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Identifying the Critical Supply Chains for Black Carbon and CO_2 in the Sichuan Urban Agglomeration of Southwest China

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Abstract: Black carbon (BC) and CO_2 emissions are the two major factors responsible for global climate change and the associated health risks. Quantifying the impact of economic activities in urban agglomerations on BC and CO_2 emissions is essential for finding a balance between climate change mitigation and pollution reduction. In this study, we utilized a city-level environmental extended multi-regional input–output model (EE-MRIO), integrated nexus strength (INS), and structural path analysis (SPA) to quantify the BC and CO_2 footprints, nexus nodes, and supply chains of 21 cities in the Sichuan urban agglomeration (SUA) from 2012 to 2017. The results revealed that approximately 70% of the BC and CO_2 footprints come from inter-city transactions, with Chengdu being the largest importing city, while the supply of other cities was greater than their consumption. The SUA has transitioned from a supply-side city cluster to a consumption-oriented city cluster in its trade with other domestic regions. The SPA analysis highlighted that the construction sector was the largest emitter of downstream BC and CO_2, while the electricity supply, metal/nonmetallic manufacture, oil refining and coking, transportation, and extraction industry sectors were the main nexus nodes for BC and CO_2 emissions in the SUA. Notably, the reduction in BC emissions was due to decreased indirect emissions from oil refining and coking, while the decrease in CO_2 emissions was a result of reduced indirect emissions from electricity supply. This article presents, for the first time, a quantification of the heterogeneous impacts and emission supply chains of BC and CO_2 emissions from economic activities in the SUA, providing valuable insights for developing climate mitigation policies tailored to different urban clusters.

Keywords: multi-regional input–output; structural path analysis; BC–CO_2 nexus; Sichuan urban agglomeration

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1. Introduction

China is not only the country with the highest CO_2 emissions [1,2], but also one of the major sources of black carbon (BC) emissions [3]. BC is produced as a byproduct of the incomplete combustion of carbon-containing fuels such as fossil fuels and biofuels.

Yang et al. [4] analyzed the associations between various $PM_{2.5}$ components and health outcomes and found that BC and organic carbon exhibited the strongest and most consistent correlations with all-cause mortality, cardiovascular mortality, and morbidity. In comparison, other components of $PM_{2.5}$ had lower toxicity compared to BC. In addition, BC can cause lung inflammation and respiratory diseases, exacerbating respiratory diseases such as asthma, bronchitis, and chronic obstructive pulmonary disease [5]. Recent studies have also shown that BC particles may penetrate the placenta and potentially impact the

fetus [6]. CO_2 is the most harmful greenhouse gas, and its emissions can have long-lasting effects on the climate for thousands of years [7]. On the other hand, BC can directly absorb sunlight, exerting influences on liquid, mixed-phase, and ice clouds, as well as depositing on snow and ice, causing a greenhouse effect [8]. BC is also considered to be the second-largest contributor to global warming, ranking just after CO_2. So, the combined emissions of BC and CO_2 can lead to climate change and extreme weather events such as heatwaves, droughts, and floods [9,10]. These extreme weather events, in turn, have direct or indirect effects on human health, resulting in conditions like heat stroke, dehydration, cardiovascular disease, and respiratory diseases [11,12]. Given the substantial role of BC and CO_2 emissions in contributing to climate change and their adverse effects on human health, it is imperative to search for effective measures to reduce these emissions [13,14].

Research has consistently shown that economic development is the primary driver of environmental pollution. Economic growth and urbanization are closely intertwined and heavily reliant on resource development [15]. However, this type of development has also led to serious environmental challenges such as climate change [16] and air pollution [17]. With the construction of urbanization and the massive migration of rural populations to cities, cities have become centers of consumption and production activities [18]. As a result, urban areas have emitted large amounts of pollutants [19] and are responsible for three-quarters of global greenhouse gas emissions [20]. Therefore, cities also serve as specific implementers of pollution reduction and carbon reduction policies. With the continuous advancement of urbanization, different cities combine population, resources, technology, and other production factors to form huge urban agglomerations [21]. The frequent interaction of materials and energy within urban agglomerations exacerbates regional environmental issues [22]. Consequently, implementing a policy for the joint control of BC and CO_2 emissions faces unprecedented challenges. It is crucial to understand how China can achieve the joint control of BC and CO_2 emissions at the city level, as this knowledge holds great significance for developing effective emission reduction policies in the future.

The Sichuan urban agglomeration (SUA) is the most populous and developed region in southwest China. As of 2022, the total population of the SUA reached 84 million, and its GDP reached CNY 5.67 trillion. The SUA holds a strategic position in China's development. With its unique geographical location, it serves as an important hub connecting the western inland regions and the eastern coastal areas, benefiting from convenient transportation networks and logistical advantages. Additionally, it is home to Chengdu, the leading new first-tier city. As China aims to achieve carbon emissions peak by 2030 and carbon neutrality by 2060, and also carry out pollution prevention and control actions and actively respond to climate change during the 14th Five-Year Plan period [23], the SUA region needs to achieve coordinated and efficient reductions in pollution and carbon emissions while promoting economic development. Zhang et al. [24] used statistics and models to establish China's BC emission inventory, which revealed that the Sichuan Basin had the third largest BC emissions, only behind the Yangtze River Delta and the Beijing–Tianjin–Hebei region. Its region's high population density and significant economic development were contributing factors to this environmental concern. According to Tao et al. [25] and Tian et al. [26], the SUA was ranked fourth among the most polluted regions in China, trailing behind Beijing–Tianjin–Hebei, the Yangtze River Delta, and the Pearl River Delta. Additionally, the SUA is also the primary provider of west-to-east power transmission, bearing a considerable environmental burden to support the developed eastern regions [27]. Due to air pollution, the SUA has become the most economically developed but vulnerable region in western China [28].

Input–output analysis (IOA), as a top-down tool, takes into account both intermediate uses and final demand. It is widely used to track the hidden footprints in trade [29–31]. The multi-regional input–output (MRIO) model is an enhanced version of the IO model, spanning multiple regions and sectors. It explores the spillover effects and resource connections linked with bilateral trade existing between different regions [32].

When MRIO is combined with environmental indicators, it creates an environmental extended MRIO (EE-MRIO), which can quantify the footprint of regions and sectors. Moreover, it can efficiently determine key factors through various supply chains, thus helping to address climate change [33]. Environmental extended IO analysis has been implemented to study CO_2 emissions [34] and BC emissions [35]. Zheng et al. [36] discovered that the rise of China's southwest and central regions has led to an increase in their hidden carbon emissions in national trade. Liang et al. [37] found that environmental sustainability can only be achieved through timely technological innovation, changes in production structure, and consumption patterns. Xing et al. [38] found that significant transfers of hidden carbon dioxide were observed in the Central Plains urban agglomeration, moving from energy-rich cities to prosperous cities.

Previous studies have primarily focused on investigating the influence of supply chains, upgrading individual pollutants such as SO_2, CO_2, and $PM_{2.5}$ [39–41]. However, there has been a lack of consideration for multiple emissions simultaneously [42], limiting the direct support for joint environmental control. Utilizing the MRIO method, Vivanco et al. [43] also proposed nexus strength (NS) as a way to rank nexus nodes based on associated environmental impacts and weighting schemes. This helps to understand the relative importance of each sector. Nexus nodes between industries and regions can be efficiently captured by simultaneously tracking different footprints [44]. Nexus-related studies based on EE-MRIO analysis have been extensively applied in water–CO_2 [45], water–$PM_{2.5}$ [46], and water–energy–food [47] fields.

A powerful tool called structural path analysis (SPA) can be utilized to identify critical supply chains that reveal key transmission paths and sectors in complex networks. SPA not only quantifies environmental transportation in the upstream production process but also determines the key supply chains with the highest potential for improvement while tracking the supply chain [48,49]. Some scholars have introduced SPA into the ecology field to better comprehend the relationship between supply chains and the environment. For instance, Xu et al. [50] combined IOA and SPA to uncover the key CO_2 transfer paths of global CO_2 emissions, while Zhang et al. [51] utilized SPA to track actual water use and greenhouse gas emissions in the Chinese supply chain. Additionally, most relevant studies have been conducted at the national [51] or local level [52], failing to account for heterogeneity among cities and hindering the formulation of effective and targeted emission reduction strategies. At the urban level, the basic use of EE-MRIO with SPA can help identify key flow paths more effectively. For example, Ding et al. [53] quantified the water–energy–CO_2 footprints of the Pearl River Delta urban agglomeration using SPA techniques and revealed that green production requires not just local promotion but also external support; hence, individual cities need to proactively integrate various sectors into the global supply chain, and computing their emission footprint will help them shoulder the responsibility of climate change mitigation.

In summary, due to the lack of city-level MRIO tables and limited research on cities, there is currently no study that investigates the footprint and supply chains of BC and CO_2 at the urban level of the SUA. Therefore, this study extracted a nested MRIO based on the China urban level MRIO table compiled by Zheng et al. [54]. As China entered a new development stage, known as the "new normal", with increasingly evident changes in economic structure after 2012, this study calculated the footprints and supply chains of the SUA at the urban level for the periods of 2012, 2015, and 2017. In summary, this study contributes to (1) constructing a nested MRIO table centered around 21 SUA cities; (2) providing the first estimation of BC and CO_2 emissions from urban and sectoral activities in the SUA, as well as the BC and CO_2 emission footprints between SUA cities and net flows generated through trade with other domestic regions; (3) identifying key nodes for the synergistic control of BC and CO_2 emissions within the SUA; and (4) analyzing the emission distribution of BC and CO_2 in the SUA on a sectoral level and quantifying changes in key supply chain pathways during the study period.

2. Methods

Figure 1 illustrates the flowchart of the methodology employed in this study. Firstly, we constructed a nested MRIO model with the SUA as the central entity, aggregating data for regions and sectors. Then, we calculated the emission footprints at the city level and investigated the BC and CO_2 footprints among cities within the SUA region, as well as the net flow of emissions between the SUA and other regions in China. Subsequently, we conducted an analysis of the BC–CO_2 nexus nodes, the spatial distribution of BC and CO_2 emissions, and the critical supply chain pathways. Lastly, we proposed policy implications for BC and CO_2 emissions in the SUA.

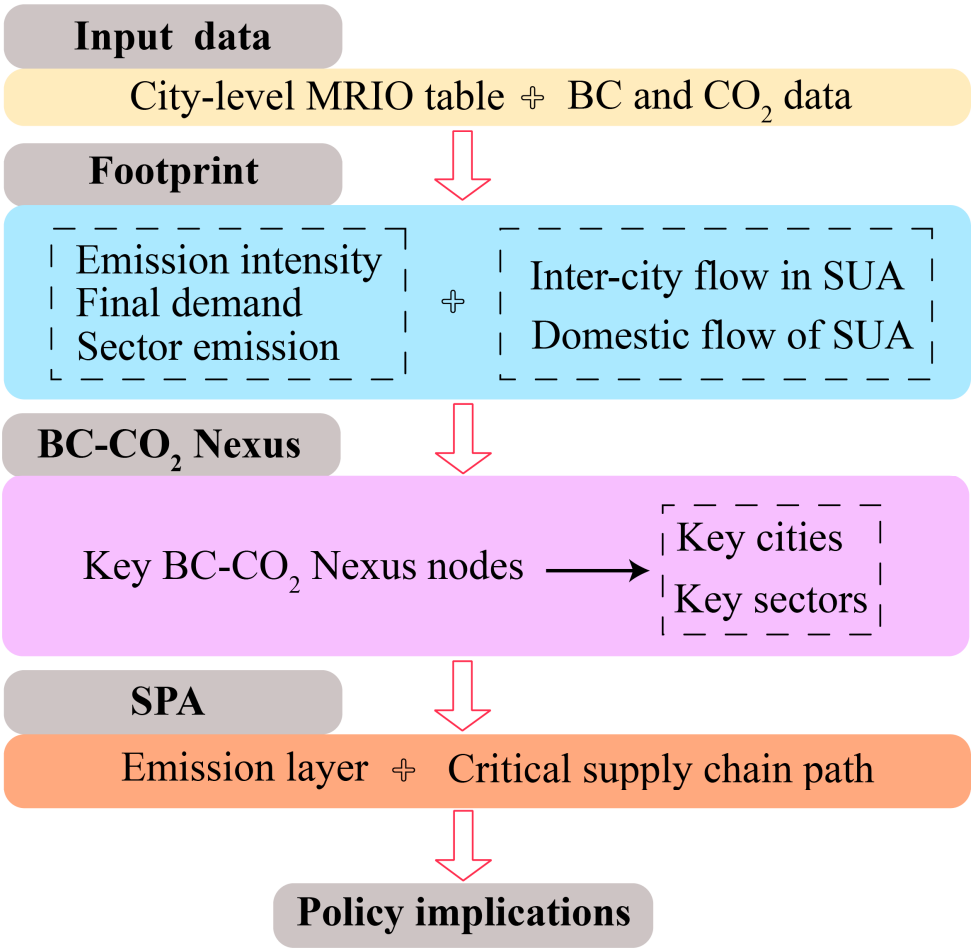


Figure 1. Flowchart of the methodology.

2.1. BC and CO_2 Footprint Calculation

2.1.1. Environmentally Extended Input–Output Analysis

IOA is a commonly applied method in emission studies. This method, initially proposed by Leontief in 1936, provides a quantitative relationship between the inputs and outputs of various industries present in the economic system [55]. Its fundamental equation is given by Equation (1).

$$T = fx = f(I - A)^{-1}Y = fLY \quad (1)$$

In Equation (1), T represents the demand-based footprint in the production chain. The parameters used are f for emission intensity; x for total output for each sector; I for the identity matrix; A for the direct requirement matrix, which can be calculated by dividing the monetary flow of the intermediate input by the economic output of the sector; and $(I - A)^{-1}$, which is commonly known as the Leontief inverse matrix. Additionally, Y is the final demand for each sector.

2.1.2. Identification of BC–CO_2 Nexus Nodes

The NS proposed by Vivanco et al. [43] represents the strength of the nexus node, accounting only for direct emissions and not the emission intensity factor. To identify the nexus sector and quantify its relationship strength in the economic system, Gao et al. [46] enhanced NS by modifying it to measure overall strength and integrated nexus strength (INS). INS factors are calculated in terms of both direct emissions and emission intensity. INS ranks socio-economic sectors that involve several resources, and the INS formula for sector © in the EE-MRIO model involving T kinds of emissions is as follows:

$$INS_i = \omega_1\left(D_i^{(1)} + ID_i^{(1)}\right) + \omega_2\left(D_i^{(2)} + ID_i^{(2)}\right) + \cdots + \omega_T\left(D_i^{(T)} + ID_i^{(T)}\right) \quad (2)$$

$$\begin{cases} D_i^{(t)} = E_i^{(t)}/MAX\left(\left\{E_i^{(t)}\right\}\right)_{i\in N} \\ ID_i^{(t)} = f_i^{(t)}/MAX\left(\left\{f_i^{(t)}\right\}\right)_{i\in N} \end{cases} \quad (3)$$

$$\begin{cases} D_i^{(t)} \geq h \cdot D_i^{(q)} \\ ID_i^{(t)} \geq h \cdot ID_i^{(q)} \end{cases} \quad (4)$$

In the equation for INS calculation, t indicates the type of emissions, while q represents resources or emissions that differ from t. ω_t stands for the importance weight and is used to assign relative significance for each emission. Specifically, in $\sum \omega_t = 1$, i represents the number of sectors, and N stands for the total number of sectors. Furthermore, E stands for the direct emission quantity of sector i in the environmental aspect, and f refers to the emission intensity of each sector, for which D_i and ID_i are equal to the sector's relative contribution to E and f. To ensure that each emission has a significant impact, a threshold value h is used to indicate the minimum contribution allowed for INS.

The larger the INS value for a sector, the more significant the sector's role in the economic system regarding BC and CO_2. Conversely, a sector's significance decreases as the INS value declines. For this study, the parameters ω_t (t = 1, 2, . . ., T) and h were set to be 0.5 and 0.01, respectively.

2.1.3. Structural Path Analysis

SPA studies economic structures through a series of Leontief inverse matrices extensions to determine critical supply chain paths accounting for environmental pressure, given by

$$L = (I - A)^{-1} = I + A + A^2 + A^3 + \cdots + A^n, \lim_{n\to\infty} A^n = 0 \quad (5)$$

By substituting Equation (5) into Equation (1), the power series expansion of the emission footprint can be obtained as follows:

$$T = f(I - A)^{-1}Y = \underbrace{fY}_{Tier0} + \underbrace{fAY}_{Tier1} + \underbrace{fA^2Y}_{Tier2} + \cdots + \underbrace{fA^nY}_{Tiern} \quad (6)$$

Equation (6) defines the production layers or tiers that represent elements in the series expansion. The first term in the equation represents Tier0, which represents the direct emissions of each sector; the second term represents Tier1, which supports the production of Tier0, and so on. Indirect emissions, which are generated by Tier1 and higher, result from infinitely expanding the production process. Thus, the equation has an infinite number of terms. However, this study focuses only on the first four tiers since previous studies have shown that the first 2–4 tiers contain the vast majority of impact [56]. The remaining layers are classified as "other". Notably, this analysis enables the calculation of both direct emissions and emissions resulting from economic transactions between sectors driven by final demand.

2.2. Data Sources

In this study, the BC emission data [57,58] for the SUA in 2012, 2015, and 2017 used are from the Multi-Resolution Emission Inventory for China (MEIC) developed by Tsinghua University (http://meicmodel.org/). The MRIO dataset for the SUA in 2012, 2015, and 2017 [54] and the CO_2 emission data [59,60] are from the Chinese Emission Accounts and Datasets (CEADs) (https://www.ceads.net/). In this study, the SUA is located in southwest China, including 21 cities, namely, Chengdu, Zigong, Panzhihua, Luzhou, Deyang, Mianyang, Guangyuan, Suining, Neijiang, Leshan, Nanchong, Meishan, Guang'an, Ya'an, Ziyang, Ganzi, Yibin, Dazhou, Bazhong, Aba, and Liangshan (Figure 2). Table S1 in the Supplementary Information presents the consolidation of the 42 sectors in the MRIO dataset into 18 sectors. Additionally, it lists the abbreviations of 21 cities in the SUA.

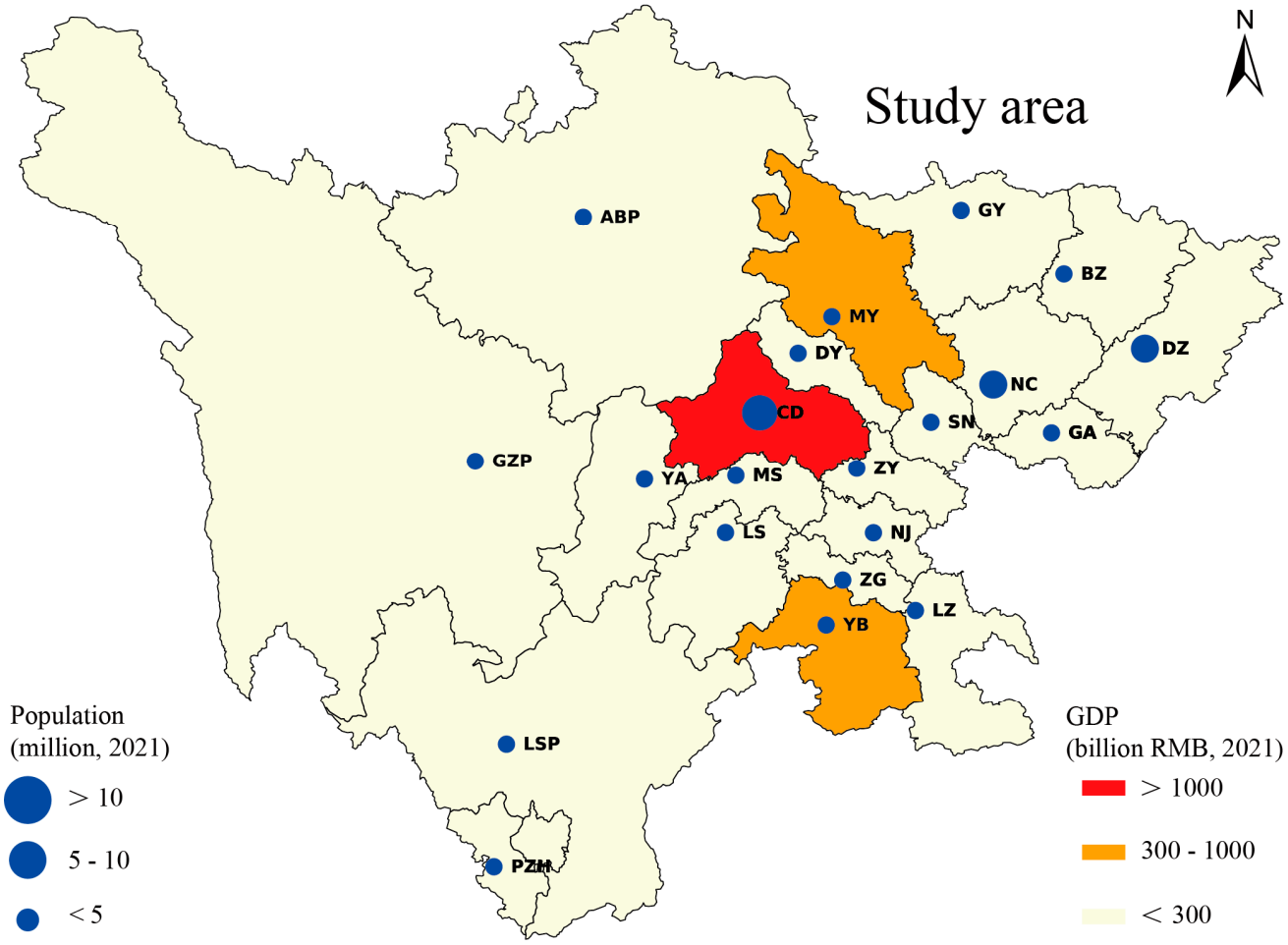


Figure 2. Urban distribution of Sichuan.

3. Results

3.1. BC and CO_2 Footprints and Interregional Flow

In the SUA, the sectoral emissions of BC and CO_2 were 36.46 Kt and 312.31 Mt in 2012, 28.32 Kt and 309.49 Mt in 2015, and 22.90 Kt and 295.35 Mt in 2017, respectively, showing a decreasing trend for both (Figures 3 and S1). These findings indicate that the phasing out of low-quality coal significantly reduced the emissions and intensity of BC as a result of China's 2013 Air Pollution Prevention and Control Action Plan [61].

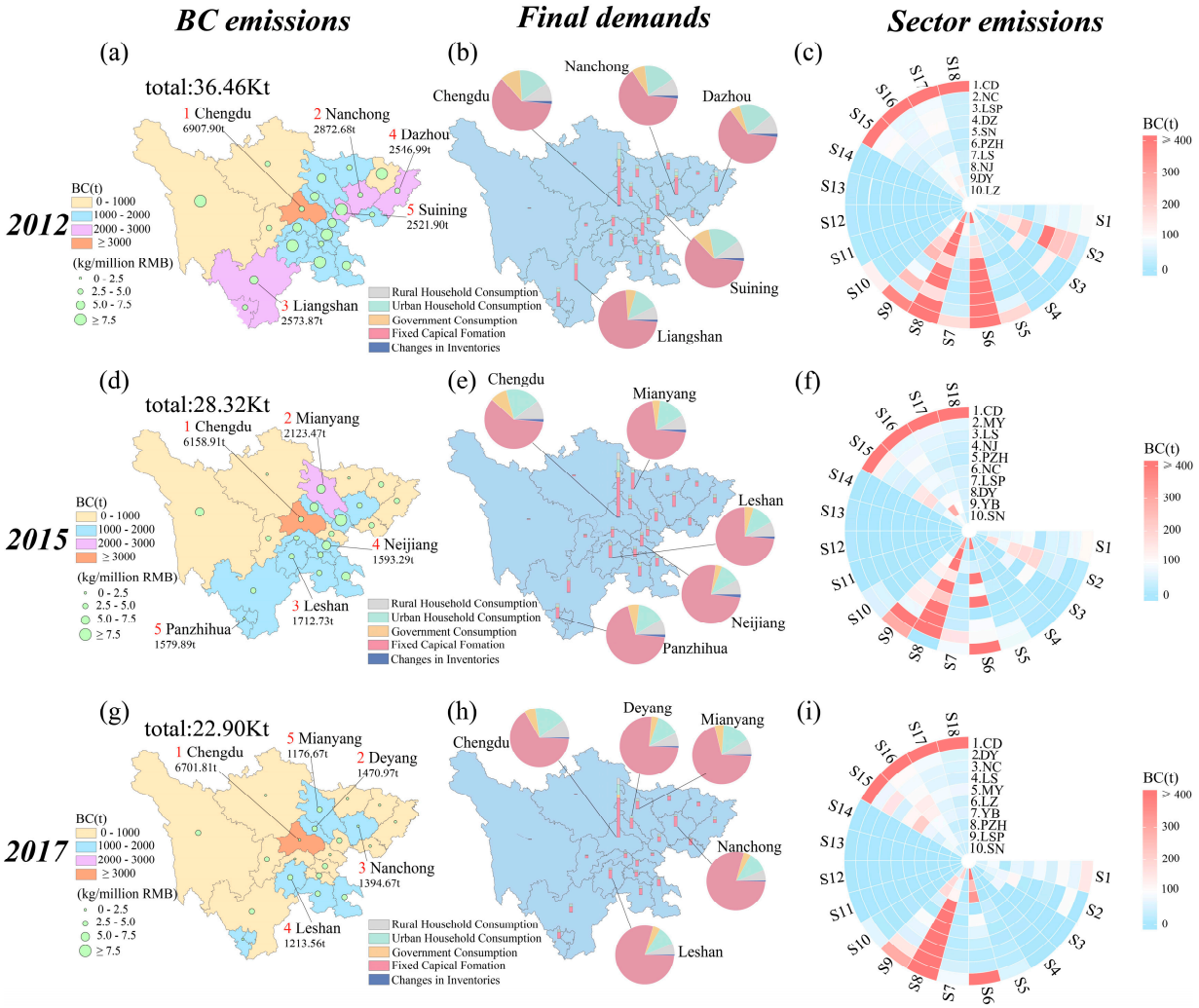


Figure 3. BC emissions, driving factors, and sectoral consumptions in the SUA. (**a**,**d**,**g**) BC footprints and emission intensities for each city in 2012, 2015, and 2017, respectively; (**b**,**e**,**h**) driving factors of BC emissions for each city in 2012, 2015, and 2017, respectively; (**c**,**f**,**i**) the sectoral emissions of BC for all sectors in the top ten cities in 2012, 2015, and 2017, respectively. (S1: agriculture, S2: extraction industry, S3: metal mining, S4: nonmetal mining, S5: light industry, S6: petroleum refining and coking, S7: chemical industry, S8: nonmetallic manufacture, S9: metal manufacture, S10: equipment manufacture, S11: other manufacture, S12: electricity supply, S13: gas supply, S14: water supply, S15: construction, S16: transportation, S17: wholesale and retail trades, S18: others).

From the BC footprint view (Figure 3a,d,g), Chengdu remained the highest in BC emissions from 2012 to 2017. In 2012, the top five cities in terms of emissions, excluding Chengdu, were different from those in 2015. The reason for this change was a significant reduction in emissions from oil refining and coke production in these four cities. However, Mianyang experienced a significant increase in BC footprint, reaching 0.78 Kt; this increase was mainly attributed to the metal manufacture sector. Between 2015 and 2017, the city with the most significant reduction in BC footprint was Mianyang, with a reduction of 0.95 Kt, while Chengdu had a significant increase in BC footprint, reaching 0.54 Kt. Neijiang experienced a significant decline in nonmetallic manufacture, while Panzhihua saw a significant decline in petroleum refining and coking. In terms of BC emission intensity, the BC emission intensity in 2017 decreased by 57.73% compared to 2012. The emission intensity of BC was highest in Suining, Bazhong, Neijiang, Yibin, Leshan, and Ganzi, exceeding 7.5 kg/million RMB in 2012; all cities had an emission intensity lower than 5 kg/million RMB by 2017. In addition, it can be seen that Chengdu, with the largest

emissions, maintained a relatively low emission intensity from 2012 to 2017; this was due to the fact that mega-cities have more developed service industries and mature industrial chains, while underdeveloped areas rely more on high-carbon emission products such as agriculture and energy consumption.

In terms of the final demands of BC emissions (Figure 3b,e,h), fixed capital formation has driven the highest BC emissions in all cities, and the proportion of BC emissions driven by fixed capital formation in most cities has increased. For instance, the proportion of BC emissions driven by fixed capital formation in Nanchong and Leshan was close to 80% in 2017. Urban household consumption and rural household consumption were found to be the second and third largest drivers of BC emissions, accounting for approximately 10–20% and 10% of the total emissions in each city, respectively. Government consumption was the fourth largest driver of BC emissions, accounting for approximately 5% of the total emissions in each city.

Moreover, we quantified the sectoral emissions of the top ten cities (Figure 3c,f,i). From the sectoral perspective, petroleum refining and coking (S6) and nonmetallic manufacture (S8) were the largest sectors in terms of BC emissions. Chengdu's construction (S15), transportation (S16), wholesale and retail trades (S17), and others (S18) also showed significant BC emissions. In terms of the biggest contribution to changes in BC emissions in the SUA, petroleum refining and coking (S6) and nonmetallic manufacture (S8) had the largest reduction in BC emissions from 2012 to 2015, reducing emissions by 2.41 Kt and 1.38 Kt, respectively. It should be noted that the increase of 1.84 Kt in BC emissions in Chengdu was due to the expansion of the petroleum refining and coking sector in the city. On the other hand, the decrease of 1.94 Kt in BC emissions in Chengdu can be attributed to both the reduction in emission intensity and increased imports from other cities within the SUA region. From 2015 to 2017, the emissions of the construction sector (S15) increased by 0.51 Kt due to the expanding demands of urban development. On the other hand, the emissions of the extraction industry (S2), nonmetallic manufacture (S8), and petroleum refining and coking (S6) decreased by 1.23 Kt, 2.07 Kt, and 3.61 Kt, respectively. Among these sectors, the petroleum refining and coking sector (S6) experienced the most significant reduction in emissions across all cities. This reduction was primarily attributed to the closure of highly polluting enterprises and substantial reductions in emission intensity.

From a CO_2 footprint perspective (Figure S1), Chengdu remains the largest emitting city with a relatively low emission intensity. Among the cities in the SUA, Mianyang showed significant emission changes from 2012 to 2015. In 2015, Mianyan's emissions reached 37.00 Mt, ranking second in the SUA; the reason behind this increase was a significant rise in emissions from nonmetallic manufacturing in Mianyang. From 2015 to 2017, Chengdu experienced significant emission changes, with an increase of 12.33 Mt. In terms of emission intensity, the CO_2 emission intensity in 2017 decreased by 36.34% compared to 2012. The eastern cities in the SUA reached lower levels in 2017, while Aba, Panzhihua, Liangshan, Ganze, Ya'an, and Leshan in the western region still had relatively high emission intensities. In terms of final demand, the emissions of the CO_2 footprint were similar to BC emissions. From a sector perspective, the difference between the CO_2 footprint and BC footprint lies in the higher emissions from electricity supply and metal manufacturing. The electricity supply sector is the main sector for reducing CO_2 emissions, but as a result of population growth and urban development, emissions from sectors like transportation and retail have increased, making it difficult to effectively offset CO_2 emissions.

It is worth noting that owing to the extreme inequality of regional development, Chengdu had the largest BC and CO_2 footprints in the SUA, accounting for approximately 20% of the total footprint, which was significantly higher compared to other cities. This is because Chengdu is the most developed city in the SUA, with the most economic trade. Moreover, with the promotion of economic integration in the SUA, trade links between cities become increasingly close; this geographical separation of resource-rich regions

and economic centers means that Chengdu transfers a substantial portion of BC and CO_2 footprints to other cities through trade.

As shown in Figure 4, the BC emissions related to trade within the SUA were 17.21 Kt in 2012, 14.89 Kt in 2015, and 12.47 Kt in 2017, accounting for 60.90%, 74.00%, and 71.11% of the BC footprint within the SUA in the respective three periods. The CO_2 emissions associated with internal trade in the SUA were 148.32 Mt in 2012, 146.92 Mt in 2015, and 159.10 Mt in 2017, accounting for 65.38%, 79.93%, and 77.14% of the CO_2 footprint within the province in the respective three periods (Figure S2). The structure of CO_2 emissions related to internal trade in the SUA is similar to that of BC emissions. Except for Chengdu, all other cities were characterized by consumption being less than supply. BC emissions caused by Chengdu's intercity imports were 6.82 Kt in 2012, 4.05 Kt in 2015, and 4.71 Kt in 2017. The top three import cities to Chengdu were Panzhihua, Liangshan, and Nanchong in 2012 (Figure 4a); these footprints were mainly generated in the petroleum refining and coking sector. In 2015 (Figure 4b), the top three import cities to Chengdu were Mianyang, Neijiang, and Liangshan, with the footprints of the first two cities mainly generated in the nonmetallic manufacture and metal manufacture sector, and those of Liangshan mainly in the petroleum refining and coking sector. In 2017 (Figure 4c), the top three import cities to Chengdu were Deyang, Nanchong, and Leshan, with footprints mainly generated in the "nonmetallic manufacture" sector. The BC emissions caused by Chengdu's exports to other cities in the SUA were 2.01 Kt, 2.38 Kt, and 2.76 Kt each year, respectively; this increase in exports indicated that while Chengdu was developing itself, it also had a feedback effect on the development of other cities. The top three export cities of Chengdu were Mianyang, Deyang, and Nanchong. The emission distribution resulting from intercity CO_2 trading was similar to that of BC. The top three import cities to Chengdu were Panzhihua, Aba, and Liangshan in 2012; the top three import cities to Chengdu were Mianyang, Yibin, and Neijiang in 2015; and the top three import cities to Chengdu were Panzhihua, Deyang, and Liangshan in 2017. Inter-city CO_2 emissions were primarily generated in the metal manufacture and the electricity supply sector. Moreover, economic progress may lead to an increase in Chengdu's production costs, such as high land rents and labor costs, which encourage carbon-intensive industries to transfer to other areas and reduce their production emissions. This measure may exacerbate the development imbalance between Chengdu and other cities.

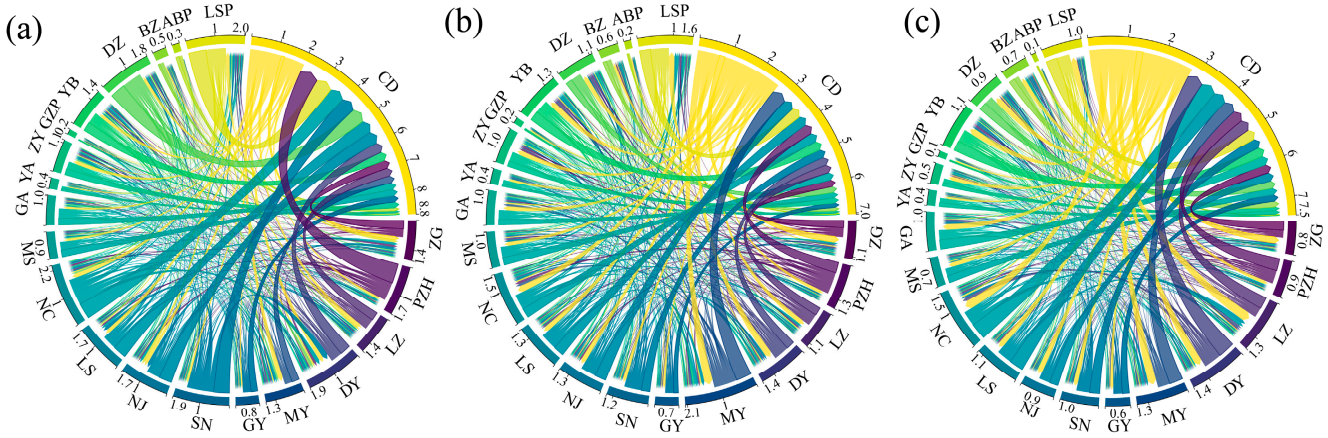


Figure 4. BC footprints between 21 cities in the SUA in 2012 (**a**), 2015 (**b**), and 2017 (**c**) (unit: Kt).

Figure 5 shows the net flow of BC between the SUA and other regions in China. The color in each region represents the net flow of domestic trade, where a positive value indicates that the region receives more implicit BC emissions than it outsources, and vice versa. The blank areas represent the absence of MRIO data, resulting in an inability to display the information. In 2012, the SUA received net BC emissions of 2472.96 t from other regions domestically. Except for northern China, the SUA acted as a supplier for

other regions, with the highest exports to the eastern coastal and southern coastal regions amounting to 956 t and 948 t, respectively. However, in 2017, the SUA transformed to the consumer side, outsourcing net BC emissions of 1511 t. Among this, the SUA transferred net emissions of 853 t to the southwest region, while still being a supplier to the eastern coastal and southern coastal regions. Figure S3 shows the net flow of CO_2 between the SUA and other regions in China. In 2012, the SUA received net CO_2 emissions of 26.94 Mt from other regions domestically, except for the northwest region of China, where the SUA had a net outflow to other regions. On the other hand, in 2017, the SUA also transferred to the consumer side, outsourcing net emissions of 24.92 Mt of CO_2, except for the southern coastal region. The SUA acted as a net importer to other regions, with a net inflow of 6.9 Mt of CO_2 emissions to the northern coastal region. This transformation of the SUA to the consumer side illustrates China's determination to develop the SUA.

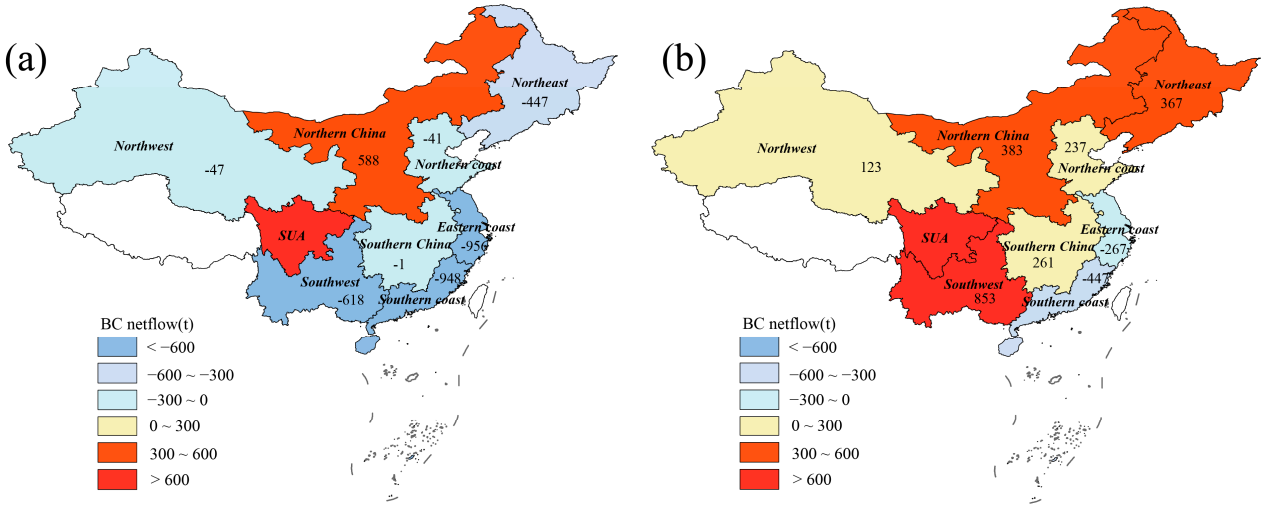


Figure 5. BC net flows of the SUA in 2012 (**a**) and 2017 (**b**).

3.2. BC–CO_2 Nexus

To evaluate the relationship between BC and CO_2 emissions in the SUA, the case study involved all 18 sectors in each city, each of which play a role in the BC and CO_2 relationship. However, to provide efficient emission reduction suggestions to decision-makers, we need to identify the key BC–CO_2 nexus nodes.

As shown in Figure 6, the average INS value was 0.18 in 2012, with petroleum refining and coking (S6) having the highest average value of 0.94, which was 5.2 times the overall average; among them, Panzhihua, Suining, Nanchong, and Liangshan had higher INS values, indicating that these cities' petroleum refining and coking sectors (S6) had a relatively strong correlation with BC and CO_2 emissions. The average INS value for the nonmetallic manufacture sector (S8) was 0.69, which was 3.8 times higher than the overall average. Among all cities, Chengdu had a higher INS value of 1.23 for the nonmetallic manufacture sector. This higher value can be attributed to the larger scale of nonmetallic manufacturing activities in Chengdu. Due to the closure of numerous highly polluting enterprises and the reduction in emissions intensity, the INS values for the petroleum refining and coking sector (S6) exhibited a significant decrease in 2015, reaching 0 in Yibin and Dazhou. This decrease was primarily attributed to the closure of high-pollution petroleum refining and coking sector enterprises in these two cities. Additionally, due to the high demand for metals in urban construction, the INS values for the metal manufacture sector (S9) in different cities exhibited a significant increase, with Mianyang having the highest INS value. In 2017, compared to 2015, the INS values for the petroleum refining and coking sector (S6) continued to decrease, and Ziyang also reached 0. This decrease in INS values can be attributed to the closure of high-pollution enterprises in Ziyang. Due to the high demand for consumables such as lime and cement in the construction sector, the INS values for

the nonmetallic manufacture sector (S8) exhibited a significant increase, with an average INS value of 1.01; among them, Chengdu, Deyang, Leshan, and Nanchong had higher INS values, indicating that the nonmetallic manufacture sector (S8) is an important node in these cities for the increase in the correlation between BC and CO_2 emissions.

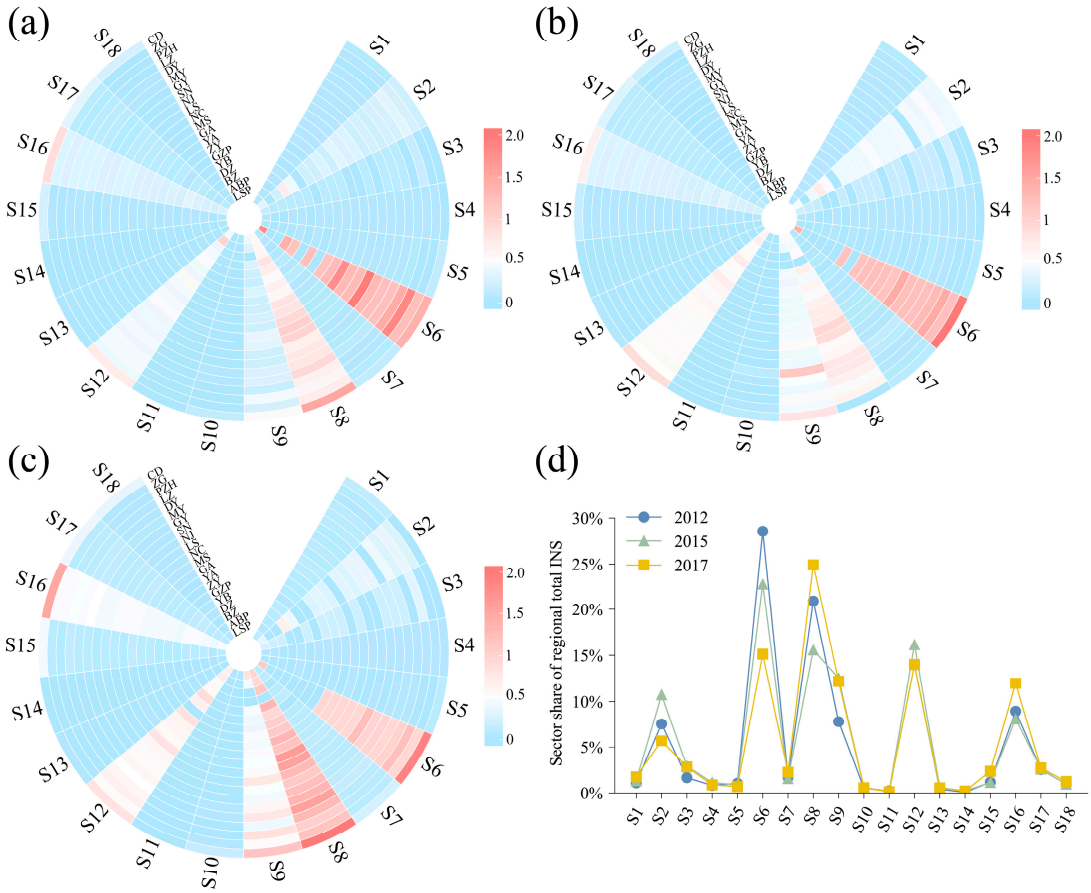


Figure 6. INS scores of each sector in 2012 (**a**), 2015 (**b**), and 2017 (**c**), and sector share of the SUA's regional total INS (**d**).

From the sectorial perspective (Figure 6d), the combined INS values of the nonmetallic manufacture (S8) and the metal manufacture (S9) sectors accounted for approximately 28.03–37.12% of the total INS in the region, with the highest INS values occurring in 2017. The proportion of the INS value of petroleum refining and coking (S6) decreased from 28.30% in 2012 to 15.38% in 2017, showing an effective reduction in emissions as industry progressed. The INS value of the electricity supply sector (S12) accounted for 14.31–16.36% of the total INS value in the region, and that of the transportation (S16) accounted for 9.16–12.17% of the total INS value in the region, with the highest INS value occurring in 2017. Additionally, the INS value of the extraction industry (S2) accounted for 5.44%-10.87% of the total INS value in the region, with the highest INS value occurring in 2015. The above industries were ranked highly in the BC–CO_2 nexus, accounting for over 85% of the total INS value in the region, indicating that these sectors are the key sectors for BC and CO_2 emissions.

3.3. Structural Path Analysis

3.3.1. Distribution of Emission Layers

More than 30% of the BC and CO_2 footprints in most cities were in Tier 1, with much of the emissions being indirectly generated (Figures 7a,c and S4a,c), so each city should pay more attention to Tier 1 of BC and CO_2 emissions. From 2012 to 2017, the proportion of BC and CO_2 emissions in the first four tiers increased in each city, indicating more efficient

resource usage. The first four tiers accounted for over 81% of total emissions in all cities in 2017, and these were the primary sources of BC and CO_2 emissions. However, the distribution of tiers in each city was different, being mainly due to different industrial structures in each city. For example, cities like Chengdu and Panzhihua have relatively higher BC emissions in the petroleum refining and coking (S6), which involves the participation of multiple intermediate sectors. As a result, the proportion of CO_2 emissions from the first four tiers in these cities is slightly higher than that of BC emissions.

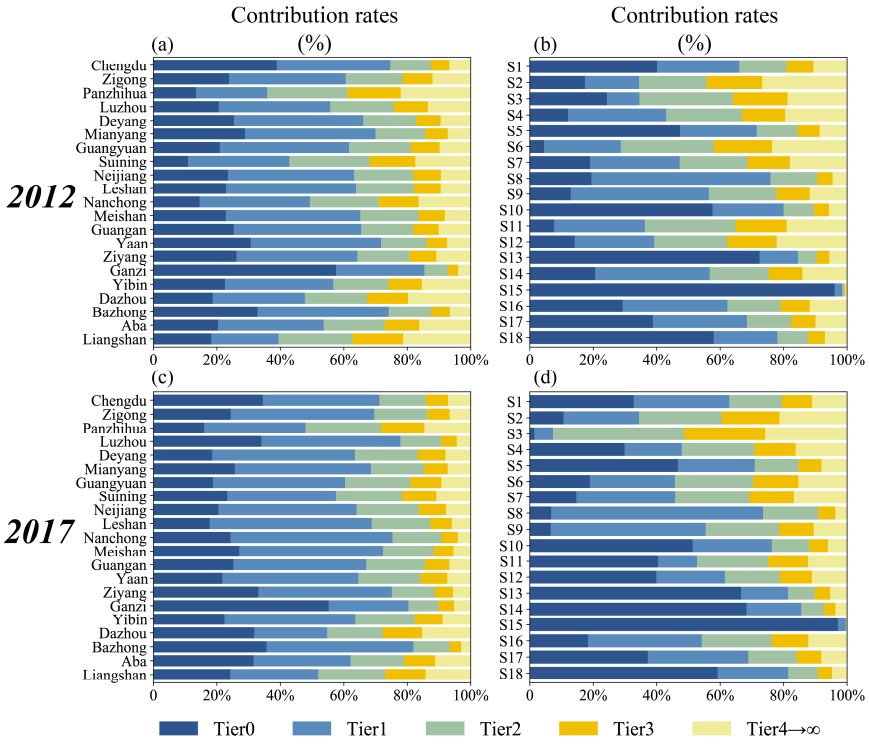


Figure 7. Contributions of each layer to the BC footprint in the SUA in 2012 and 2017.

As shown in Figures 7b,d and S4b,d, the BC and CO_2 emissions from the 18 sectors were also dominated by the first four tiers. Compared to 2012, the proportion of the first four tiers of emissions from each sector increased in 2017, but the distribution of tiers by structure in each sector was significantly different. From the emission distributions of each sector in 2017, emissions from the extraction industry (S2), metal mining (S3), oil refining and coking (S6), chemical industry (S7), nonmetallic manufacture (S8), metal manufacture (S9), and transportation (S16) mostly belonged to the first and second tiers These sectors, except for metal mining (S3), played key codes of BC-CO_2 emissions, indicating significant indirect emissions contribution. On the other hand, other sectors predominantly contributed to direct emissions, with the construction sector being the major contributor, accounting for over 95% of the total emissions.

Between 2012 and 2017, there were variations in resource utilization across different production tiers among sectors. Moreover, there was a significant increase in the proportion of direct emissions from nonmetal mining (S4), petroleum refining and coking (S6), other manufacturing (S11), electricity supply (S12), and water supply (S14). These changes suggest optimization in the structure of intermediate inputs, resulting in improved efficiency. In contrast, the proportion of direct emissions from the extraction industry (S2), metal mining (S3), nonmetallic manufacture (S8), and metal manufacture (S9) sectors decreased significantly, indicating an increase in indirect emissions. This transition reflects a shift towards a supply-side transformation in these sectors.

3.3.2. Critical Supply Chain Path

To identify significant nodes and supply chains, the MRIO table was isolated as a general table, and SPA was employed to obtain all BC and CO_2 supply chain paths. As there are numerous supply chain paths, it is difficult to display all the paths locally; appropriate thresholds enable decision-makers to determine the most sensitive and energy-intensive paths, thereby enabling them to take appropriate energy-efficient measures and accelerate energy efficiency [48].

Since the first five tiers accounted for more than 80% of the total BC and CO_2 footprints (Figure 7), we mainly focused on Tier 0, Tier 1, Tier 2, Tier 3, and Tier 4, and the results of other tiers were classified as "other". Figure 8 shows the distribution of the BC and CO_2 supply chains in the SUA in 2012, 2015, and 2017; the width of the lines indicates the emissions from one sector to another, arranged from high to low, and the gray rectangles represent the footprint consumed in the next tier. For example, the gray rectangle in Tier 1 of the 2012 BC footprint represents the BC footprint emitted by various industries in Tier 0, which was 8677.38 t in the first tier. From a consumption perspective, rural consumption, urban consumption, government consumption, capital formation, domestic exports, and international exports, respectively, accounted for 7.39%, 12.44%, 5.82%, 50.64%, 15.47%, and 1.19% of the SUA's total BC emissions in 2012.

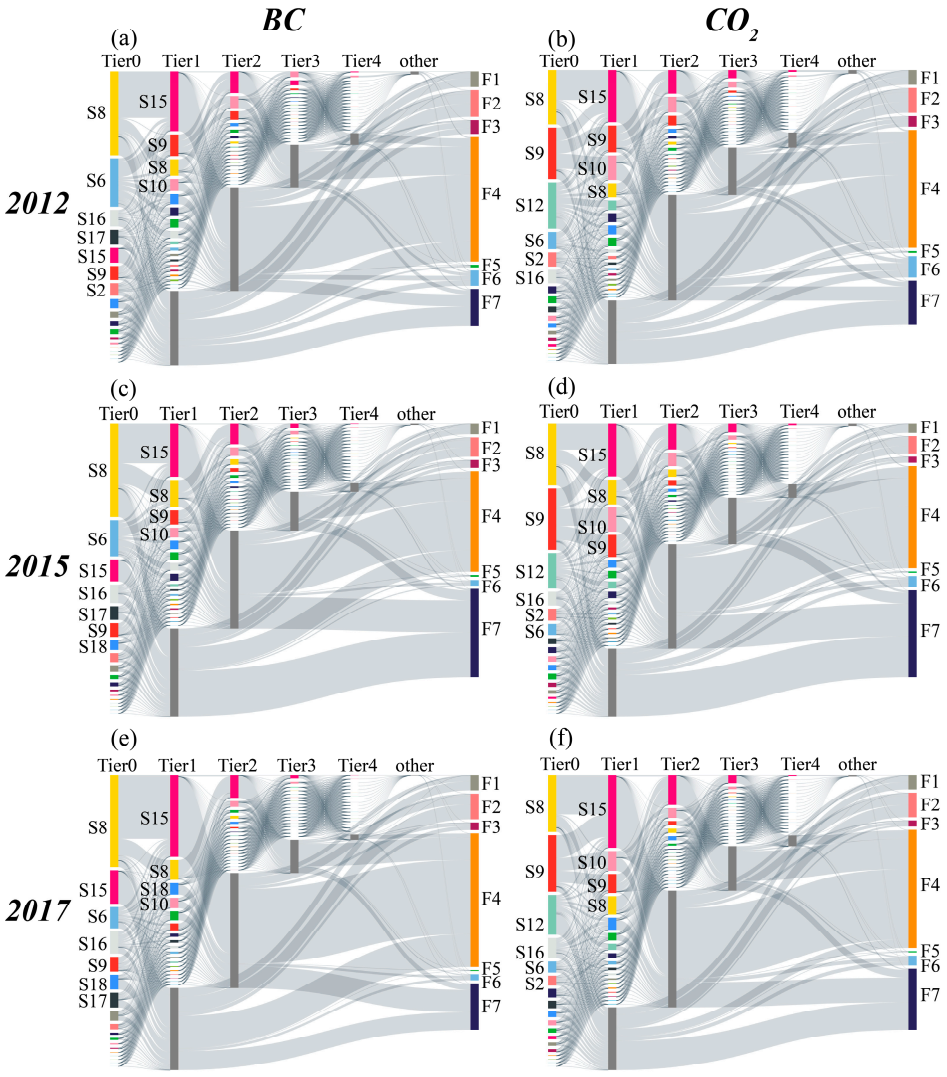


Figure 8. The main BC and CO_2 supply chains in the SUA. (F1: rural consumption, F2: urban consumption, F3: government consumption, F4: fixed capital formation, F5: inventory increase, F6: international exports, F7: domestic exports).

In Figure 8a,c,e, we can directly observe that in the main supply chain of BC. In terms of direct emissions, nonmetallic manufacturing (S8) and petroleum refining and coking (S6) are relatively large upstream sectors, while construction (S15) is the largest downstream sector. Furthermore, the proportion of construction (S15) in Tier 0 emissions is continuously in-creasing, indicating that construction (S15) is also gradually increasing its direct emissions. In 2017, the direct emissions from the construction (S15) even surpassed those from petroleum refining and coking (S6), becoming the second largest sector in terms of direct emissions. In the main supply chain of CO_2 (Figure 8b,d,f), nonmetallic manufacture (S8), metal manufacture (S9), and electricity supply (S12) are the significant upstream sectors with a substantial proportion, while construction (S15) is the largest downstream sector. Additionally, we can see that equipment manufacture (S10) is the second major down-stream sector for both CO_2 and BC, and Tier 1 is the level where the largest amount of CO_2 and BC emissions are generated.

Furthermore, each sector played a role as an upstream, transfer, or downstream sector as all sectors were closely linked; if we can capture the critical sectors or supply chains with significant emissions and identify the key contributing factors for each, policies and emission controls can become more specific and targeted.

Tables S4–S6 presented in the Supplementary Information list the top 20 supply chains for BC and CO_2 emissions in the years 2012, 2015, and 2017, accounting for 39.17% (32.27%), 40.95% (31.98%), and 50.01% (39.15%) of the SUA's total BC (CO_2) footprint, respectively. BC and CO_2 emissions were increasingly concentrated in the top 20 supply chains. Tables S4–S6 also show the CO_2 and BC emission proportions in relation to specific BC and CO_2 emissions. CO_2 emissions accounted for more than 25% of total emissions in the top 20 BC supply chains. Moreover, in the top 20 CO_2 supply chains in 2012 and 2017, BC emissions accounted for a higher proportion than CO_2 emissions; this suggests that there was a high synergy between CO_2 emissions and BC emissions. Additionally, more than half of the top 20 supply chains for both emissions were common paths. From the perspective of final demand, capital formation and domestic exports play a dominant role in driving BC and CO_2 emissions, and in 2015, the supply chains driven by exports were the most abundant, reflecting the SUA's period of outward-oriented economy.

From an emission supply chain perspective, the construction sector (S15), as the main downstream sector, drives the majority of BC and CO_2 supply chains, and its proportion of emissions is increasing. The nonmetallic/metal manufacture (S8, S9) and transportation sectors are the main supplying sectors for construction. Despite being an important downstream sector, the equipment manufacture (S10) sector has seen a decrease in its proportion of emissions year after year. The supply chain "extraction industry (S2)/nonmetallic manufacture (S8)/metal manufacture (S9) → domestic exports" is also a significant contributor to BC and CO_2 emissions. Notably, outside of the common supply chain, key supply chains in the BC supply chain include "petroleum refining and coking (S6) → construction (S15) → fixed capital formation" and "transportation (S16)/wholesale and retail (S17)/others (S18) → consumption". Meanwhile, key supply chains in the CO_2 supply chain include "electricity supply (S12) → construction (S15) → fixed capital formation", "electricity supply (S12) → domestic exports" and "metal manufacture → international exports/domestic exports".

Analyzing the top five CO_2 and BC emission supply chains for 2017 reveals that the synergistic emissions of BC and CO_2 were mainly found in the following supply chains: "nonmetallic manufacture (S8)/metal manufacture (S9) → construction (S15) → fixed capital formation", "nonmetallic manufacture (S8) → nonmetallic manufacture (S8) → construction (S15) → fixed capital formation", and "metal manufacture (S9) → construction (S15) → domestic exports". Among them, the supply chain "metal manufacture (S9) → construction (S15) → fixed capital formation" contributed the most to the BC and CO_2 footprints, and four of the top five supply chains for both types of emissions were the same. These findings suggest that SUA's development is still heavily reliant on the construction sector and follows an extensive development model. Therefore, emission reduction efforts

should focus on optimizing nonmetallic/metal manufacture process control, reducing initial emission intensity, controlling intermediate inputs, improving the IO efficiency of transfer sectors, and utilizing cleaner replacement products for terminal sectors.

Table S7 outlines the top 30 BC and CO_2 emission supply chains that experienced an increase from 2012 to 2017. In the BC system, three sectors (construction, petroleum refining and coking, and others) had primarily direct emissions in the supply chains where BC emissions increased, while one sector (transportation) emitted indirect emissions. Similarly, in the supply chains where CO_2 emissions increased, three sectors (electricity supply, petroleum refining and coking, and other sectors) had primarily direct emissions, while two sectors (nonmetallic/metal manufacture) contributed indirect emissions. Notably, the SUA's electricity supply had the highest reduction in CO_2 emissions; however, the "electricity supply $\rightarrow$ domestic exports" supply chain was the largest supply chain where CO_2 emissions increased. These findings highlight that while the SUA actively develops infrastructure, other provinces bear a significant environmental cost.

Table S8 outlines the top 30 BC and CO_2 emission supply chains that experienced a reduction from 2012 to 2017. In the BC system, three sectors (extraction industry, transportation, and wholesale and retail) primarily contributed direct emissions in the supply chains where BC emissions decreased, while one sector (petroleum refining and coking) contributed indirect emissions. Interestingly, nonmetallic manufacture had significant reductions in both direct and indirect BC emissions. In the supply chains where CO_2 emissions increased, three sectors (nonmetallic/metal manufacture, extraction industry) primarily emitted direct emissions, while two sectors (electricity supply, petroleum refining and coking) contributed indirect emissions. Obviously, in the BC and CO_2 supply chains, petroleum refining and coking had an increase in direct emissions, but the emission reduction effect of its indirect emissions was more significant. The electricity supply sector in the CO_2 supply chains exhibited a similar pattern. Additionally, the equipment manufacture sector driven by fixed capital formation had reduced emissions, while the equipment manufacture sector driven by domestic exports had increased emissions; this finding implies that the SUA's industrial chain heavily relies on other regions within China.

4. Discussions and Conclusions

Reducing BC and CO_2 emissions is a feasible approach to mitigate global warming and prevent air pollution. In order to achieve coordinated progress in carbon reduction, pollution control, afforestation, and economic growth in the SUA, decision-makers need to comprehensively manage the economic environment. Therefore, it is crucial to identify the key supply chain of BC and CO_2 in the SUA.

The SUA exhibits significant spatiotemporal disparities. In terms of spatial scale, Chengdu accounts for over 20% of the BC and CO_2 footprints. Over time, due to proactive environmental policies, the BC and CO_2 emissions intensities in 2017 decreased by 57.73% and 36.34%, respectively, compared to 2012. From an urban perspective, our research underscores the shift of the SUA from a supply-side urban agglomeration to a consumption-side urban agglomeration in its trade relations with other regions within China. The SUA can facilitate the coordinated development of eastern and western regions, enabling the realization of resource complementarity and synergistic industrial growth, thereby propelling economic advancement and societal progress in the western region. Within the intercity transactions of the SUA, Chengdu stands out as a consumer-oriented city, strategically reducing emissions by procuring high BC- and CO_2-emitting products from other regions. Consequently, other upstream cities (Deyang, Mianyang, etc.) will gradually supplant Chengdu's outdated industries to foster their own economic growth. While striking a balance between environmental preservation and economic development, emphasis should be placed on industrial technological upgrades and enhanced energy efficiency. Furthermore, in response to the "classified, regional, staged, and orderly promotion of carbon peaking" outlined in China's Carbon Peak Action Plan, Chengdu should establish linkages with

other regions within the SUA to create a carbon market and to facilitate technology transfer and knowledge sharing, thereby driving collective emission reduction efforts.

We need to focus on the sectors with the highest and increasing BC–CO_2 nexus node scores. One such sector is nonmetallic manufacture, which is also an important sector supplying the construction sector. The strict control of emissions from this sector or promotion of cleaner alternatives is crucial for building a green supply chain. Another sector that requires significant regulatory attention is the metal manufacture sector, which plays a vital role in coordinating BC and CO_2 emissions pathways. During the research period, there was a substantial increase in emissions from the metal manufacture in Mianyang. Therefore, it is important to closely monitor the emission intensity of this sector and prevent excessive pollution.

Compared to more developed regions like coastal areas, the SUA has relatively lower average levels of wealth. The development of the SUA is primarily centered around the construction sector. From an environmental perspective, not only should we improve production methods, but we should also guide enterprises to make sound investments and reduce the number of short-lived buildings in order to improve investment efficiency.

The BC–CO_2 nexus score of the transportation sector has also been increasing over the years. Increasing the utilization rate of new and renewable energy, as well as reducing the consumption of high-emission fuels such as diesel, will play a significant role in reducing BC and CO_2 emissions. Effective measures in various cities include reducing indirect emissions and shutting down high-pollution enterprises in the petroleum refining and coking sectors. Since petroleum processing is related to various intermediate sectors, it is necessary to improve the sector's production efficiency and promote cleaner usage.

Although the SUA is transitioning towards the consumer side, the electricity supply sector (S15) in the region, being the largest hydroelectric power area in the country, still experiences increasing CO_2 emissions caused by exports. Therefore, it is crucial for SUA to ensure the efficient utilization of hydropower and accelerate the development of solar and wind energy resources. In comparison to the relatively developed Pearl River Delta [53], the manufacturing sector in the SUA is relatively weak. The SUA should leverage the development policies of the Chengdu–Chongqing Economic Zone to strengthen the advantages of industries worth CNY 4 trillion, namely, electronic information, automobiles, equipment manufacturing, and consumer goods, in both international and domestic markets. This will enhance the value and competitiveness of industrial products and promote technological innovation while also paying attention to highly polluting manufacturing industries.

As the first study on the sustainable development policy pathways of BC and CO_2 in the SUA, this research has certain limitations. Firstly, the study focused on a detailed analysis of BC and CO_2 emissions generated from fossil fuels and industrial processes, highlighting their contributions to economic and industrial development. However, it did not examine direct emissions from residential sources. Secondly, the study categorized SUA exports into domestic and international exports, without calculating the net flow of SUA in international trade. With the increasing level of globalization, SUA's cross-border trade is growing. These issues need to be further explored in future research.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/su152115465/s1.

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