: Schematic of urban carbon footprint accounting based on IOA.

The production structure matrix that is derived from IOTs, is a key element of IOA, expressing the complex economic relations of supply and demand between various sectors. To measure the carbon emissions both from production and consumption perspectives, we first account for the total output as follows:

$$AX + Y = X \tag{1}$$

$$A = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1j} \\ x_{21} & \cdots & \cdots & x_{2j} \\ \vdots & \cdots & \cdots & \vdots \\ x_{i1} & x_{i2} & \cdots & x_{ij} \end{bmatrix} \tag{2}$$

where A is the production coefficient matrix, which is meant to show the direct input of sector i into sector j; X is the total out- put vector; AX represents for the intermediate output; Y is the final demand vector including consumption, imports and excluding exports within the region; x_{ij} is the input x of sector i into sector ; and i and j represent for different sectors.

Afterwards, Eq. (1) can be transformed as follows:

$$(1 - A) \cdot X = Y \tag{3}$$

$$X = (1 - A)^{-1} \cdot Y \tag{4}$$

$$Y = \begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_i \end{bmatrix}, \hat{Y} \qquad (5)$$

$$X' = (1 - A)^{-1} \cdot \hat{Y} \qquad (6)$$

where $(1-A)^{-1}$ is the Leontief inverse matrix, which is meant to allocate the overall demands among different sectors in production; $\hat{Y}$ is the diagonal matrix of Y representing the total demand of the market; y is the final demand of sector ; and X' differs from matrix X in that X' represents the detailed demands of each sector. By doing so, we have measured the intermediate and total demands of each sector in the X' matrix, and disclosed the economic relationship among all sectors involved. Furthermore, we translate economic relationship to the relationship of carbon emissions with the environmental coefficient matrix as follows:

$$C = \begin{bmatrix} c_1 \\ c_2 \\ \vdots \\ c_i \end{bmatrix}, \hat{c} \qquad (7)$$

$$E = \begin{bmatrix} e_{11} & e_{12} & \cdots & e_{1j} \\ e_{21} & \cdots & \cdots & e_{2j} \\ \vdots & \cdots & \cdots & \vdots \\ e_{i1} & e_{i2} & \cdots & e_{ij} \end{bmatrix} = \hat{c} \cdot X' = \hat{c} \cdot (1-A)^{-1} \cdot \hat{Y} \qquad (8)$$

Where C is a carbon intensity vector representing the carbon emissions per unit; $\hat{c}$ is the diagonal matrix of C; and E is the carbon emission matrix of all sectors with e_{ij} representing the input of carbon emissions of sector i to sector j. Due to data availability, we consider CO_2 emitted from the entity merely. To calculate the carbon emissions both from production and consumption perspectives, two formulas are used to measure the carbon emissions of different sectors in a comparative sense.

$$EP_j \sum_{j=1}^{n} e_{1j},(j=1,2,3,...) \tag{9}$$

$$EE_i = \sum_{i=1}^{n} e_{i1},(i=1,2,3,...) \tag{10}$$

Where EP_j is carbon emissions of sector j based on a production perspective, which is the sum of each row of matrix E; and EE_i is carbon emissions of sector i embodied in consumption, which is the sum of each column of matrix E.

Furthermore, we define Indirect/Direct Ratio Index (IDRI) as a measure of dividing the indirect carbon emissions by the direct to quantify the distinction between direct and indirect carbon emissions in different sectors both from production and consumption perspectives, thus distinguishing carbon emissions from the internal and external, and clarifying the responsibility of individual entities to some extent respectively from a production or consumption perspective (Eq.(11) and (12). Likewise, to explore the relationship of carbon emissions among various sectors both from production and consumption perspectives, a new indicator named Production/Consumption Ratio index (PCRI) is developed as a measure of dividing carbon emissions from a production perspective by that from a consumption perspective (Eq. (13)). The PCRI focuses on the carbon emissions of the supply chain by contrasting the upstream and downstream, thus could be informative for policy makers to optimize the composition of the supply chain. e_{ii}

$$IDRI[P]_i = \frac{e_{ii}}{EP_i}, (i = 1, 2, 3, ...) \qquad (11)$$

$$IDRI[C]_i = \frac{e_{ii}}{EE_i}, (i = 1, 2, 3, ...) \qquad (12)$$

$$PCRI_i = EP_i / EE_i, (i = 1, 2, 3, ...) \qquad (13)$$

Where P and C represent the carbon emissions based on a production or consumption perspective respectively.

2.2. Scenarios design

To test the approach feasibility and highlight policy implications, scenarios of urban industrial symbiosis are designed for case analysis

2.2.1. Supply and demand match for symbiotic network design

Supply and demand match is conducted as the basis for setting urban industrial symbiosis scenarios. Potential of material/waste exchange between enterprises and or sectors will be analyzed with technology feasibility analysis (to see whether two parts can be linked with material/energy/waste flows from engineering perspective), if not, the symbiotic design will be denied. If yes, the amount of exchanged flows will depend on the analysis on both the resource capacity and the feasibility of material/energy flows synergies (technological feasibility). An analytical scheme for supply-demand match is illustrated in Fig. 5. When the material (and or wastes/energy) flows (W_{ij}) of upstream enterprise i can-not satisfy the feasible demand (D_j) in downstream enterprises j, the exchange flow is set into W_j. In another condition, when the flows (W_{ij}) of upstream enterprise i are over the feasible demand (D_j) in downstream enterprises, the flows of synergy are set as D_j. The whole symbiotic network is designed following this way. The related resource and technological capacity is referred according to survey and expert consulting to engineers in related companies via our project (described in data acquisition).

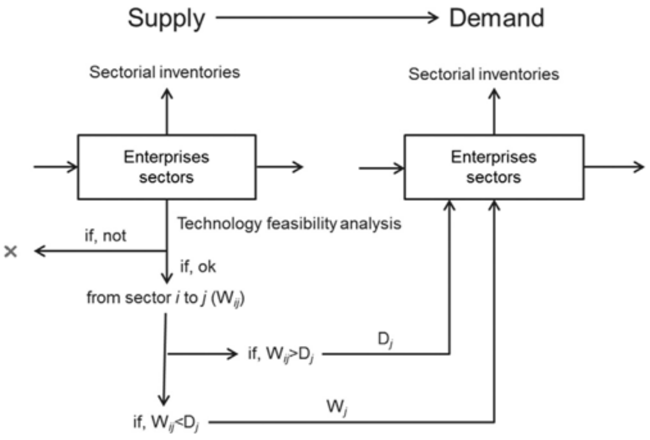


Fig.5: Scheme of supply and demand match. Note: arrows refer to material/energy/waste flow

2.2.2. Scenarios setting

According to the above scheme, scenarios are set based on local condition. China's IOTs (the basis for the established CFP approach) has been published every five years (e.g., in the year of 1997, 2002, 2007, and 2012, which is the most updating one), hence our analytical scenarios basically follow the 5-year time span. In addition, during 2000–2014, several milestones happened achieved in the environmental perspective protection in our case city, Guiyang (more about the case will be described in next section), including that: a. it became China's Circular Economy City pilot in 2005;b. it became the national Low-Carbon City pilot in 2011; and c. it became the Ecological Civilization City pilot in 2014. Such promotions were reflected in the change of resource efficiency with economic growth (GDP per capita), e.g., domestic material consumption (DMC)/capita. Such information are summarized in Fig. 6. Based on this, our scenarios are designed as follows:

[a] Business as usual (BAU) scenario: in the year of 2002. According to Fig. 6, its GDP/capita and DMC/capita were increasing quickly;

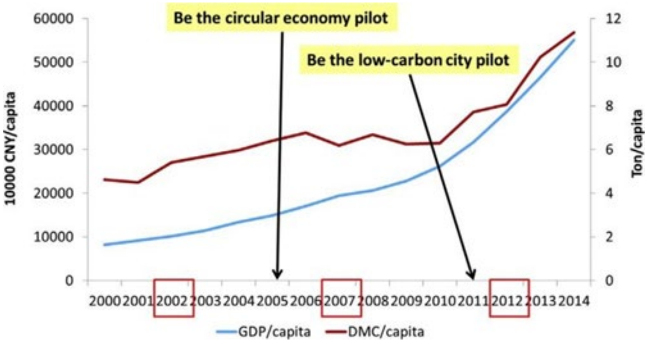


Fig. 6: Urban development for Guiyang.

[b] Urban development after becoming the circular economy pilot: the year of 2007, two years after becoming the circular economy pilot;

[c] Urban development after years of circular economy promotion: the year of 2012, seven years after becoming the circular economy pilot and 1 year after becoming the Low-Carbon City pilot;

[d] Urban industrial symbiosis (UIS) scenario in 2012 (2012-UIS): to enhance the circular economy promotion, Guiyang has implements implemented the urban

industrial symbiosis planning in 2011, and t. This scenario considers several selected urban industrial symbiosis options.

As to the 2012-UIS scenario, the urban industrial symbiosis is designed based on local condition, which is illustrated as Fig. 7. The key synergies designed include:

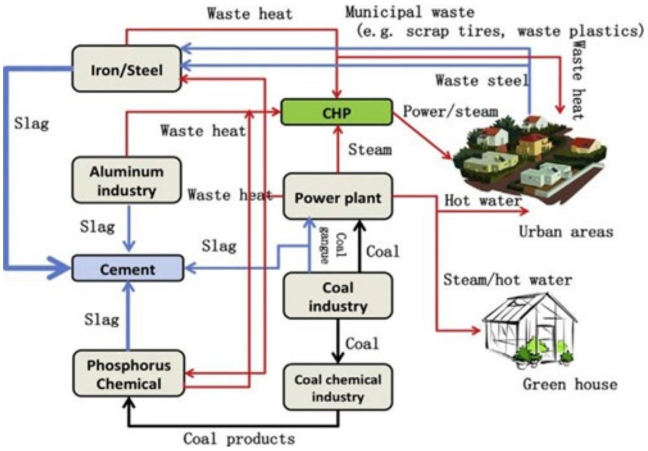


Fig.7: Urban industrial symbiosis design in Guiyang.

[a] Industrial solid waste exchange: slag from iron/steel industry, aluminum industry and phosphorous chemical industry, slag as well as coal gangue from power plant and coal industry to cement industry;

[b] Traditional recycling: like waste steel recycling;

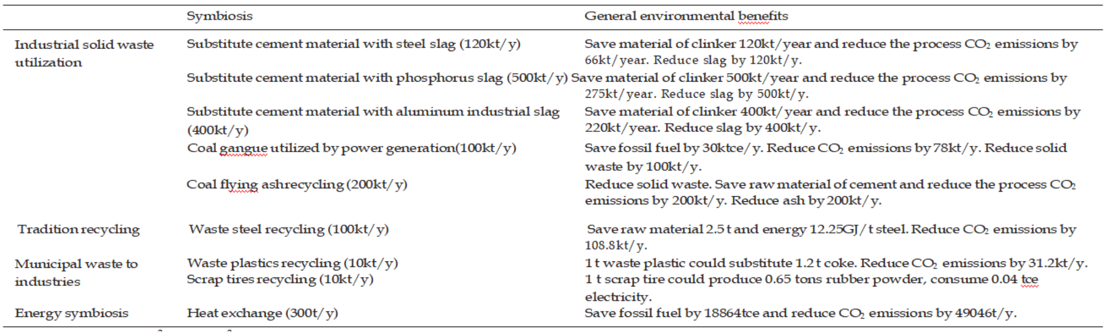
[c] Municipal solid waste that is able to be energy resource produce energy sources to substitute fossil fuels (like scrap tires and waste plastics) be recycled into the furnaces of iron and steel sector;

[d] Energy symbiosis: waste heat utilization between industrial sectors (from iron/steel to power generation; from aluminum processing to power generation; from

power plant to nearby industrial plants), and industrial waste heat provision to urban areas (e.g., commercial and residential buildings) and agriculture sector (e.g., steam provision to green house).

As complementary information for the scenarios, the general environmental benefits (direct analysis) are summarized in Table 1. More detailed information about the urban industrial symbiosis can be found in our previous studies. Based on the analysis on the environmental benefits, CFP can be further evaluated. It was should be noted that, due to data availability (e.g. some project's data is confidential), not all the synergies in Fig.7is are quantified.

Table1: Resource savings and waste reductions through industrial and urban symbiosis in Guiyang.



	Symbiosis	General environmental benefits
Industrial solid waste utilization	Substitute cement material with steel slag (120kt/y)	Save material of clinker 120kt/year and reduce the process CO_2 emissions by 66kt/year. Reduce slag by 120kt/y.
	Substitute cement material with phosphorus slag (500kt/y)	Save material of clinker 500kt/year and reduce the process CO_2 emissions by 275kt/year. Reduce slag by 500kt/y.
	Substitute cement material with aluminum industrial slag (400kt/y)	Save material of clinker 400kt/year and reduce the process CO_2 emissions by 220kt/year. Reduce slag by 400kt/y.
	Coal gangue utilized by power generation(100kt/y)	Save fossil fuel by 30ktce/y. Reduce CO_2 emissions by 78kt/y. Reduce solid waste by 100kt/y.
	Coal flying ashrecycling (200kt/y)	Reduce solid waste. Save raw material of cement and reduce the process CO_2 emissions by 200kt/y. Reduce ash by 200kt/y.
Tradition recycling	Waste steel recycling (100kt/y)	Save raw material 2.5 t and energy 12.25GJ/t steel. Reduce CO_2 emissions by 108.8kt/y.
Municipal waste to industries	Waste plastics recycling (10kt/y)	1 t waste plastic could substitute 1.2 t coke. Reduce CO_2 emissions by 31.2kt/y.
	Scrap tires recycling (10kt/y)	1 t scrap tire could produce 0.65 tons rubber powder, consume 0.04 tce electricity.
Energy symbiosis	Heat exchange (300t/y)	Save fossil fuel by 18864tce and reduce CO_2 emissions by 49046t/y.

Note:1tce = 29.27×103 GJ. kt: 103 ton.1 t cement production needs 1.4 t ore mining (based on the survey on local cement company).

2.3. Data acquisition

In view of the lack of IOT for Guiyang, accounting for Guiyang's CFP would require a harmonized combination of province-wide and city-wide datasets as stated in Fig. 4. To that end, an updated IOA method will be employed to combine the IOTs of Guizhou Province with fiscal data from Guiyang City, both of which are aggregated to the same level of details. To contrast the carbon emissions both from production and consumption perspectives, we are about to combine the IOTs of 2002, 2007 and 2012 for Guizhou Province with the data for consumption of various types of energy of this province and data for final demands of Guiyang each year, which offers the opportunity to explore the effects of China's strategy perfectly through the reflection of production technology changing in 2002 (the baseline), 2007 (after becoming the circular economy pilot) and 2012 (with implementation of urban industrial symbiosis. The IOTs for Guiyang Province in 2002, 2007 and 2012 are derived from Guizhou Bureau of Statistics containing 42 economic sectors, whilst the final demands of Guiyang are from the Guiyang Statistic Yearbook (GSY) of 2002, 2007 and 2012. Since China does not official release the carbon intensity of sectors and the details on provincial data are insufficient especially in early period of this research, the IPCC method will be employed to yield these parameters, together with the Energy Statistic Yearbook (ESY) of Guizhou Province published for the same year.

As extensive sectors aggregation may lead to signification inaccuracy of the accounting, data availability remains a great barrier for disaggregation of energy consumption data especially at early years. To harmonize the sectorial categorization in the IOTs and ESY and allow them to have different levels of details with Guiyang GSY ,we aggregate the 42 sectors provided by IOTs into five aggregated sectors, namely Agriculture and Forestry, Industry, Construction, Transportation, Storage and Postal Service, and Whole sales and Retail. Note that this kind of aggregation is common and effective to reduce the deviation as far as possible (Lin et al., 2013), thus yielding the best datasets to our knowledge (Su et al., 2010; Zhang et al., 2015). Furthermore, to explore the efficiency of industrial transformation mostly from the second to the third and disclose the inner relationship of carbon emissions among industries in production and consumption, we also aggregate those five sectors into three domains (Agriculture, Industry, and Service), which could offer a policy-oriented insight to the reveal the overall carbon map among industrial structure transformation in Guiyang or even in China. Accordingly, the final demands derived from GSY follow the same schemes for aggregation; that is, the aggregation of three sectors consists of Agriculture, Industry and Service, and the aggregation of five sectors consists of Agriculture and Forestry, Industry, Construction, Transportation, Storage and Postal Service, and Wholesales and Retails.

Besides, given the composition of national GHG inventory of China, we will replace the data for energy consumption with those for the consumption and carbon intensity of standard coals in calculating the carbon intensity of each sector. The direct consumption coefficient matrix in 2002, 2007 and 2012 as well as GDP of five sectors are provided in Tables 2 and 3.

Table 2: Direct consumption coefficient matrix in 2002, 2007 and 2012.

	2002					2007					2012				
	A	B	C	D	E	A	B	C	D	E	A	B	C	D	E
A	0.17	0.09	0.00	0.00	0.03	0.15	0.04	0.00	0.02	0.01	0.14	0.04	0.00	0.02	0.01
B	0.13	0.42	0.57	0.31	0.15	0.15	0.49	0.59	0.16	0.15	0.17	0.49	0.56	0.23	0.14
C	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.01	0.01	0.00	0.00	0.01	0.02	0.01
D	0.02	0.06	0.05	0.02	0.03	0.02	0.06	0.05	0.04	0.04	0.03	0.06	0.05	0.10	0.05
E	0.03	0.09	0.14	0.10	0.22	0.04	0.10	0.12	0.31	0.18	0.05	0.09	0.13	0.17	0.20

Note: A represents Agriculture and Forestry; B represents Industry; C represents Construction; D represents Transportation, Storage and Postal Service; and E represents Whole Sales and Retail (the same below).

Table 3: GDP of each sector in 3 years.

	GDP (100 million yuan)		
	2002	2007	2012
A	41.01	71.55	62.55
B	104.99	248.90	454.90
C	34.68	71.57	121.94
D	22.27	35.64	187.72
E	255.39	642.65	733.68

3. Overview on the case city

Guiyang City, the capital of Guizhou Province, is one of China’s national pilots of the Circular Economy City and the Low-Carbon City. The location information is illustrated in Fig.8. More recently, it has launched a new strategy towards an Eco-Civilized City in sup- port of China’s circular economy actions. The situation is, however, that Guiyang’s economy has still been depending heavily on the inputs of fossil energy particularly coals over past decades (Dong et al., 2016b; Li et al., 2015). Even though Guiyang's economic output of service in terms of GDP has exceeded that of industry recently, equipment manufacturing, chemical industry, aluminum processing, modern medicine, specialty food and tobacco products are still dominating sectors that require a great amount of energy input (Liang and Jin, 2011). All this has posed a serious challenge to the low-carbon urban transition. For this reason, it is necessary to evaluate the performance of circular economy practices on carbon emission reductions by investigating the dynamics of Guiyang's CFP (Liu et al., 2014b).

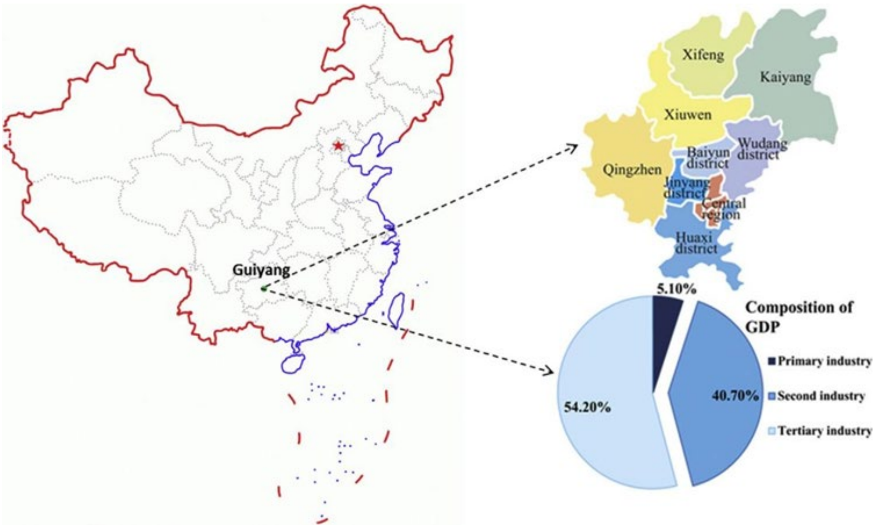


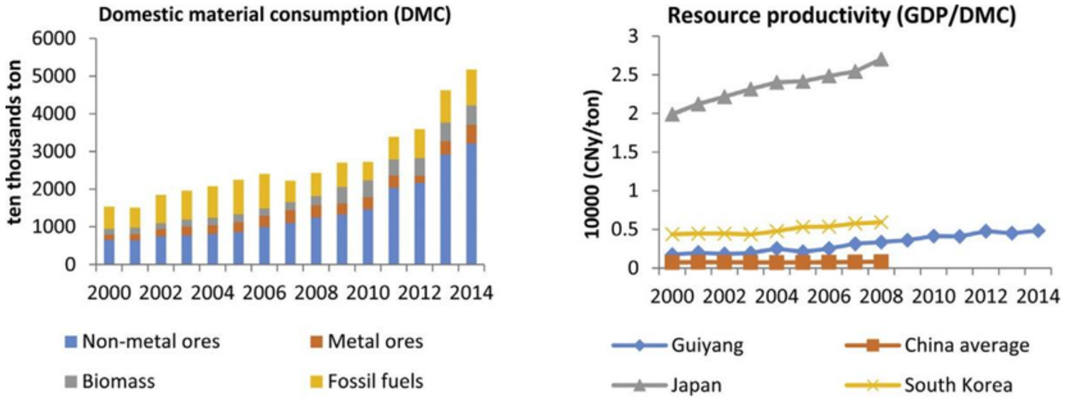
Fig. 8: Geographical information of Guiyang City in China.

Catching up with the national "environmental legislation" campaign since 2000, Guiyang has implemented atmospheric quality improvement project aimed at making use of cleaner energy as well as formulating strict environmental standards for enterprises and organizations, altogether with several other projects towards water governance and green belt rebuilt. Afterwards, Guiyang was selected as a Circular

Economy Pilot City in 2005 and as a Low-Carbon Pilot City in 2011. In line with the implementation of these strategies raised in Guiyang, some sustainable development goals have been achieved gradually, such as the fight for acid rain. However, it remains questionable whether the effect of the circular economy strategy is able to continue benefiting the population after 2012 and in the future.

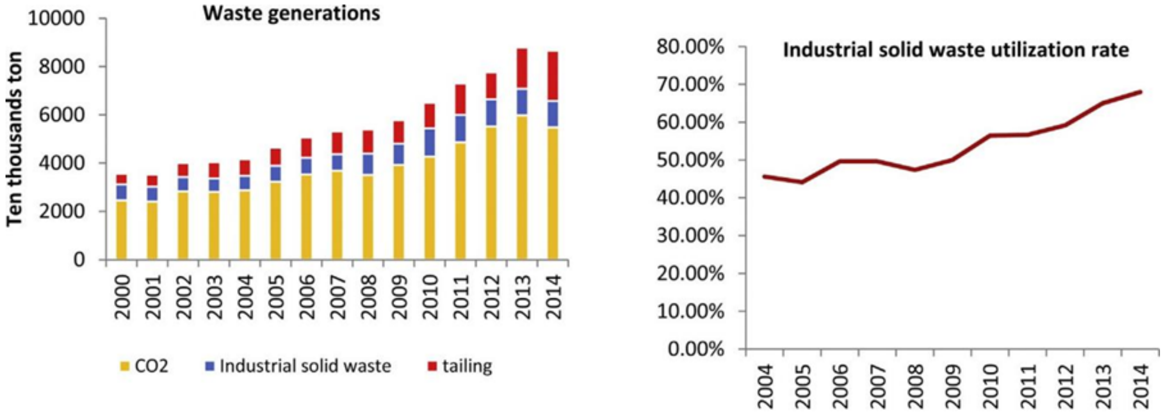
In terms of resource exploration and consumption (Fig.9(a)), the resource consumption of Guiyang (we present the data of domes- tic material consumption (DMC) in the categories of metal ores, non-metal ores, fossil fuels and biomass) had increased from 15.3 million tons to 51.7 million tons, nearly 3.5 times changed. From an efficiency perspective, the resource productivity (economic out-put per unit of resource consumption), which was a key resource efficiency indicator for measuring the circular economy by National Development and Reform Commission (NDRC) (Dong et al., 2016b), had significantly increased, from 1700 to 4800 CNY/t. However, compared with the resource productivity of developed countries (here we compared with Japan and South Korea as Asian members), there still to be ample room to improve (Fig.9 (b)). In terms of wastes generations, industrial waste as well as mining waste, like the tailings were a big issue for Guiyang. Although the absolute amount kept increasing in general trend, the comprehensive utilization rate for industrial solid waste had been improved as a result of continuous circular economy practices (Fig. 10(a) and (b)). The next step for Guiyang would be to deepen the circular economy implementation, particularly to enhance the urban industrial symbiosis practice to further improve the bulky waste exchange among industrial sectors and urban areas.

The following analysis will trace the benefits of urban environment improvements of Guiyang and the impacts of urban industrial symbiosis on urban CFP reductions based on the hybrid approach we constructed in previous section.



(a) Resource consumption of Guiyang (b) Resource productivity of Guiyang and comparison

Fig. 9: Resource consumption and efficiency in Guiyang, 2000–2014.



(a) Amounts trends of selected wastes generations (b) Example of solid waste utilization rate

Fig. 10: Waste generation and utilization condition in Guiyang, 2000–2014.

4. Results and discussions

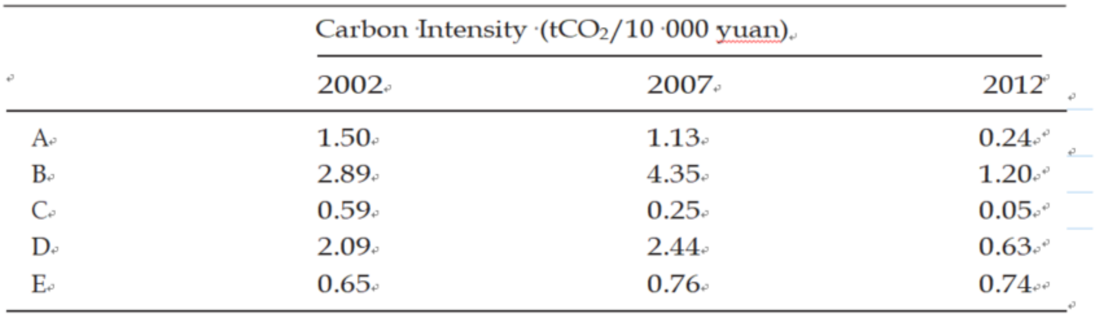
4.1. Scenarios analysis and comparison for 2002, 2007 and 2012

Based on the scenarios setting, we systematically investigate and compare the urban CFP in 2002, 2007 and 2012 to trace the CFP mitigation along with urban development.

4.1.1. Carbon intensity of sectors

The carbon intensity of Industry, Transportation, Storage and Postal Service, and Whole sales and Retail increased between 2002 and 2007 (Table 4), among which the carbon intensity of Industry surged as a result of rapid industrialization and urbanization. Afterwards the carbon intensity of all sectors went down notably during 2007–2012, in which circular economy promotions have been fully implemented; with the exception of Wholesale and Retail, whose carbon intensity fluctuated slightly over the same period of time. Supporting data is presented in “Supporting information”, Table S1 and S2.

Table 4: Comparison of carbon intensity in 3 years



	Carbon Intensity (tCO$_2$/10 000 yuan)		
	2002	2007	2012
A	1.50	1.13	0.24
B	2.89	4.35	1.20
C	0.59	0.25	0.05
D	2.09	2.44	0.63
E	0.65	0.76	0.74

Note: Data for fossil energy consumption and GDP derive from Guizhou ESY and GSY, and data for emission inventories and factors derive from IPCC.

4.1.2. Carbon footprint of sectors

With respect to the three-sector classification, Industry always occupied the largest proportion of the total CFP while Agriculture took the least (Fig. 11). The proportion of Industry in production-based carbon emissions increased from 11.1 million tCO_2 in 2002–35.3 million tCO_2 in 2007 and then decreased to 18.7 million tCO_2 in 2012. Trends in Agriculture and Service were on the contrary, ranging from ‘1.53-1.35-0.39 million tCO_2 and from ‘3.9-4.9-9.4 million tCO_2, respectively. Furthermore, the proportion of Industry in production-based carbon emissions was always much higher than that in consumption-based carbon emissions in the three years, whilst Service was the other way around. Compared with these two sectors, changes to Agriculture were tiny since its proportion in production-based and consumption-based carbon emissions was quite similar.

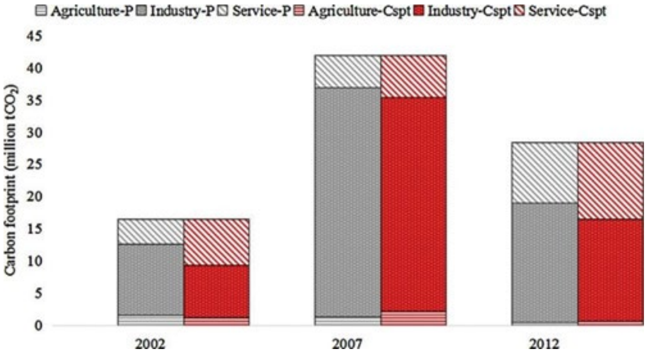


Fig. 11: Comparison of carbon footprint between production and consumption perspectives aggregated to 3 sectors.

Note: P represents carbon emissions from a production perspective; and represents carbon emissions from a consumption perspective (the same below).

When it comes to the five-sector classification (Fig.12), Industry took the largest proportion both in the production-based and consumption-based carbon emissions. During 2002–2012, trends in consumption-based carbon emissions of all the five sectors were similar but the proportions varied widely, for Agriculture ranging from "1.53-1.34-0.39"million tCO_2, for Industry ranging from "11.1-35.4-18.6"million tCO_2, for Construction ranging from "0.02-0.1-0.1"million tCO_2, for Transportation, Storage and Postal Service ranging from "1.3-2.5-2.3"million tCO_2, and for Wholesale ranging from"2.6-2.5-7.0"million tCO_2. Agriculture and Forestry is the only sector whose proportion in both production-based and consumption-based carbon emissions kept falling. The proportion of Transportation, Storage and Postal Service and Wholesale was always closed to zero when it comes to the production-based carbon emissions, which was very different from the case of the consumption-based carbon emissions. We also find that the proportion of Agriculture and Transportation, Storage and Postal Service failed to differ not so much between production and consumption perspectives.

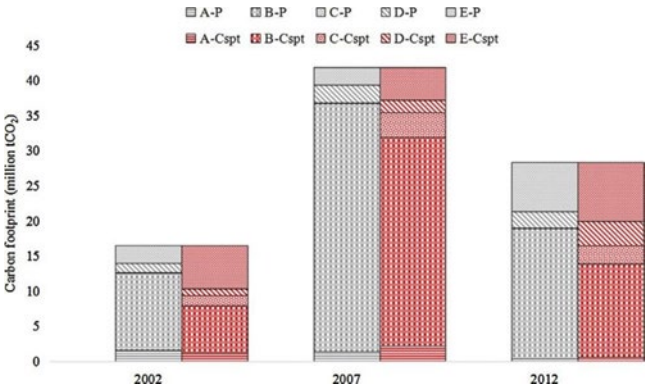


Fig.12: Comparison of carbon footprint between production and consumption perspectives aggregated to 5 sectors.

4.1.3. Comparison of carbon emissions both from production and consumption perspectives

The total CFP of Guiyang City changed from 16.5 million tCO_2 in 2002, to 41.9 million tCO_2 in 2007, and to 28.4 million tCO_2 in 2012. Thus the amount of CFP in 2007 was 60.6% higher than that of 2002 and 43.3% higher than that of 2012. With the five-sector classification, we find the gap between the direct and indirect carbon emissions from both production and consumption perspectives to be considerably large (Fig.13 (a) to (c)). The results of the two indicators (IDRI and PCRI) are presented in Table 5, showing that the direct carbon emissions from Agriculture and Forestry, Industry, and Construction all experienced an increase in 2002–2007 and a decrease in 2007–2012, and the same as the indirect carbon emissions from Industry, Transportation, Storage and Postal Service from a production perspective. In addition, the direct carbon emissions from Transportation, Storage and Postal Service based on production rose all the time, and the indirect ones of Construction and Wholesale based on consumption rose as well. As for the indirect carbon emissions from a consumption perspective, those of Agriculture and Forestry, Industry, and Construction went up and down while those of Transportation, Storage and Postal Service always increased during 2002–2012.

Table5.IDRI and PCRI of sectors in 3 years.

	2002			2007			2012		
	IDRI[P]	IDRI[C]	PCRI	IDRI[P]	IDRI[C]	PCRI	IDRI[P]	IDRI[C]	PCRI
A	0.99	2.02	0.85	1.64	0.68	0.40	1.25	0.60	0.63
B	1.12	3.54	1.76	7.26	13.38	8.09	1.66	1.19	1.40
C	8.20	20.61	6.59	0.01	0.04	0.03	0.02	0.04	0.03
D	0.63	0.56	1.48	1.03	1.01	0.69	1.32	1.40	0.69
E	7.14	1.41	3.03	0.57	0.47	1.66	0.42	0.54	0.83

Note: Indirect/Direct Ratio Index is abbreviated to IDRI; and Production/Consumption Ratio index is abbreviated to PCRI.

In addition, the dynamics of CFP per GDP and per person was tracked and presented in Fig. 14. Both of these two indicators increased from 2002 to 2007 and decreased afterwards.

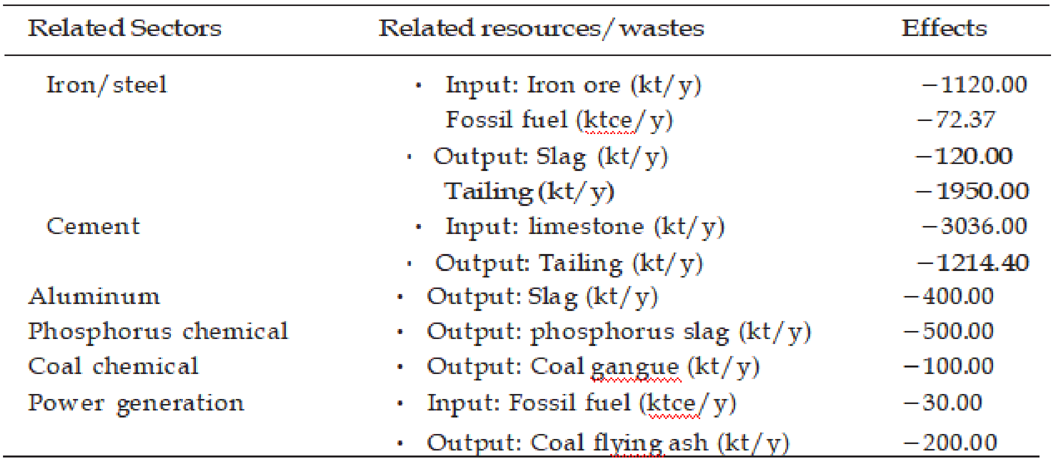
4.2. Extra CFP reduction benefits from urban industrial symbiosis

Urban industrial symbiosis has been proved to be able to offer additional environmental benefits, via waste exchange, energy recovery and other resource efficiency options. This section will further investigate their impacts on the mitigation of urban CFP.

First of all, a general analysis on the direct effects (resource saving, waste mitigation and pollutants reduction via direct material flow analysis) of the symbiosis is done and the impacts on the key industrial sectors are investigated. According to the case introduction in previous section, the main industrial sectors include “Aluminum industry”, “Phosphorus chemical industry”, “Iron/steel industry”, “Cement sector”, “Coal chemical industry” as well as “Power generation industry”. They are also the key sectors highlighted in Guiyang’s local document of “12th five year plan of industrial integration” (Dong et al., 2016b).

According to the data presented in Table 1 and the coefficients (“Supporting information”, Table3 And sectorial information was summarized in Table4.) of material consumption and wastes generation related to the above sectors, effects of resource saving, waste reduction through the symbiosis design were presented and allocated to certain sector in Table 6. It was highlighted that, with urban industrial scenarios, significant resource saving and wastes mitigation effect was achieved. In summary, iron ore (iron/steel sector) and limestone mining (Cement sector) decreased by 1120.00 and 3036.00 kt/y. Benefiting from this, tailings (which was a significant issue for industrial cities like Guiyang and did had serious negative impacts on eco-system) reduced by 3164.40 kt/y. In the process consumption, total fossil fuel consumption decreased by 102.37ktce/y. Solid waste as slag and flying ash reduced by 1320.00kt/y. Such benefits were critical to the industrial city, which engaging in the huge material and energy flows in the life cycles from resource mining, processing, consumption to waste disposal.

Table6: Effects of resource saving/wastes mitigation in key sectors in urban industrial symbiosis scenario.

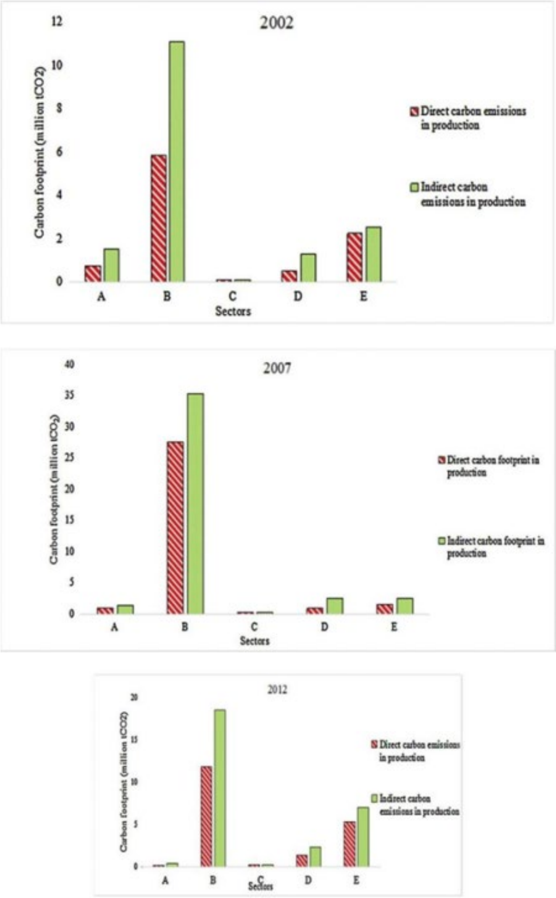


Related Sectors	Related resources/wastes	Effects
Iron/steel	• Input: Iron ore (kt/y)	−1120.00
	Fossil fuel (ktce/y)	−72.37
	• Output: Slag (kt/y)	−120.00
	Tailing (kt/y)	−1950.00
Cement	• Input: limestone (kt/y)	−3036.00
	• Output: Tailing (kt/y)	−1214.40
Aluminum	• Output: Slag (kt/y)	−400.00
Phosphorus chemical	• Output: phosphorus slag (kt/y)	−500.00
Coal chemical	• Output: Coal gangue (kt/y)	−100.00
Power generation	• Input: Fossil fuel (ktce/y)	−30.00
	• Output: Coal flying ash (kt/y)	−200.00

Apart from the direct impacts, the impacts regarding to the whole supply chain was further analyzed with CFP approach. The total CFP impact was presented in Fig. 15

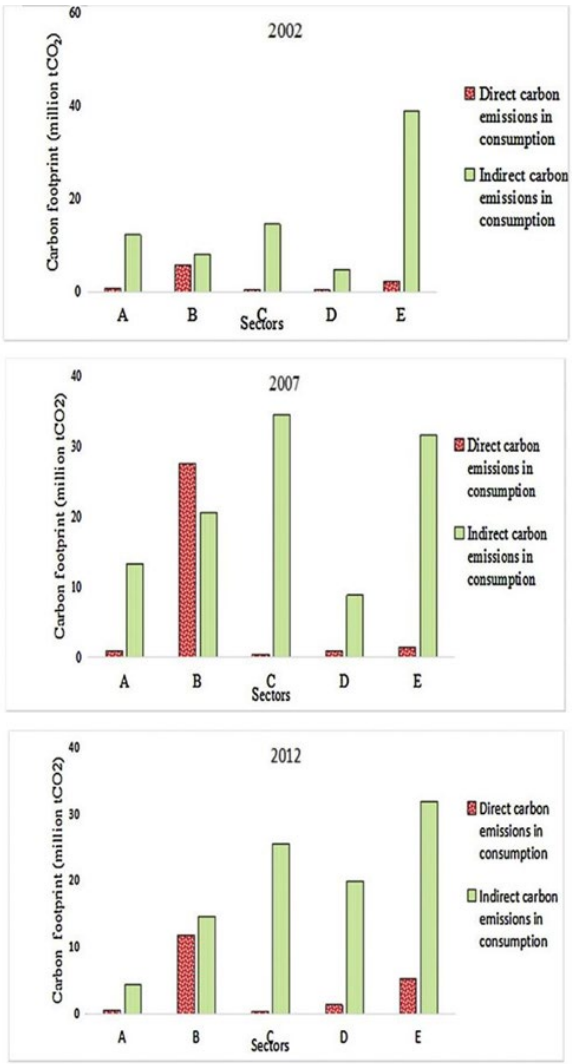
by comparison with the scenarios in 2002 and 2012. Results highlight that the implementations of urban industrial symbiosis in Guiyang would enable to further reduce the urban CFP by about 1090 thousand tCO_2 annually.

In detail, industrial solid waste exchange, traditional recycling, municipal solid waste utilization and energy symbiosis would reduce the CFP by 839, 109, 94 and 49 tCO_2/y, respectively (Fig. 16). Due to the large amount of exchange, industrial solid waste utilization was still the most effective way to reduce the urban CFP .What's more, since urban industrial symbiosis can utilize the waste as raw materials, life cycle benefits can be gained from up-stream resources saving. This is the other reason why industrial waste exchange could generate significant CFP mitigation effects. In addition, even though the benefits of municipal solid waste utilization and energy symbiosis was not as large as those of industrial waste use (mainly due to the limited scale), they could be seen as an emerging style of resource and energy reuse, and even the main driver for urban CFP mitigation with the help of more mature and efficient technologies.



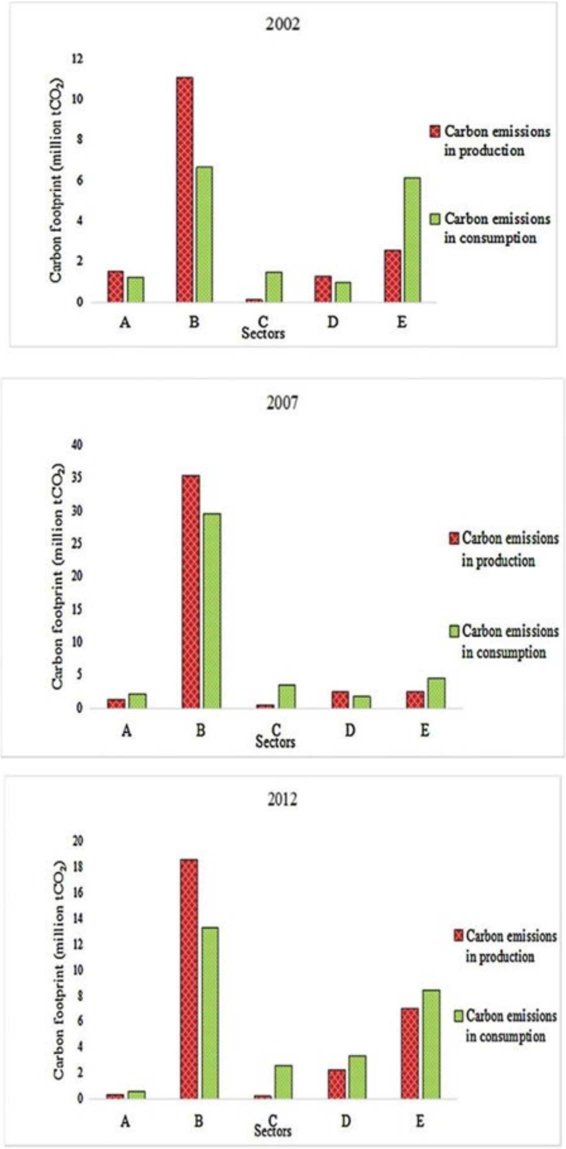
(a) Comparison of direct and indirect carbon emissions from a production perspective with five-sector classification

Fig.13: Comparison of direct and indirect carbon emissions from production and consumption perspectives.



(b) Comparison of direct and indirect carbon emissions from a consumption perspective with five-sector classification

Fig.13: (Continued)



(c) Comparison of carbon emissions from production and consumption perspectives with five-sector classification

Fig.13: (Continued)

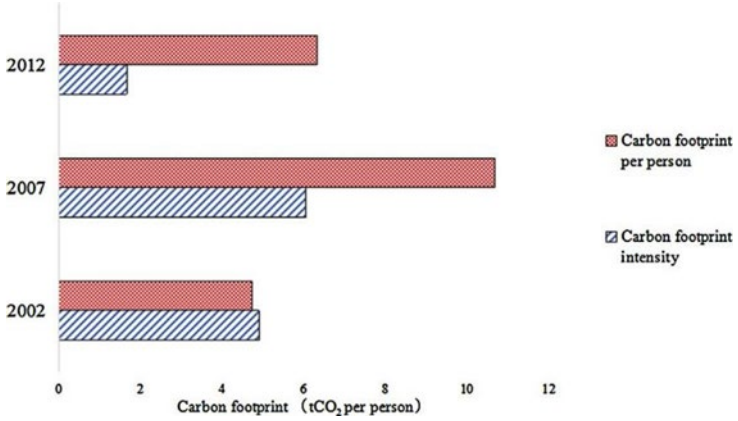


Fig.14: Comparison of carbon footprint intensity and carbon footprint per person.

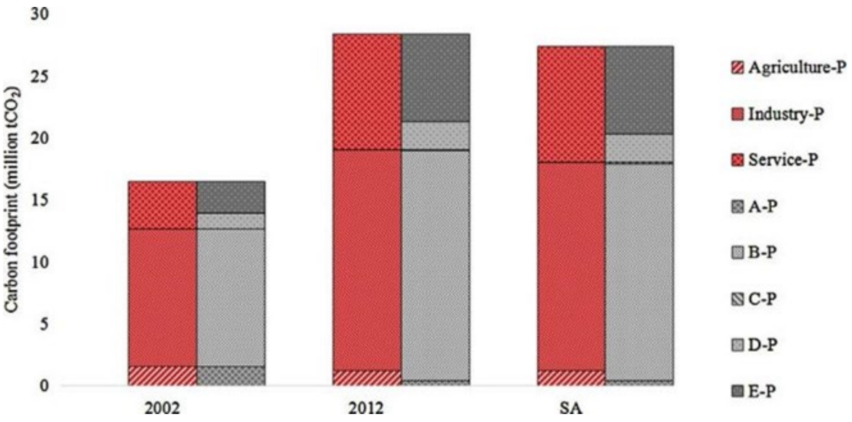


Fig.15: Comparison of carbon footprint of urban industrial symbiosis scenario and other scenarios.

Note: SA represents “Scenario Analysis”.

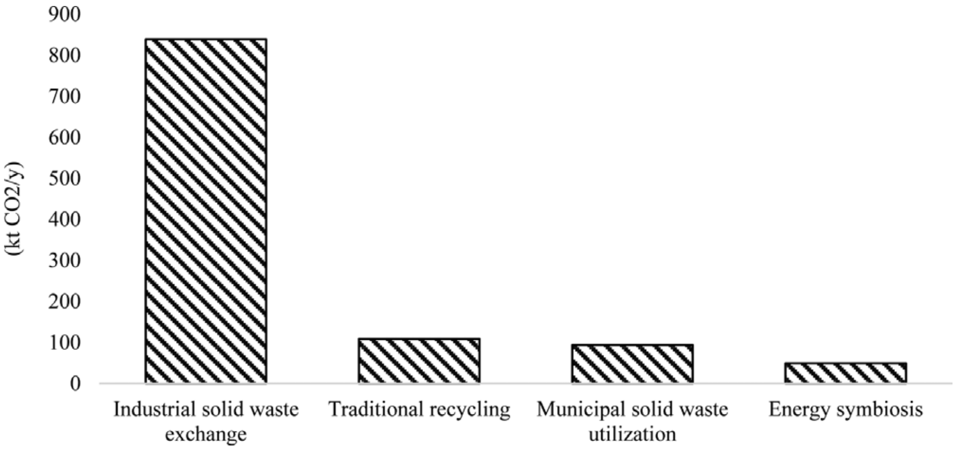


Fig.16: CFP reduction for each type of symbiosis.

4.3. Discussion

Based on the review of the state-of-the-art in CFP studies, it has been noticed that so far the mainstream methods for the city- level CFP accounting are far from satisfactory. The IPCC method is found incapable of addressing indirect carbon emissions embodied in traded goods, and the hybrid LCA considers both the direct and indirect emissions while neglecting materials beyond food, water, fuels and cements and still suffering from truncation error in some cases. As a result, an updated IOA method has been employed in this paper that combines the IOTs of Guizhou Province with fiscal data from Guiyang City, both of which are aggregated to the same level of details.

Contrary to many existing IO-based studies calculating the CFP merely for a single year, we measure the CFPs of 2002, 2007 and 2012 in a comparative sense by taking 2002 as the BAU scenario, in which circular economy promotions have not yet been implemented. The results therefore could assist policy makers in tracking the trends in urban CFP but also in understanding the role of a long-term circular economy policy in speeding up urban transition towards a low-carbon society.

Furthermore, we compare the carbon emissions of several cities and provinces as circular economy pilots including Beijing, Liaoning, Shanghai, Shandong and Chongqing, in comparison to Guiyang (Fig. 17). As shown below, Guiyang has the smallest amount of CFP.

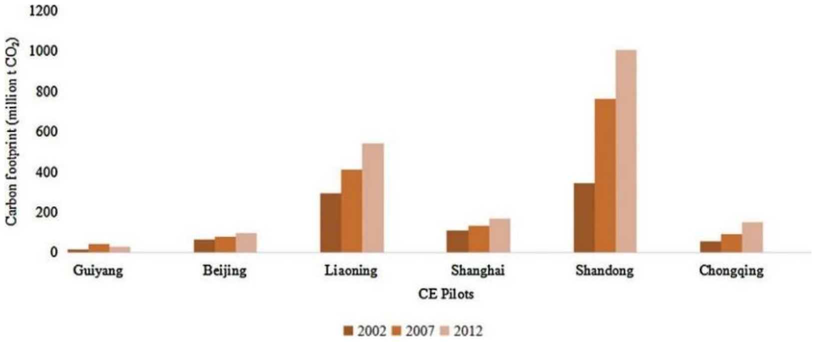


Fig.17: Comparison of carbon footprint of circular economy Pilots.

Note: Data for Guiyang are calculated by this paper, and data for others come from China Emission Accounts & Datasets (CEADs).

Moreover, it is the only pilot of which CFP began to go down after 2007, which examines that the low-carbon economy and industry transformation related to circular economy strategy has played an important role in carbon emission reduction. Besides, the CFP growth rate of Beijing, Liaoning and Shandong decreased from 25.1% to 19.3%, 39.6% to 32.3%, and 121.4% to 31.6%, respectively. On the contrary, the CFP growth rate of Chongqing and Shanghai increased from 58.0% to 63.3% and 20.4% to 28.1% respectively, probably because of their highly advanced industry structure that may shrink the potential in carbon emission reductions. Overall, China’s circular economy strategy has proved useful for pilots to mitigate the growing carbon emissions, especially for Guiyang City of which an absolute decoupling of GDP and CFP has achieved since 2007.

However, we acknowledge that our research still exist limitations to be solved in the near future. First, the carbon intensity is calculated with data from Guizhou Province rather than from Guiyang City due to the poor local data availability, which may deviate the final estimate away from the actual condition of production structure of Guiyang. Second, the inconsistence between the GSY, ESY and IOTs the best currently available data sources for Guiyang, may lead to a rough aggregation of sectors. We believe that this issue could be better addressed with the help of increasingly explicit and consistent energy consumption data and fiscal data in addition to the IOTs. Moreover, single-regional IOTs seem not to eliminate the influence of exports when being used to measure the urban CFP from a consumption perspective.

5. Conclusions and implications

This paper began with a review of CFP analysis using different methods at multiple scales. On the basis of a deeper understanding of the pros and cons of existing foot printing methods particularly at the city level, we have made efforts to track the CFP of Guiyang City in specific three years using an updated IOA method by combining the IOTs and energy data of Guizhou Province and the fiscal data of Guiyang City, examine the relationship of CFP between various sectors aggregated to three or five ones, compare the direct and indirect CFPs of production or consumption using two novel indicators named IDRI and PCRI. Moreover, we identified scenarios related to the proposed urban industrial symbiosis.

The major findings are as follows: 1) Guiyang's CFP (both in total and per capita) of almost all the sectors increased from 2002 to 2007 and turned to decline afterwards as a result of the continuous implementation of circular economy strategy; 2) Industry always took the largest proportion of Guiyang's CFP wherever a production or consumption perspective (especially from a production perspective), suggesting that the supply of Industry to other sectors would be greater than demand; 3) Agriculture had the lowest proportion and the distinction between production-based and consumption-based accounting was insignificant, implying that Agriculture may occupy the middle position in the supply chain mostly; 4) The proportion of Service in consumption-based carbon emissions was much higher than that in production-based carbon emissions, which suggested that Service would be placed in the tail of the supply chain and rely a lot on the inputs from Agriculture or Industry; 5)

The CFP of Construction became negligible when being aggregated to five sectors as its proportion in production-based carbon emissions approached zero but, from a consumption perspective, its proportion increased significantly as enormous carbon emissions embodied in the raw materials were taken into account;

6) There was a gap between the allocation of direct and indirect carbon emissions in Construction or Industry, thus adding more stress on the supply chain management; and 7) urban industrial symbiosis, in term of industrial solid waste exchange, traditional recycling, municipal solid waste utilization and energy symbiosis, was able to offer extra CFP mitigation effects via improving the life cycle closing loops.

We hereby drew the conclusion that Guiyang's circular economy promotions had already come into force particularly after 2007 and would continue to facilitate its urban transition to a low-carbon society. We also realized that the present research remained limitations. For instance, due to a lack of reliable IOTs at the city level, combining the provincial and urban data was likely to result in a respectively rough aggregation of sectors. Meanwhile, the IOTs from Guizhou Province did not consider the region-of-origin production technology on imported products, thus bringing the risk of misestimating Guiyang's CFP from a consumption perspective. As such, the development of data availability and quality for China's less-developed regions deserve a priority for future endeavors in the modeling and accounting of CFP of urban transition.

(1)CFP discloses the differences between direct and indirect carbon emissions based on production and consumption of a given entity, which reflects some hidden linkages among various sectors along the supply chain. By doing so, it could be possible to trace the hotspot carbon emitters of a region, allowing policy makers to look at the carbon emissions over the life cycle of supply chain with a special focus on sectors and industries that are highly carbon-intensive, but also to launch some incentives or regulations to achieve concrete reduction goals.

(2)Attach great importance to the nation-wide urban industrial symbiosis promotion which, in essence, aims to optimize the supply chain and the relationship of industries and urban area by improving the life cycle closing loops. China owns consider- ably large scale of industries and the rapid urbanization process, serving as an ideal laboratory to examine the effects of urban industrial symbiosis strategy. Therefore, the local stakeholders are encouraged to use this win–win strategy (urban and industrial symbiosis) for economy growth and environment protection.

(3)As a follow up discussion, it is well known that China has begun to promote the “New Normal Economy Development”, which emphasizes the quality of economy rather than the quantity, with more focuses on sustainable development and optimized economic structure. As an eco-industrial development measure, urban industrial symbiosis does provide an innovative pathway for Guiyang to promote its new normal economic development, via optimizing the interaction of industries and urban areas. For the resource industries dominant cities like Guiyang, it is necessary to consider how to utilize systematical approach to better green its industries and meanwhile, keep economic growth. In addition, innovative decision making support tools and indicators can help the policy makers to better measure and monitor the new normal economic development, by integrating economic, environmental and ecological values.

Our paper verifies the feasibility of CFP as an indicator, which can be considered to be further applied into the index system for new normal economic development evaluation.

(4)This paper highlights the significance of R&D to technological innovations in promoting urban industrial symbiosis in China. Effective and efficient technologies always provide a fundamental basis for formulating innovative strategies, the key technologies for circular economy and technologies standards, as well as quality standards for the input material as guidance for waste generators.

(5)Though CFP has proved useful in dealing with the problems related to emissions, the precondition of accounting for CFP remains challenging, partially due to the lack of access to reliable data particularly on the micro scales (e.g. cities) and, even if available, the quality of data is often far from satisfactory and varying over time and across regions. Therefore, there is a great need for the establishment of standardized databases (e.g. multi-regional IOTs), which could provide a basis for wise environmental decision making in various regions

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.ecolmodel.2017.09. 024.

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