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Why Are the Carbon Footprints of China's Urban Households Rising? An Input–Output Analysis and Structural Decomposition Analysis

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Abstract: A rise in China's economy and urbanization has brought about obvious growth in the carbon footprints of urban households over the past years. In this study, input–output analysis was adopted to calculate the carbon footprints of urban households in China. Furthermore, a detailed analysis of the impact factors on indirect carbon footprints was carried out by using the structural decomposition analysis at both holistic and sectoral levels. The results showed that the carbon footprints of urban households were 941.37 MtCO₂ in 2002, 1498.11 MtCO₂ in 2007, and 2139.50 MtCO₂ in 2012. Electricity was the main contributor to the direct urban household carbon footprints, accounting for over 40%. The category of “household facilities” contributed the most to indirect carbon footprints (306.00 MtCO₂) in 2012, and the “transportation” had the fastest growth rate (395%) during 2002–2012. The industrial sector of “wearing apparel” had the largest increments (139.92 MtCO₂) in carbon footprints during the past decade. Generally, consumption level and population size presented positive effects on the increments in indirect carbon footprints, while emission intensity decreased indirect carbon footprints. However, the impact of consumption structure and intermediate demand on indirect carbon footprints varied at holistic and sectoral levels. The mitigation efforts should focus on reducing emission intensity, shifting consumption structure and changing intermediate demand.

Keywords: carbon footprints; urban households; input–output analysis; structural decomposition analysis; China

1. Introduction

China's booming economy during the past three decades has made it the largest CO₂ emitter in the world [1–3]. Amid mounting international pressures, China has made a commitment to capping its carbon emissions around 2030 and making best efforts to make them peak early [4,5]. Specifically, to tackle climate change, the government has pledged to reduce CO₂ emissions per unit of gross domestic product (GDP) by 60% to 65% by 2030 compared to 2005 levels and increase the share of non-fossil fuels in primary energy consumption to around 20% [6]. Thus, it is urgent to coordinate the economic development, energy consumption, and emission reduction [7].

The energy consumption and related carbon emissions from households play an important role all over the world [8–11]. Reportedly, more than 80% energy consumption and corresponding carbon emissions were allocated to the household sector for the United States [12], 75% for India [13], 74% for the UK [14] and 52% for the Republic of Korea [15]. Lower than in these countries, this

allocation was more than 40% for China [16]. However, as the largest developing country, China has experienced fast urbanization during the last two decades, leading to a spike in household energy requirements [17–19]. Moreover, along with the improvement of income level and the changes in consumers' lifestyle, the Chinese households generally spent more money on enhancing the quality of life, such as enjoying luxurious consumption (such as overseas traveling and air conditioning) and purchasing high-carbon products (such as private cars with high gasoline consumption and home appliances with high power) [20,21]. In addition, the increasingly fast urbanization process also has a significant impact on household carbon emissions. China's urbanization rate increased from 18% in 1978 to 58% in 2017. Compared to rural households, urban households' carbon emissions are much larger because of the higher income level and modern lifestyle [22–25]. It is noteworthy that China is still accelerating the development of urbanization. One hundred million rural populations will be settled in urban areas by 2020. The urbanization rate will reach 60% by 2020 and 70% by 2030. With intensified rural-to-urban migration, the impact of urban residents on the carbon emissions will be further magnified. The research on carbon emissions of China's urban households should draw widespread attention [26–28]. The concept of carbon footprint is widely applied to identify both direct and indirect carbon emissions from a broader accounting perspective [29–31]. The carbon footprints of households represent the carbon emissions not only triggered by direct use of energy in household activities but also embodied in the production of goods and services. The emission coefficient method (ECM) [32] is widely used to calculate direct household carbon footprints, and consumer lifestyle approach (CLA) [12] and input-output analysis (IOA) [33] are main research methods studied for indirect household carbon footprints. In recent years, the studies on carbon footprints of households have been a hot topic in China. For example, Wei et al. [22] quantified the energy use and carbon emissions influenced by the lifestyle of urban and rural residents from 1999 to 2002. The results showed that residence contributed the largest carbon emissions to urban residents, while food contributed the most to rural residents. Wang and Yang [34] utilized energy ecological footprint (EEF) to explore the indirect carbon emissions of household consumption in the urban and rural areas of China. They discovered that the EEF of indirect energy use was on the rise for urban residents but was declining for rural residents. Xu et al. [35] examined the carbon inequality in urban households based on the survey data of 24 cities in China, and the results indicated that household carbon inequality was ascribed to different household characteristics and consumption categories. Liu et al. [16] examined the carbon footprints of urban and rural households in China from 1992 to 2007. The results showed that miscellaneous commodities and services caused most carbon emissions for urban households, while food and tobacco caused most carbon emissions for rural households. Tian et al. [36] explored the effects of Shanghai's household consumption pattern on energy use and carbon emissions from 2002 to 2007. They declared that the change in household consumption patterns would increase energy use and carbon emissions from 2007 to 2030. Han et al. [37] used a representative resident survey to analyze the embedded carbon emissions of urban households. They discovered that young people and children emitted more embedded carbon emissions than adults, and the employed persons emitted more than the unemployed and retired persons. Tian et al. [23] qualified the historical household carbon footprints in Liaoning province during 1997–2007. They uncovered that population size and per capita consumption were the key drivers of increasing household carbon footprints. These studies mainly concentrated on how household consumption affected energy demand and carbon emissions from the demand side. However, it should be noted that most carbon emissions generated from industrial production are to meet household consumption demand. Industrial sectors provide goods and services for residents by consuming energy and generating carbon emissions. Therefore, it is significant to explore how household consumption drives the industrial sector to generate carbon emissions, as well as how to mitigate household carbon emissions from the industry perspective.

In recent times, decomposition analysis methods have been applied to analyze the impact factors affecting energy use or carbon emissions. Index decomposition analysis (IDA) and structural decomposition analysis (SDA) are the most popular methods [38]. Compared with IDA, SDA is a

better option to decompose and compare the effects of different impact factors on carbon footprints. Extensive studies used SDA to uncover the driving forces for historic changes in carbon footprints at the national level [39–43], the regional level [44–46], and the city level [47–49]. However, few studies focused on the impact factors of increasing urban household carbon footprints in China. It is necessary to initiate such research so that the effects of different impact factors on carbon footprints from urban households can be presented. In addition, the same driving forces may have different effects at the holistic, sectoral, and sub-sectoral levels [46]. Therefore, we should focus on not only the impact factors of the total carbon footprints but also the effects of driving forces on industrial sectors.

According to the above-mentioned reviews, this study attempts to estimate the carbon footprints of urban households in China from the industrial sector perspective and identify the driving forces for the changes in carbon footprints. In order to provide a detailed and comprehensive explanation of urban household carbon footprints, we used the detailed 110-sector input-output tables (IOTs) and 68-item consumption expenditure data of China for the years 2002, 2007, and 2012. Based on these data, the IOA model was applied to delineate the patterns of urban household carbon footprints. Additionally, the SDA approach was employed to explore the impact factors influencing the growth of China's urban household carbon footprints from 2002 to 2012. This study is expected to provide decision-makers with extensive valuable information to develop a low-carbon economy from the view of urban household consumption.

2. Methods and Data

2.1. Direct Urban Household Carbon Footprints

The direct carbon footprints of urban households refer to the carbon emissions caused by direct consumption of energy in domestic activities, such as cooking, heating, cooling, and mobility. Direct urban household carbon footprints can be calculated by Equation (1):

$$DCF = DCF_i + DCF_e + DCF_h = \sum_{i=1}^n M_i \times EF_i + M_e \times EF_e + M_h \times EF_h \quad (1)$$

here, DCF is the total direct carbon footprint of urban households. DCF_i is the carbon footprint caused by direct consumption of fuel type i . DCF_e is the carbon footprint from direct consumption of electricity. DCF_h is the carbon footprint from direct consumption of heat. M_i , M_e , and M_h are direct consumption of fuel type i , electricity, and heat of urban households, respectively. EF_i , EF_e , and EF_h are carbon emission coefficient of fuel type i , electricity and heat of urban households, respectively. The carbon emission coefficient of fuel type i can be calculated by Equation (2) [32]:

$$EF_i = 44/12 \times LCV_i \times C_i \times O_i \quad (2)$$

here LCV_i denotes the average low calorific value of fuel type i . C_i represents the default carbon content of fuel type i . O_i refers to the default carbon oxidation factor of fuel type i and $44/12$ means the ratio of molecular weights of carbon dioxide and carbon. The carbon emission coefficient of electricity can be estimated as follows:

$$EF_e = \frac{\sum_{j=1}^4 \sum_{i=1}^n N_{ij} \times EF_i}{P} \quad (3)$$

here, N_{ij} is the consumption of fuel type i by power plants j (including thermal power, hydropower, nuclear power, and wind power plants). EF_i refers to the carbon emission coefficient of fuel type i , and P is the total annual power generation. The carbon emission coefficient for heat can be estimated as follows:

$$EF_h = \frac{\sum_{i=1}^n M_i \times EF_i}{Q} \quad (4)$$

here, M_i is the consumption of fuel type i by heat. EF_i refers to the carbon emission coefficient of fuel type i , and Q is the total annual heat generation.

2.2. Indirect Urban Household Carbon Footprints

The indirect carbon footprints of urban households refer to the carbon emissions embodied in the production of goods and services purchased by urban households, such as food, clothes, and home appliances. Indirect urban household carbon footprints are calculated with the input–output analysis [16,23,31,50,51], which is a normally accepted method to quantify sectoral CO₂ emissions under full consideration of the supply chain. Indirect carbon footprints of urban households can be calculated by Equation (5):

$$ICF = F(I - A)^{-1}Y \quad (5)$$

here, ICF denotes the row vector of sectoral indirect carbon footprints of urban households. F is the row vector of sectoral direct carbon emission intensity, whose elements (F_j) equal the carbon emissions per unit gross output from industrial sector j . To obtain the sectoral emission intensity, the sectoral carbon emissions were divided by the total output of the corresponding industrial sectors. I is an identity matrix. A is the direct intermediate coefficient matrix showing the monetary relationship between sectors in the economy system (the technology). $(I - A)^{-1}$ is the Leontief inverse matrix. Y refers to the diagonal matrix converted from the column vectors of sectoral consumption expenditure of urban households. We replaced the final demand of urban households with the consumption expenditure of urban households. However, the classifications of industrial sectors (110 sectors) and consumption activities (68 items) mismatched with each other. Based on our previous research [26], we established linkages between consumption activities and industrial sectors. As we were concerned with urban households only, the consumption expenditure of 74 industrial sectors associated with urban household consumption was assigned. The values of the other sectoral consumption expenditure are zero. The relationships between the expenditure of consumption activity t (E_t) and the expenditure of industrial sector j (E_j) can be summarized as follows:

Case A: One-to-one correspondence between consumption activities and industrial sectors (see Table S1 in Supplementary Materials). In this case, we considered that the expenditure of each consumption activity was equal to the expenditure of the corresponding industrial sector caused by urban households.

Case B: Many-to-one correspondence between consumption activities and industrial sectors (see Table S2 in Supplementary Materials). In this case, the sum of the expenditure of consumption activities was equal to the sectoral consumption expenditure caused by urban households.

Case C: One-to-many correspondence between consumption activities and industrial sectors (see Table S3 in Supplementary Materials). In this case, the expenditure of the industrial sector was proportionally assigned. We supposed that there were p ($p > 1$) sectors corresponding to activity t and the expenditure of industrial sector j can be estimated as follows:

$$E_j = \omega_j \times E_t \quad (6)$$

$$\omega_j = c_j / \sum_1^p c_j \quad (7)$$

where c_j is the urban household final demand of sector j in input-output tables, and $c_j / \sum_1^p c_j$, which is the multiplier ω_j in this paper, refers to the ratio of the urban household final demand of sector j against the subtotal urban household final demand of p sectors related to consumption activity t .

Case D: Many-to-many correspondence between consumption activities and industrial sectors (see Table S4 in Supplementary Materials). In this case, we calculated the sum of the expenditure of consumption activities, and then proportionally assigned the total amount to get the sectoral consumption expenditure.

2.3. Structural Decomposition A(SDA)

The impact factors influencing the increasing urban household indirect carbon footprints were analyzed by SDA. As shown in Equation (5), the indirect urban household carbon footprints can be decomposed into three driving forces: Emission intensity F , intermediate demand L ($L = (I - A)^{-1}$), and the urban household consumption expenditure Y . For deeper study, we further broke urban household consumption expenditure Y into consumption structure S , per capita consumption volume V and urban population P . Hence, the indirect urban household carbon footprints can be expressed as $ICF = F \times L \times S \times V \times P$. The change in ICF from base period 0 to target period t can be decomposed into the sum of contributions of driving forces, shown as Equation (8):

$$\begin{aligned}\Delta ICF &= \Delta ICF_t - \Delta ICF_0 \\ &= F_t \times L_t \times S_t \times V_t \times P_t - F_0 \times L_0 \times S_0 \times V_0 \times P_0 \\ &= f(\Delta F) + f(\Delta L) + f(\Delta S) + f(\Delta V) + f(\Delta P)\end{aligned}\quad (8)$$

here, $\Delta F, \Delta L, \Delta S, \Delta V$ and ΔP represent the changes of each driving force, respectively, and $f(\Delta F)$, $f(\Delta L)$, $f(\Delta S)$, $f(\Delta V)$, and $f(\Delta P)$ represent the carbon emission changes triggered by each driving force with all other forces remaining constant, respectively. Using the pole decomposed method [52], the contribution of each driving force to carbon emission changes can be illustrated as below:

The emission intensity effect:

$$f(\Delta F) = \frac{1}{2} \Delta F \times L_0 \times S_0 \times V_0 \times P_0 + \frac{1}{2} \Delta F \times L_t \times S_t \times V_t \times P_t \quad (9)$$

The intermediate demand effect:

$$f(\Delta L) = \frac{1}{2} F_t \times \Delta L \times S_0 \times V_0 \times P_0 + \frac{1}{2} F_0 \times \Delta L \times S_t \times V_t \times P_t \quad (10)$$

The consumption structure effect:

$$f(\Delta S) = \frac{1}{2} F_t \times L_t \times \Delta S \times V_0 \times P_0 + \frac{1}{2} F_0 \times L_0 \times \Delta S \times V_t \times P_t \quad (11)$$

The consumption level effect:

$$f(\Delta V) = \frac{1}{2} F_t \times L_t \times S_t \times \Delta V \times P_0 + \frac{1}{2} F_0 \times L_0 \times S_0 \times \Delta V \times P_t \quad (12)$$

The population size effect:

$$f(\Delta P) = \frac{1}{2} F_t \times L_t \times S_t \times V_t \times \Delta P + \frac{1}{2} F_0 \times L_0 \times S_0 \times V_0 \times \Delta P \quad (13)$$

2.4. Data Sources

The detailed input–output tables (IOTs) for 2002 with 122 sectors, 2007 with 135 sectors and 2012 with 139 sectors in current prices were obtained from the National Bureau of Statistics of China (NBSC) [53]. To make results comparable, all these IOTs have been aggregated into a unified classification with 110 sectors in 2007 price by using the double deflation method [54].

The data on the energy use of urban households and industrial sectors were extracted from the China Energy Statistical Yearbook [55]. The default carbon content and default carbon oxidation factor were extracted from IPCC guidelines [32], and the average low calorific value could be found in China Energy Statistical Yearbook. The sectoral carbon emissions were calculated by multiplying the energy use of industrial sectors by emission coefficients. The sectoral emissions datasets were primarily in a 44-sector format. We disaggregated data in the 44-sector format into a 110-sector format based on the

input-output tables and assumed that all industrial sectors mapping to one energy sector have the same emission intensity [31,56,57].

China's Urban Life and Price Yearbook (CULPY) provided detailed consumption expenditure data listing 68 consumption items. Unfortunately, CULPY was unavailable after the year 2011. However, China Statistical Yearbooks provided 38 consumption items, which were the aggregation of 68 consumption items. In order to preserve as much detailed as possible, the CULPY [58] was selected in our study and the data in 2012 was adjusted as follows: We assumed that the consumption structure in 2012 was the same as that in 2011, then, we distributed the data in China Statistical Yearbooks (2012) proportionally for detailed 68 consumption items. The values of consumption expenditure were converted into 2007 constant prices by consumer price indices [59].

3. Results

3.1. Characteristics of Urban Household Carbon Footprints

3.1.1. Total Urban Household Carbon Footprints

Figure 1 showed that the total carbon footprints of China's urban households were 941.37 MtCO₂, 1498.11 MtCO₂ and 2139.50 MtCO₂ in 2002, 2007, and 2012, respectively. It indicated that the total carbon footprints rose by 127.28% from 2002 to 2012. The direct urban household carbon footprints were 245.70 MtCO₂, 398.32 MtCO₂ and 585.63 MtCO₂, respectively, in 2002, 2007, and 2012, and the indirect urban household carbon footprints were 695.67 MtCO₂, 1099.79 MtCO₂ and 1553.87 MtCO₂. Even though the direct carbon footprints of urban households continued to go up every year, they still trailed far behind the indirect carbon footprints, which was an average of approximately 2.75 times higher than the direct ones. It signified that indirect carbon footprints played a primary role in the total urban household carbon footprints in China, and the concentrated mitigation should be facilitated on the indirect carbon footprints.

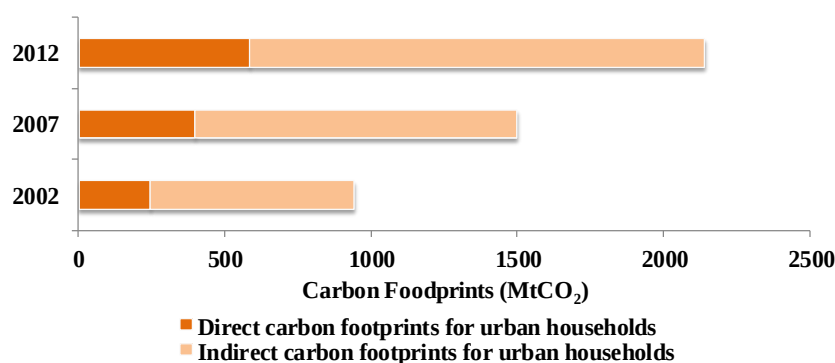


Figure 1. Total carbon footprints of urban households for 2002, 2007, and 2012 in China.

3.1.2. Direct Urban Household Carbon Footprints

Figure 2 indicated the direct urban household carbon footprints in 2002, 2007, and 2012, while Figure 3 depicted the corresponding components in 2002, 2007, and 2012. With regard to energy consumption structure, raw coal, gasoline, diesel oil, LPG, natural gas, heat, and electricity were the main energy sources accounting for about 90% of direct urban household carbon footprints. It was clear that electricity was the main contributor to the direct urban household carbon footprints, accounting for over 40%. The carbon emissions from electricity increased from 100.32 MtCO₂ in 2002 to 274.56 MtCO₂ in 2012. The carbon emissions of heat increased around three times from 28.14 MtCO₂ to 112.36 MtCO₂ during the ten years. Such rapid growth was mainly caused by the expanded areas of central heating, which has become the main mode of heating in cities. From 2002 to 2012, the use of raw coal decreased by 43.44%, and the proportion of direct carbon footprints declined from 16.33% to

3.88%. While the use of natural gas grew significantly by 461.94% and became the third emitter in 2012, accounting for 10.72% of the total direct carbon footprints. In addition, the carbon emissions of gasoline and diesel oil in 2012 were more than 10 times as much as in 2002 (from 5.46 MtCO₂ to 55.51 MtCO₂ together), which mainly caused by dramatic demand of gasoline and diesel oil meeting the demand of growing vehicles.

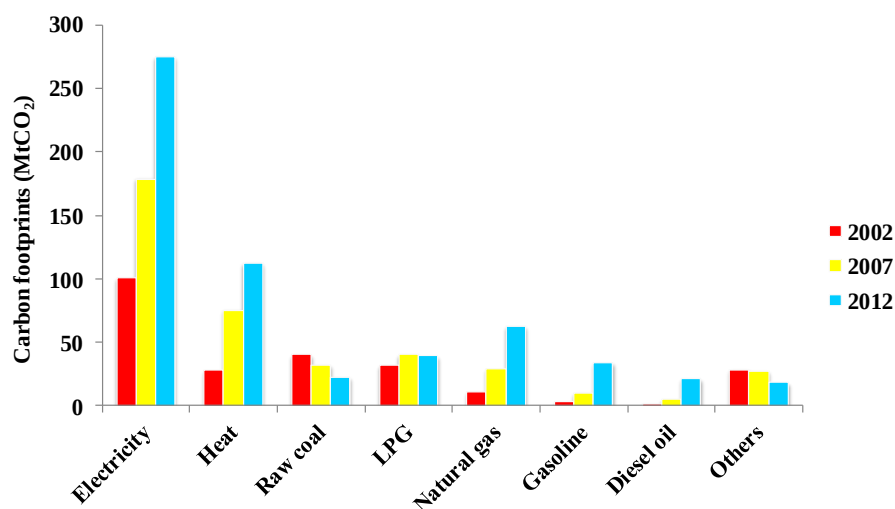


Figure 2. Direct carbon footprints of urban households for 2002, 2007, and 2012 in China.

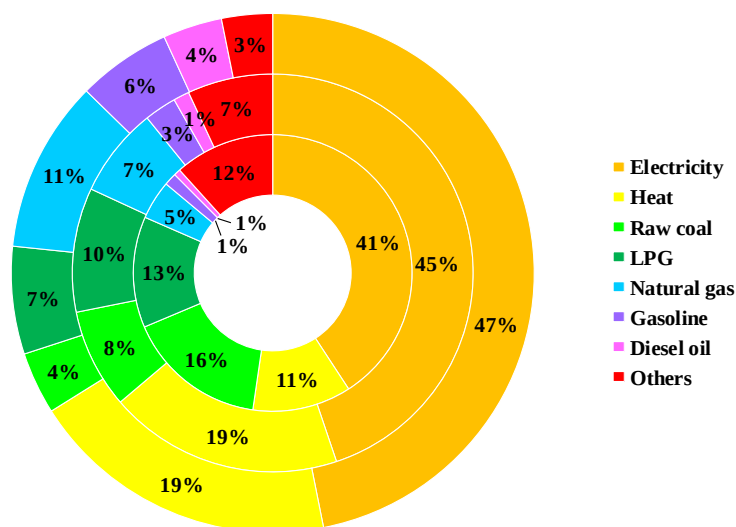


Figure 3. Components of direct carbon footprints from urban households for 2002, 2007, and 2012 in China (from the inside to the outside).

3.1.3. Indirect Urban Household Carbon Footprints

Figure 4 shows the indirect urban household carbon footprints in 2002, 2007, and 2012, while Figure 5 depicts the corresponding components in 2002, 2007, and 2012. To further analyze the amount and proportion of sectoral carbon emissions, the 74 industrial sectors were aggregated into 10 categories (see Table S5 in Supplementary Materials). The carbon footprints of “food” increased from 202.88 MtCO₂ in 2002 to 277.28 MtCO₂ in 2012. However, the component of “food” decreased from 29% to 18% during 2002–2012. The carbon footprints for “household facilities” were 125.79 MtCO₂, 219.55 MtCO₂ and 306.00 MtCO₂ in 2002, 2007 and 2012, respectively. Meanwhile, “household facilities” had the biggest increment with 180.21 MtCO₂ from 2002 to 2012. The carbon footprints of

“transportation” increased from 36.23 MtCO₂ to 179.37 MtCO₂, and the component increased from 5% to 12% from 2002 to 2012. The growth rate of “transportation” was put ahead of other categories with over 395%, followed by “information and communication” with 329%. The carbon footprint of “education” increased 14.77 MtCO₂ in 2002–2007 while declined 7.47 MtCO₂ in 2007–2012, making “education” the only category with a downward trend in all periods.

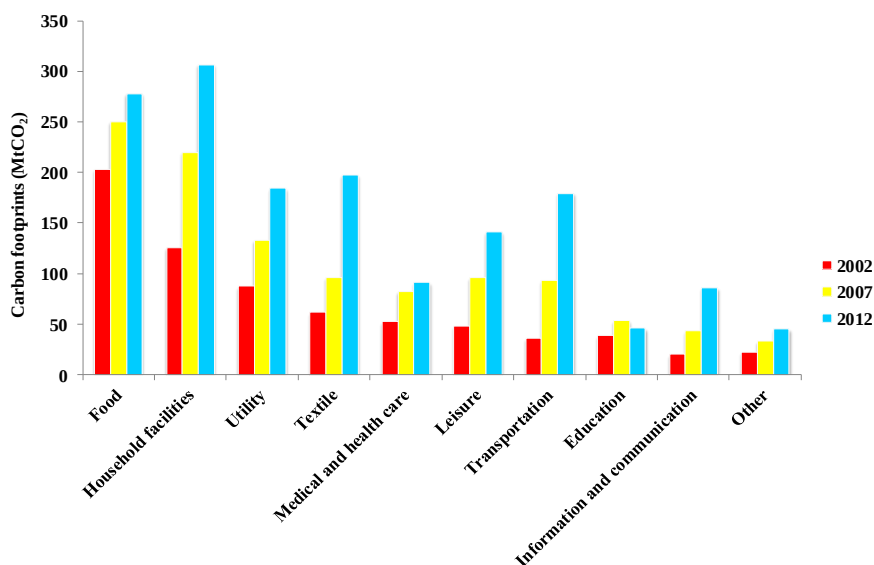


Figure 4. Indirect carbon footprints of urban households for 2002, 2007, and 2012 in China.

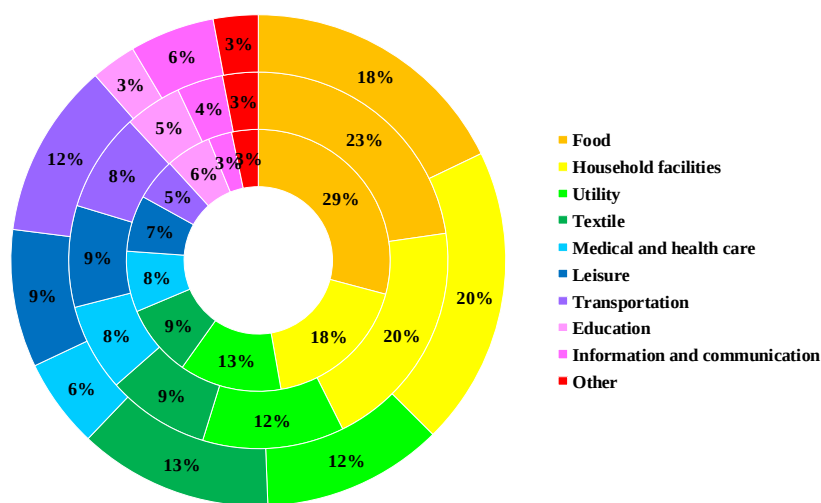


Figure 5. Components of indirect carbon footprints from urban households for 2002, 2007, and 2012 in China (from the inside to the outside).

Regarding the industrial sectors, the top 10 sectors that shaped the indirect carbon footprints by urban households in 2002, 2007, and 2012 are listed in Table 1. The sector that yielded the highest carbon emissions in 2002 was “all other food manufacturing” (48.91 MtCO₂), and that was very close to the tenth sector of “travel agency, tour operator, and tourist guide services” in 2012. The carbon emissions from “wearing apparel” topped the ranking in 2007 and 2012. Especially in 2012, the carbon emissions of “wearing apparel” were 179.34 MtCO₂ which were a quarter of the total indirect carbon footprints in 2002. This implied that the reduction of carbon emissions from “wearing apparel” has become a key point. The sector of “motor vehicles” was the second largest contributor (106.15 MtCO₂) to high indirect carbon footprints in 2012 illustrating the large demand for vehicles in urban households.

The “electricity, steam and hot water production and supply”, as the main energy provider, had a high level of carbon emissions in three years, and the trend was expected to continue in the future due to the increasing demand of electricity and heat. The high level of carbon emissions in “medical and pharmaceutical products” demonstrated a large demand for medicine and great health concerns in urban households. Nevertheless, the emissions from “medical and pharmaceutical products” did not rise rapidly along with the population booming in cities. Especially, the emissions of “medical and pharmaceutical products” in 2012 showed slightly lower than that of 2007. Given that the consumption of medicine still presented an upward trend, the effective way to reduce the carbon emissions of “medical and pharmaceutical products” would depend on the lower emission intensity of medicine by technology promotion.

Table 1. Top ten commodity sectors with highest carbon footprints for 2002, 2007, and 2012.

Rank.	2002		2007		2012	
	Commodity Sectors	Carbon Footprints (Mt CO ₂)	Commodity Sectors	Carbon Footprints (Mt CO ₂)	Commodity Sectors	Carbon Footprints (Mt CO ₂)
1	All other food manufacturing	48.91	Wearing apparel	86.72	Wearing apparel	179.34
2	Electricity, steam and hot water production and supply	45.77	Electricity, steam, and hot water production and supply	67.17	Motor vehicles	106.15
3	Animal Husbandry	43.36	Food and beverage services	60.94	Electricity, steam and hot water production and supply	88.16
4	Medical and pharmaceutical products	40.08	Medical and pharmaceutical products	55.52	Food and beverage services	68.11
5	Wearing apparel	39.42	All other food manufacturing	54.30	All other food manufacturing	58.25
6	Food and beverage services	35.43	Agriculture	45.09	Culture goods and other recreation products	57.61
7	Educational services	31.24	Motor vehicles	44.59	Medical and pharmaceutical products	55.36
8	Agriculture	30.19	Culture goods and other recreation products	41.92	Agriculture	52.19
9	Grain mill products	22.63	Educational services	39.20	Chemical products for daily use	50.27
10	Culture goods and other recreation products	20.65	Leather, fur, down and related products	37.88	Travel agency, tour operator and tourist guide services	48.83

Table 2 ranks 10 sectors with the largest increments in indirect carbon footprints between 2012 and 2002. It was clear that the most remarkable increase in indirect carbon footprints was 139.92 MtCO₂ from “wearing apparel”. The main reason was the largest rise in per capita consumption expenditure on such sector by urban households, from 291.75 CNY in 2002 to 1581.66 CNY in 2012. The large carbon emission increases in “motor vehicles” (99.34 MtCO₂) caused by the large demand for motor vehicles in the past ten years. Meanwhile, the products related with “motor vehicles”, such as “road transport” and “petroleum processing”, also presented a large growth. The increase of carbon emissions of “travel agency, tour operator and tourist guide services” (43.18 MtCO₂) and “culture goods and other recreation products” (36.96 MtCO₂) indicated the change of lifestyle of China’s urban households. They preferred to spend more money on leisure and recreation to satisfy their pursuit of spiritual civilization. The increase in carbon emissions from the “telecommunication equipment” following the consumption in urban households had increased by an astonishing 15 times over the past ten years.

Of this, the growth in the mobile telephone was obvious, for it has risen from 62.89 per 100 urban households to 212.64 between 2002 and 2012. The growth rate of mobile phones was very fast because of the rapid development of technology. Thus, urban households should consider the pressures on the environment while enjoying the quality of life brought about by science and technology.

Table 2. Largest differences in indirect carbon footprints.

Rank.	Commodity Sectors	Difference (MtCO ₂)	Percentage (%)
1	Wearing apparel	139.92	355.00%
2	Motor vehicles	99.34	1459.00%
3	Travel agency, tour operator and tourist guide services	43.18	764.89%
4	Electricity, steam and hot water production and supply	42.38	92.60%
5	Petroleum processing	42.36	953.39%
6	Chemical products for daily use	42.19	521.80%
7	Culture goods and other recreation products	36.96	178.98%
8	Slaughtering and meat processing	36.13	389.61%
9	Telecommunication equipment	33.32	805.32%
10	Road transport	32.91	312.74%

3.2. Structural Decomposition Analysis of Increasing Indirect Carbon Footprints of Urban Households

Table 3 lists the effects of various impact factors on the growth of indirect carbon footprints and their contributions to the indirect carbon footprints increment of urban households in China during the periods of 2002–2007, 2007–2012, and 2002–2012. As shown in Table 3, the total indirect carbon footprints increased by 404.12 MtCO₂, 454.09 MtCO₂ and 858.21 MtCO₂ during 2002–2007, 2007–2012, and 2002–2012, respectively. There were four impact factors presenting a positive effect on the growth of indirect carbon footprints during 2002–2012, and the order of the factors contributing to increasing indirect carbon footprints was: Consumption level (859.97 MtCO₂) > population size (374.15 MtCO₂) > consumption structure (193.15 MtCO₂) > intermediate demand (13.91 MtCO₂). This implied that consumption level played a dominant role in the growth of indirect carbon footprints of urban households in China, and its contribution to the carbon footprints increment was up to 100.21%. Meanwhile, the impact factor of emission intensity (−582.98 MtCO₂) had a great negative impact on the increment in carbon footprint in 2002–2012, and its contribution was −67.93%. Therefore, the emission intensity of goods and services should be further lowered to mitigate carbon footprints from urban households in China.

Table 3. Structural decomposition analysis of various impact factors in China's urban households (2002–2012).

Impact Factors.	Carbon footprints Increment (Mt CO ₂)			Contribution (%)		
	2002–2007	2007–2012	2002–2012	2002–2007	2007–2012	2002–2012
Emission intensity	−257.78	−243.71	−582.98	−63.79	−53.67	−67.93
Intermediate demand	91.46	−98.43	13.91	22.63	−21.68	1.62
Consumption structure	66.91	68.4	193.15	16.56	15.06	22.51
Consumption level	336.83	517.02	859.97	83.35	113.86	100.21
Population size	166.7	210.81	374.15	41.25	46.42	43.60
Total effect	404.12	454.09	858.20	100.00	100.00	100.00

Between 2002–2007 and 2007–2012, the consumption level, consumption structure, and population size showed rising trends with consumption level impacting the increment of carbon footprints the most. It increased the carbon footprints by 336.83 MtCO₂ in 2002–2007 and 517.02 MtCO₂ in 2007–2012, and its contribution increased from 83.35% to 113.86%, respectively, for those periods. The emission intensity exhibited a negative effect on carbon footprints. It decreased carbon emissions from 257.78 MtCO₂ in 2002–2007 to 243.71 MtCO₂ in 2007–2012, and their contribution has declined from −63.79%

to -53.67% , respectively, for those periods. This showed that the emission intensity was still the main factor in carbon reduction of China's urban households, although its effect on the carbon footprints decrement declined slightly. The impact factor of intermediate demand increased carbon footprints in 2002–2007 (91.46 MtCO_2), whereas it decreased carbon footprints in 2007–2012 (-98.43 MtCO_2). It implied that the effect of intermediate demand had transformed from carbon emissions accumulation to carbon emissions reduction during the past decade. The reason for this change was mainly due to the transitions in intermediate demand based on industrial restructuring and technological advance. Therefore, accelerating technological progress and innovation, as well as promoting industrial structure optimization and upgrading, will play an important role in emission reduction in the future.

The impact factors of each category from 2002 to 2012 are shown in Figure 6. It was obvious that all the categories had positive contributions to the increased carbon footprints, but the impact factors had different effects on the categories. From 2002 to 2012, emission intensity decreased carbon footprints, while consumption level and population size increased carbon footprints in all categories. However, the contributions of intermediate demand and consumption structure were significantly different. The intermediate demand increased carbon footprints for “food”, “utility”, “medical and health” and “leisure”, while consumption structure increased carbon footprints for “textile”, “household facilities”, “transportation”, “leisure” and “communication”. At the same time, the contribution of various impact factors to the carbon footprints in the categories is different as well. The consumption level contributed the most to carbon emission increases in most categories except for “transportation” and “communication”, and the greatest contribution of consumption level was 217.62 MtCO_2 on “food”. The emission intensity had a mainly negative impact on the reduction of carbon emissions of most categories in addition to “food” and “education”, and the greatest contribution of emission intensity effect was -129.93 MtCO_2 on “food”. The consumption structure played a dominant role in adding carbon emissions in “transportation” and “information and communication” with the value of 108.59 MtCO_2 and 50.91 MtCO_2 , respectively. Meanwhile, it had the greatest inhibitory impact on carbon emissions in “food” and “education” with the value of -134.17 MtCO_2 and -24.39 MtCO_2 , respectively.

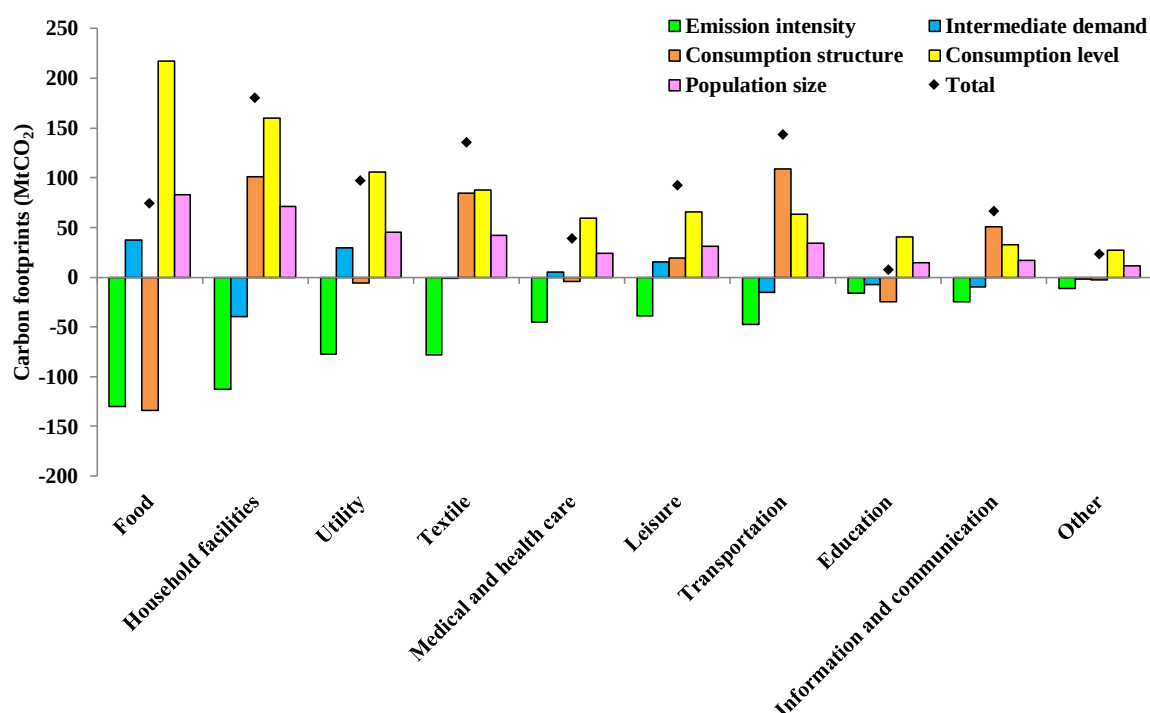


Figure 6. Structure decomposition analysis of consumption categories in China from 2002 to 2012.

As mentioned in Section 3.1.3, the carbon footprints from ten industrial sectors had the greatest contribution to the growth of carbon footprints from 2002 to 2012. Thus, it is necessary to further decomposed the carbon footprint increment in these sectors. In contrast to consumption categories, the increment of carbon emissions of these sectors mostly contributed by consumption structure, in addition to “electricity, steam and hot water production and supply”, “culture goods and other recreation products” and “road transport”, the main positive impact of which was consumption level and responsible for 53.93 MtCO₂, 27.69 MtCO₂, and 16.77 MtCO₂, respectively (see in Figure 7). The greatest contribution of consumption structure was 109.16 MtCO₂ in “wearing apparel”, followed by 107.42 MtCO₂ in “motor vehicles” and 47.64 MtCO₂ in “telecommunication equipment”. The only one negative effect of consumption structure was presented in “electricity, steam and hot water production and supply” with −7.67 MtCO₂. Similar to the consumption categories, the reduction in carbon emissions of these sectors mostly contributed by emission intensity except for “telecommunication equipment”, the main negative impacts of which was intermediate demand and responsible for −19.26 MtCO₂. The greatest contribution of emission intensity was −67.70 MtCO₂ in “wearing apparel”, followed by −44.83 MtCO₂ in “electricity, steam and hot water production and supply” and −33.40 MtCO₂ in “motor vehicles”.

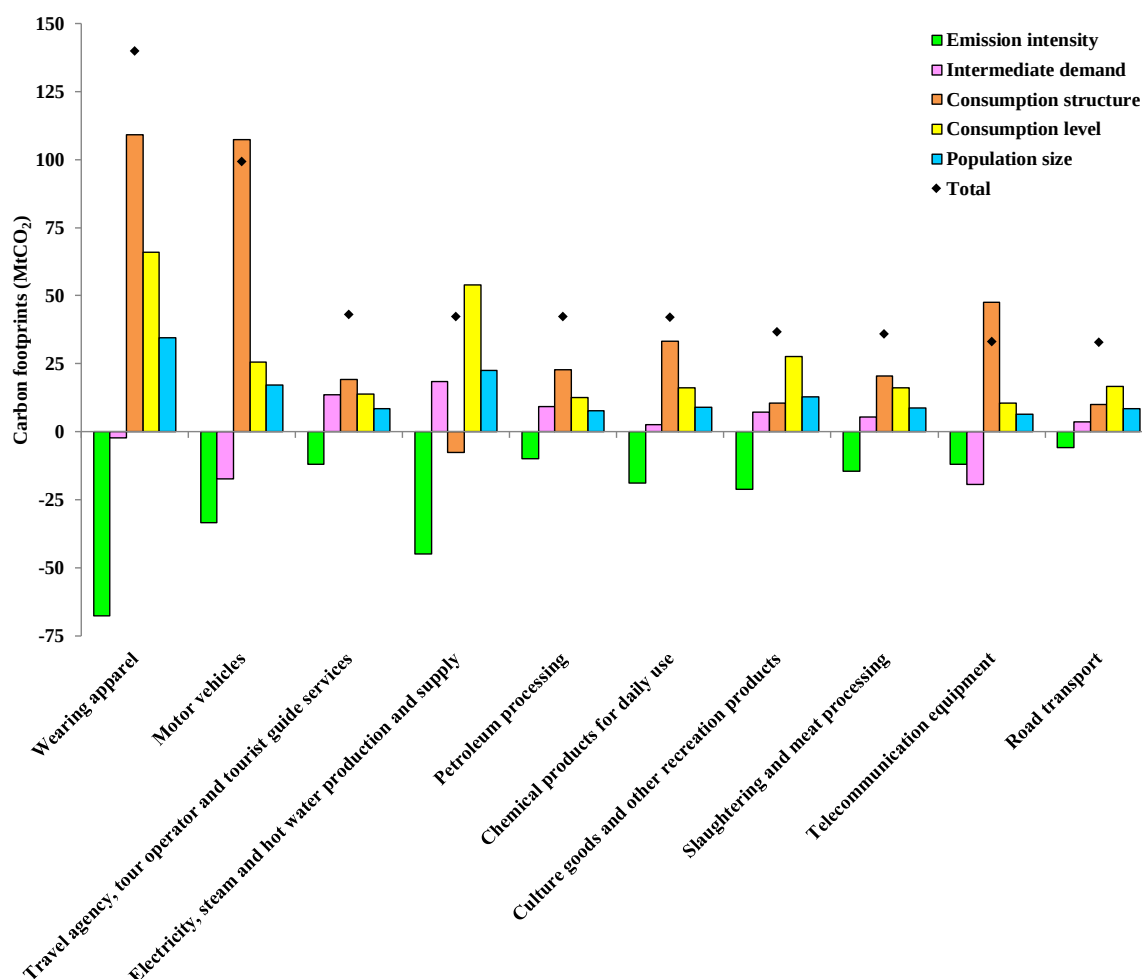


Figure 7. Structure decomposition analysis of ten industrial sectors in China from 2002 to 2012.

4. Discussion

4.1. The Growth of Direct Carbon Footprints of Urban Households and Mitigation Policies

The growth of direct carbon footprints of urban households stemmed from the increased direct energy consumption caused by the high living standards of urban households. For example, the urban households' consumption of electricity increased by 204.49% from 2002 to 2012. Such a phenomenon was mainly due to the increment of the use of household appliances. Statistically, the number of household appliances (such as televisions, refrigerators, air conditions, washing machines, and computers) per 100 urban households in 2012 was 1.8 times that of 2002. Particularly, the number of household appliances with high power in 2012, such as air conditioners, was 2.4 times that of 2002. Similar to electricity, the growing use of gasoline and diesel oil was mainly because of the dramatic increase in the number of vehicles. According to the official statistics, the number of vehicles per 100 urban households rose from 0.88 to 21.54 in 2002–2012. With the increasing income of urban residents, the number of vehicles will continue to rise, as well as the energy consumption.

Therefore, the reduction of direct carbon footprints of urban households can be summarized from the three aspects. Firstly, energy conservation is an effective way to reduce carbon footprints, especially for the use of electricity which played the main role in the direct carbon footprints of urban households. Secondly, shifting the energy consumption structure of urban households is another useful method. The evidence from 2002–2012 has demonstrated that the energy consumption structure of urban households had been gradually changed from highly contaminating energy sources (such as raw coal) to clean energy sources (such as natural gas). Thirdly, the technological progress is expected to play a decisive role in carbon emission reduction in the future. In recent years, electric vehicles, as one of the clean technology alternatives, have drawn widespread attention in the Chinese society because of their higher energy efficiency and lower air pollutant emissions. However, due to immature technology and limited charging facilities, they have not yet been vigorously promoted. With technological breakthroughs and support policies, the use of electric vehicles would have a broad prospect with regard to energy conservation and carbon emission reduction.

4.2. The Growth of Indirect Carbon Footprints of Urban Households

Based on the results of indirect carbon footprints of urban households, there are some interesting findings that need further discussion.

Firstly, with the rapid growth of income level and living standards, urban households concentrate on other types of consumption instead of food. In 2002 and 2007, the category of “food” was the main contributor to indirect carbon footprints of urban households. However, “food” was outclassed by “household facilities” in 2012. From the perspective of industrial sectors, the first rank of indirect carbon footprints transformed from “all other food manufacturing” in 2002 to “wearing apparel” in 2007 and 2012. Moreover, the carbon footprints of sectors related to high-quality living, such as “travel agency, tour operator and tourist guide services” and “motor vehicles” played an important role in 2012. However, the amount of carbon footprints in the industrial sectors related to diet was reasonably remarkable, such as “food and beverage services”, “agriculture”, and “all other food manufacturing” (as shown in Table 1). This indicated that the carbon footprints of diet were still important for urban households.

Secondly, the carbon footprints of “transportation” and “information and communication” would have a growth trend in the future. The amazing growth rate of “transportation” and “information and communication” can be attributed to the development of related industry, which has influenced the transformation of spending propensities in urban household consumption expenditures. The per capita consumption expenditure of “transportation” increased from 227.04 CNY to 1196.39 CNY during 2002–2012, and the component rose from 3.32% to 8.13%. Similar to “transportation”, the per capita consumption expenditure of “information and communication” increased from 307.03 CNY to 1082.62 CNY during 2002–2012, and the component rose from 4.48% to 7.36%. Since China, as the largest

developing country, is experiencing a new round of urbanization, the demand for “transportation” and “information and communication” seems to continue to increase, so it is important for the government and corporate sectors to prioritize the development of technological improvements to cut down emissions.

Finally, the decline in indirect carbon footprints of “education” was due to the development of technology. The carbon footprint of “education” increased 14.77 MtCO₂ in 2002–2007 while declined 7.47 MtCO₂ in 2007–2012. Of this, the decline in carbon footprints from the industrial sectors of “paper and paper products” and “printing, reproduction of recording media” were the most significant, which mainly focused on the products and services related to paper and prints. With the booming development of the Internet, the demand for paper and prints is offset by electronic documents. Meanwhile, online education and paperless office are widely popular with urban households. In other words, scientific and technological progress have been embodied in carbon emission reduction.

4.3. The Way to Reduce Indirect Carbon Footprints of Urban Households

From the SDA, we knew that consumption level and population size had a greatly positive contribution to the increment in indirect carbon footprints. However, in the current situation, it is difficult for us to reduce carbon footprints from these two aspects. On the one hand, the increase of income raised the living standard and made the consumption expenditures increase year by year. The per capita consumption expenditure of urban households was 6846.54 CNY in 2002, while it increased 114.96% to 14717.35 CNY in 2012. At the same time, promoting consumption was one of the most important means for the government to stimulate economic growth. On the other hand, urbanization has greatly increased the urban population over the past ten years, from 502.12 million in 2002 to 711.82 million in 2012. With the promoting urbanization of the rural population and the universal implementation of the second-child policy, the urban population would have a stable rising trend in the near future. Therefore, the consumption level and population size would continue to push up the urban household carbon footprints for a long time. That is to say, the effective mitigation efforts should focus on emission intensity, consumption structure, and intermediate demand.

First of all, reducing emission intensity was helpful to reduce the carbon footprints of urban households in China. It had a negative effect on increasing carbon footprints in all household lifestyle and industrial sectors during the ten years. In the future, measures of reducing emission intensity, such as improving energy efficiency, shifting energy structure and developing clean energy will remain the key points of emission reduction. In particular, these actions should be taken in high-intensity categories (such as utility and transportation) and industrial sectors (such as chemical products for daily use and electricity, steam, and hot water production and supply).

In addition, changing consumption structure also contributed to mitigating carbon footprints of urban households. The contribution of consumption structure to increasing carbon footprints was 16.56% during 2002–2007, while it slightly decreased to 15.06% during 2007–2012. The changes in consumption structure of five categories, including “food”, “utility”, “medical and health care”, “education”, and “other”, had a negative effect on carbon footprints. The negative effect on these categories was due to the decreasing proportion of the total consumption expenditures from 2002 to 2012. The same phenomenon could also be found among industrial sectors. Therefore, urban households should reduce the consumption proportion of high-intensity goods and transform consumption behaviors to low-intensity products.

Last but not least, intermediate demand presented a fluctuant effect on carbon footprints between 2002–2007 (91.46 MtCO₂) and 2007–2012 (−98.43 MtCO₂), indicating that there is likely to be a large potential to reduce China’s urban household carbon footprints by changing intermediate demand. As shown in Figure 6, six consumption categories, including “household facilities”, “textile”, “transportation”, “education”, “information and communication”, and “other”, had a negative effect on urban household carbon footprints in terms of changes in intermediated demand. And the carbon emissions of industrial sectors, such as “wearing apparel”, “motor vehicles” and “telecommunication

equipment”, decreased because of changing intermediate demand as well. It means that technical improvements played a role in emission reduction in these sectors. Therefore, it is important for the government to formulate policies aimed at encouraging technical improvement. In addition, corporate sectors should make rational use of new technologies to develop low-intensity products.

5. Conclusions

With rapid economic growth and fast urbanization, the carbon footprints of urban households have increased dramatically and have become an important part of the total carbon emissions in China. Under such circumstances, the urban household carbon footprints in 2002, 2007, and 2012 were discussed in this paper. To investigate the key driving forces, the SDA method was applied to explore the effect of five impact factors on the increasing carbon footprints of urban households.

The research results showed that both direct and indirect carbon footprints experienced fast growth during the study period. Electricity was the main source of direct urban carbon footprints, accounting for over 40%. The ratios of heat, natural gas, gasoline, and diesel oil-induced carbon footprints increased while the ratios of raw coal, LPG and others decreased. The indirect carbon footprints accounted for the most in the total carbon footprints and became the focus of emission mitigation. Of this, “food” and “household facilities” contributed mostly to the carbon footprints of urban households, “household facilities” had the biggest increment, “transportation” had the fastest growth rate. From the view of industrial sectors, “wearing apparel” contributed most in 2007 and 2012 and had the biggest increment from 2002 to 2012. The industrial sectors related to diet had a large amount of carbon footprints, while the industrial sectors related to “transportation” and “information and communication” had a large growth. In terms of impact factors, consumption level, population size, consumption structure, and intermediate demand had a positive effect while emission intensity had a negative effect on the growth of indirect carbon footprints from urban households. From the perspective of categories and industrial sectors, consumption level and population size increased carbon footprints, and emission intensity decreased carbon footprints during 2002–2012, while consumption structure and intermediate demand presented a fluctuant influence on the indirect urban carbon footprints in China. Thus, given that consumption level and population size will increase in the future, the mitigation efforts should focus on reducing emission intensity, shifting consumption structure, and changing intermediate demand.

Still, this study has some limitations. Due to data availability, the latest detailed input–output table was published for 2012. The slow update hinders our understanding of the carbon footprints of urban households in recent years. Once the data are updated, our future work will concentrate on the changes in carbon footprints after 2012. In addition, this study estimated the carbon footprints of urban households at the national level. To be much better for policy interventions, our future work will focus on the variations and distributions of carbon footprints at the geographical level.

Supplementary Materials: The following are available online at <http://www.mdpi.com/2071-1050/11/24/7157/s1>, Table S1: One-to-one correspondence between consumption activities and industrial sectors; Table S2. Many-to-one correspondence between consumption activities and industrial sectors; Table S3. One-to-many correspondence between consumption activities and industrial sectors; Table S4. Many-to-many correspondence between consumption activities and industrial sectors; Table S5. Relationships between 74 industrial sectors and 10 categories.

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