atmosphere

Article

Comparative Study on the Influencing Factors of the Greenhouse Gas Budget in Typical Cities: Case Studies of Beijing and Shenzhen

Kuo Liu [1,2], Shishuai Yang [2], Binbin Huang [2], Chaofan Xian [2], Baolong Han [2], Tian Xie [2], Chengji Shu [2], Zhiwen Chen [2], Haoqi Wang [2], Haijun Wang [3,*] and Fei Lu [2,4,*]

1 School of Ecology and Environmental Sciences, Yunnan University, Kunming 650504, China
2 State Key Laboratory of Urban and Regional Ecology, Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, Beijing 100085, China
3 Institute for Ecological Research and Pollution Control of Plateau Lakes, School of Ecology and Environmental Science, Yunnan University, Kunming 650504, China
4 Beijing-Tianjin-Hebei Urban Megaregion National Observation and Research Station for EcoEnvironmental Change, Beijing 100085, China
* Correspondence: wanghaijun@ynu.edu.cn (H.W.); feilu@rcees.ac.cn (F.L.)

Abstract: Clarifying the pattern of the urban greenhouse gas (GHG) budget and its influencing factors is the basis of promoting urban low-carbon development. This paper takes Beijing and Shenzhen—the capital city and the most rapidly developing city in China, respectively—as case studies, comprehensively accounts their GHG budgets from 2005 to 2020, and investigates and compares the factors affecting their GHG budgets. The total GHG emissions in Beijing were lowest in 2005 (160.3 TgCO_2 equivalents) and peaked at 227.7 TgCO_2 equivalents in 2019, and then decreased to 209.1 TgCO_2 equivalents in 2020. Meanwhile, the total GHG emissions in Shenzhen gradually increased from 36.0 TgCO_2 equivalents in 2005 to 121.4 TgCO_2 equivalents in 2019, and then decreased to 119.1 TgCO_2 equivalents in 2020. The energy activity sector was the greatest contributor to GHG emissions in this period, accounting for 82.5% and 76.0% of the total GHG emissions in Beijing and Shenzhen, respectively. The carbon sink of the ecosystems of these two cities could absorb only small parts of their emissions, and the neutralization rates of sinks ranged from 1.7% to 2.3% in Beijing and from 0.3% to 1.5% in Shenzhen. The enhancement of population, economic product, and consumption increased the greenhouse gas emissions in both cities. A 1% increase in population size, per capita GD (gross domestic product), and residential consumption level would increase total GHG emissions by 0.181%, 0.019%, and 0.030% in Beijing, respectively. The corresponding increases in Shenzhen would be 0.180%, 0.243%, and 0.172%, respectively. The household size had opposite effects on the two cities, i.e., a 1% increase in household size would increase GHG emissions by 0.487% in Shenzhen but reduce them by 2.083% in Beijing. Each 1% increase in secondary industry and energy intensity would reduce GHG emissions by 0.553% and 0.110% in Shenzhen, respectively, which are more significant reductions than those in Beijing.

Keywords: Beijing; Shenzhen; greenhouse gas emissions; carbon sinks; influencing factors

check for updates

Citation: Liu, K.; Yang, S.; Huang, B.; Xian, C.; Han, B.; Xie, T.; Shu, C.; Chen, Z.; Wang, H.; Wang, H.; et al. Comparative Study on the Influencing Factors of the Greenhouse Gas Budget in Typical Cities: Case Studies of Beijing and Shenzhen. *Atmosphere* **2023**, *14*, 1158. https://doi.org/10.3390/atmos14071158

Academic Editor: László Haszpra

Received: 16 April 2023
Revised: 20 June 2023
Accepted: 13 July 2023
Published: 17 July 2023

1. Introduction

1.1. Motivations

The global average temperature increased by 0.8 °C~1.3 °C from 1900 to 2019 [1], and human activities are the main cause of global warming. Significant increases in atmospheric greenhouse gas (GHG) concentrations (especially CO_2, CH_4, and N_2O) since the Industrial Revolution have been considered to be the main cause of global warming. Adaptation to global warming and mitigation of the warming rate are currently the main issues faced in the development of the international community [2,3]. China has proposed to strive to cap its CO_2 emissions by 2030 and to strive to achieve carbon neutrality by 2060. Concurrently, cities have become hotspots for GHG emissions [4]. Urban areas accounted for 61.8% of global greenhouse gas emissions in 2015, and the proportion of urban emissions in overall global GHG emissions will gradually increase in the future, possibly exceeding 80%; this is related to rapid urban economic development and the increasing urban population. It has been further suggested that improving the energy-use efficiency and shifting consumption patterns will help reduce emissions, and slowing the rate of urban expansion and increasing urban green infrastructure will help protect carbon sinks [5]. Moreover, during urbanization, the constructed land area will expand, while the area of natural ecosystems such as forests will simultaneously shrink, resulting in a reduction in urban carbon sinks and an expansion of carbon sources; this change will aggravate the imbalance of urban GHG sinks and sources [6,7]. Therefore, cities are important carriers and key components for reducing greenhouse gas emissions. Establishing a scientific and systematic urban greenhouse gas budget accounting system, clarifying the patterns of urban GHG budgets, and analyzing their influencing factors are the foundation for regulating the urban greenhouse gas budget and promoting low-carbon development in cities.

1.2. Literature Review

Energy consumption has always been the sector with the highest greenhouse gas emissions in urban areas. According to a report released by the International Energy Agency (IEA), Paris, France, China is the world's largest greenhouse gas emitter, accounting for about one-quarter of global emissions, and approximately 85% of China's CO_2 emissions come from urban energy consumption [8]. Energy consumption was reported as accounting for the highest proportion of CO_2 emissions from Chinese cities between 2001 and 2015, ranging from 85.14% to 89.3% [9]. During this period, the GHG emissions from energy consumption increased by 188%. Some studies on the GHG emissions of single cities also indicated that energy consumption accounted for the highest proportion of emissions and had increased continuously in recent decades [10]. In recent years, with the continuous expansion of cities, the implicit GHG emissions caused by intercity power and heat inputs and outputs has drawn broad concern in academic circles. In Bursa, Turkey, the GHG emissions from electricity were found to have reached one-quarter of the total GHG emissions of the city in 2016 [11]. In addition, it was reported that GHG emissions from the external electricity industry had the highest dependency on external power transfers in Beijing and accounted for approximately 19.5% of the city's total emissions [12].

A series of studies focusing on GHG budgets outside the energy sector have also been conducted in recent years. For example, Markolf et al. estimated the GHG emissions of 100 US cities, of which industrial production processes contributed to 18% of total emissions and became the second-highest sector after energy consumption [13]. GHG emissions from the waste sector are also increasing in many countries around the world. For instance, GHG emissions from Mexico's waste sector increased by 180% from 1998 to 2012 [14], while GHG emissions from domestic waste in Tianjin increased by 65.9% from 2013 to 2018 [15]. At the urban level, along with socioeconomic development, cities are more often consumption centers rather than production entities. Therefore, the "hidden" GHG emissions from city commodities and services are enormous. Hachaichi et al. conducted a comparative study of the carbon footprints of 252 cities worldwide, which indicated that food consumption and commodity consumption accounted for approximately 25% and 9% of the total carbon footprint, respectively [16]. Guo studied the household carbon emissions in Beijing and found that durable goods, food, and clothing consumption accounted for 15%, 8%, and 2% of greenhouse gas emissions, respectively [17]. Previous studies have indicated that urban carbon sinks could offset a certain proportion of carbon sources. However, the urbanization process (especially the expansion of constructed area) would reduce both the area and carbon sink of the ecosystem and exacerbate the imbalance of sink and source in the urban area. For example, from 1995 to 2019, the urban area in the Monterrey metropolitan area of Mexico expanded by 2.6 times, and the regional carbon sink decreased by 38.6% [18]. Studies in China have also paid increasing attention to the offsetting or neutralization effect of urban carbon sinks. In 2020, the neutralization rates of green spaces in Beijing, Shenzhen, and Tianjin on total GHG emissions were 0.99%, 0.15%, and 0.84%, respectively. Wang et al. found that the offset rate of CO_2 emissions from fossil fuel consumption through ecological restoration reached 9.9% in Beijing [19].

Currently, the main method for analyzing factors affecting urban GHG emissions is factor decomposition. This method decomposes the GHG emissions into different influencing factors and analyzes the main factors affecting GHG emissions in different types of cities by comparing their contribution values. The models used to study the influencing factors of GHG emissions are mainly the Kaya model, LMDI decomposition model (logarithmic mean Divisia index method), IPAT model (Impact = Population × Affluence × Technology), and STIRPAT model (stochastic impacts by regression on PAT) [20–22]. In 1990, the Japanese scholar Kaya first proposed the Kaya formula, which points out the relationship between CO_2 emissions and carbon emission coefficients, energy intensity, economic development, and population size. Based on this, different scholars have conducted related exploration and research. Ang et al. proposed the LMDI decomposition method, which decomposes the GHG budget into different factors and analyzes the degree to which each factor contributes to the GHG budget [23]. This method solves the problem of residual error and zero value existence in the decomposition results. In 1971, Ehrlich first proposed the IPAT model, which divides the influencing factors into population size, economic development, and technological factors [24]. Due to certain limitations of the IPAT model, Dietz et al. established the STIRPAT model based on the IPAT model in 1997. The STIRPAT model still maintains the original product structure of the IPAT model and still regards population, economy, and technology as determining factors, but it is more flexible and can add, modify, or decompose relevant influencing factors according to the research purposes. Subsequently, this model has been widely used in studies of influencing factor analysis [25].

To date, research on the influencing factors of urban GHG budgets has mainly decomposed changes in GHG emissions into the population scale, urbanization, economic development, energy intensity, and other influencing factors and then analyzed the degree of contribution of each factor to emissions.

Regarding the impact of population factors on the GHG budget, existing studies have focused mainly on the impacts of the urban population and its changes on GHG emissions. For example, in Shanghai, carbon emissions increase by 2.62% for every 1% increase in the permanent population [26]. A total of 23 cities in the Guangdong–Hong Kong–Macao Greater Bay Area and its surrounding areas were taken as the research area for analysis. The results showed that with a sharp increase in the urban population, the total emissions of the 23 cities increased by 43.19% from 2000 to 2016 [27]. Urban expansion leads to the transformation of natural ecosystems into urban ecosystems, and the transformation of ecosystems leads to changes in vegetation and soil carbon pools, affecting the urban GHG budget [28]. Taking Leipzig, Germany, as the research area, the carbon storages corresponding to different urbanization levels were calculated. The study found that the carbon storage of the central area with higher urbanization was lower, while the carbon storages of the areas with lower urbanization were the highest]. Based on an analysis of urbanization and changes in the soil and plant carbon cycles in North America, the soil organic carbon pool in Denver was found to have decreased by approximately 60% in 50 years [29].

Past studies show a close relationship between economic development and the greenhouse gas budget. Based on a dataset of 274 typical cities in the world, the multiple regression method was used to analyze the influencing factors of the urban GHG budget [30]. The results show that economic activities are most closely related to greenhouse gas emissions. A study on the economic development and GHG emissions of seven typical cities in the world, such as New York and London, showed that countries with high GDP per capita have higher greenhouse gas emissions [31]. In a Chinese study, the LMDI decomposition method was used to analyze the factors influencing greenhouse gas emissions from energy consumption in 11 typical Chinese cities, and the findings showed that economic development was the main contributing factor to the increase in CO_2 emissions from urban energy consumption [32]. China's coal-based energy consumption structure is the main factor leading to its substantial growth of greenhouse gas emissions [33]. By analyzing the relationship between GHG emissions and the industrial structure in 30 major cities in China [34], the results showed that the industrial structure is positively correlated with GHG emissions, and with the upgrading and adjustment of the urban industrial structure, the impact of the industrial structure on GHG emissions is decreasing annually. Therefore, adjustment of the industrial structure and energy structure is critical for reducing GHG emissions.

These studies have made great progress in clarifying the pattern of the urban GHG budget and analyzing its influencing factors, thereby providing a basis for promoting urban low-carbon development and regulating the urban greenhouse gas budget. However, existing research on the influencing factors of GHG budgets has been based mostly on individual cities, while there is a lack of comparative research examining different cities to reveal the common laws and differences in GHG budgets among different cities.

This paper selects Beijing and Shenzhen—two low-carbon pilot cities in China—to comprehensively account for their urban greenhouse gas budgets by using the coefficient method, and then analyzes the influencing factors of these typical cities' greenhouse gas budgets from 2005 to 2020 based on the improved STIRPAT (stochastic impacts by regression on population, affluence, and technology) model and the ridge regression method to explore the dynamic patterns, influencing factors, and causes of differences in the two cities' GHG budgets.

2. Methods

2.1. Study Area

Beijing is the capital of China, the political and cultural center of the country, and a world-famous city with a history of over 3000 years. Located in the northern part of the North China Plain, Beijing has a warm, temperate, semi-humid (Table 1), semi-arid monsoon climate [35,36]. Unlike southern cities, Beijing provides all-day heating during winter. Beijing is strategically important in China and, as the capital and the world's first "dual-Olympic" city, it has a good foundation and conditions for green and low-carbon transformation. It is capable of and responsible for playing a leading role in the national dual-carbon action. Shenzhen, located in southern China, has a transitional oceanic climate from subtropical to tropical and abundant wetland resources. Shenzhen is the window and flag of China's reform and opening up, serving as a bridge connecting the inland region and Hong Kong, and was the first city in China to achieve comprehensive urbanization. Unlike Beijing's historical background, Shenzhen is a modern metropolis with more prominent modern entertainment facilities, such as the Window of the World. Moreover, as one of the first pilot cities promoting low-carbon development in China and an experimental demonstration zone for socialism with Chinese characteristics, Shenzhen leads the trend of institutional innovation and reform in China. Therefore, we chose Beijing and Shenzhen as research areas.

Table 1. Social and economic indicators in Beijing and Shenzhen.

	Beijing	**Shenzhen**
Administrative level	Municipality directly under the central government	Sub-provincial city
Geographical location	Northern China	Southern China
Land area	16,410.54 km^2	1997.47 km^2
Resident population in 2005	15.38 million	8.28 million
Resident population in 2020	21.89 million	17.63 million
Urban GDP in 2005	CNY 715.0 billion	CNY 503.6 billion
Urban GDP in 2020	CNY 3610.26 billion	CNY 2767.02 billion
GDP ratio of three industries in 2005	1.22:26.68:72.10	0.19:53.81:46.00
GDP ratio of three industries in 2020	0.30:15.83:83.87	0.09:37.78:62.13
Growth rate of the per-capita consumption expenditure from 2005 to 2020	192.74%	155.04%
Growth rate of the secondary industry output value from 2005 to 2020	199.70%	285.80%
Growth rate of the tertiary industry output value from 2005 to 2020	487.31%	642.14%

2.2. Data Sources

The sources of GHG budget accounting data and emission factors applied in this paper are shown in Table 2. Since the statistical concepts of China's cities are often divided according to administrative units rather than built-up areas, as well as due to data availability, it is difficult to separately account for activities such as energy consumption and residential consumption, so the emissions involved in agricultural activities within the administrative units of specific cities (Beijing and Shenzhen, in this study) are also included. Because the main industrial products in Shenzhen do not include cement or steel, this study calculated the GHG emissions only from industrial processes in Beijing.

Table 2. Sources of GHG activity data and emission factors.

	Sources of Activity Data	Sources of Emission Factors
Energy activities	China Energy Statistical Yearbook [34]; Guangdong Statistical Yearbook [35]; Shenzhen Statistical Yearbook [36].	Shan, et al., 2018 [37]; Provincial Greenhouse Gas Inventory Preparation Guidelines (Trial) [38].
Industrial processes	Beijing Statistical Yearbook [39].	Provincial Greenhouse Gas Inventory Preparation Guidelines (Trial); Liu, et al., 2016 [40].
Waste disposal	China Statistical Yearbook on Environment [41]; Information Announcement on Prevention and Control of Environmental Pollution by Solid Wastes Shenzhen [42].	Provincial Greenhouse Gas Inventory Preparation Guidelines (Trial).
Household consumption	Beijing Statistical Yearbook; Shenzhen Statistical Yearbook.	Liu, et al., 2018 [43].
Agricultural activities	Beijing Statistical Yearbook; Shenzhen Statistical Yearbook.	Provincial Greenhouse Gas Inventory Preparation Guidelines (Trial).
Carbon sinks	Land change survey in Beijing [44]; land change survey in Shenzhen [45].	Accounting Standards of Gross Ecosystem Product (Trial) [46]; Yu, et al., 2022 [47]; Zhang, et al., 2022 [48].
Analysis of influencing factors	Beijing Statistical Yearbook; Shenzhen Statistical Yearbook.	-

The energy activity data of Shenzhen are incomplete, so they were calculated according to the provincial activity data. By consulting the Shenzhen Statistical Yearbook, we found that the statistical energy consumption data include the energy consumption of raw coal, crude oil, gasoline, kerosene, diesel, fuel oil, liquefied petroleum gas, natural gas, and electricity in the industrial sector, and that the total energy consumption of each of these parts is less than the terminal consumption of Shenzhen. Therefore, the missing energy consumption data of Shenzhen can be calculated by combining the obtained energy consumption data with the consumption data of Guangdong Province. The specific accounting formula is shown in Equation (1) as follows:

$$\mathrm{E}'_{\mathrm{ij}} = \mathrm{E}_{\mathrm{ij}} \times \left(\mathrm{E}'_{\mathrm{ia}} - \mathrm{E}'_{\mathrm{ib}}\right) / \left(\mathrm{E}_{\mathrm{ia}} - \mathrm{E}_{\mathrm{ib}}\right) \quad (1)$$

where $\mathrm{E}'_{\mathrm{ij}}$ is the energy consumption of category j in sector i of Shenzhen (Tgce), E_{ij} is the energy consumption of category j in sector i of Guangdong Province (Tgce), $\mathrm{E}'_{\mathrm{ia}}$ is the terminal consumption of department i of Shenzhen (Tgce), $\mathrm{E}'_{\mathrm{ib}}$ is the sum of all kinds of energy consumption available for sector i in the Shenzhen Statistical Yearbook (Tgce), E_{ia} is the terminal consumption of sector i in Guangdong Province (Tgce), and E_{ib} is the sum of the energy consumption of sector i in Guangdong Province corresponding to the energy contained in $\mathrm{E}'_{\mathrm{ib}}$ (Tgce).

2.3. Accounting for Urban GHG Emissions

GHG emission sectors include urban energy activities, industrial processes, waste disposal, household consumption, and agricultural activities, and the main GHGs included are CO_2, CH_4, and N_2O.

2.3.1. GHG Emissions from Energy Activities

GHG emissions from energy activities include the direct emissions of GHGs from fossil fuel consumption and the indirect emissions of GHGs from the external transfer of power and heat. GHG emissions from fossil fuel consumption are accounted for with reference to the method provided by the IPCC [49], and the coefficient method is adopted to determine the GHG emissions from energy external transfer; this term is estimated according to Formula (2) as follows:

$$E = \sum_{i}\sum_{j}\left(E_{ij} \times NCV_i \times EF_i \times O_{ij} \times 44/12\right) \tag{2}$$

where the subscripts i and j in the equation refer to the fossil fuel types and sectors, respectively, E represents the CO_2 emissions ($GgCO_2$), E_{ij} represents fossil fuel consumption (Gg), NCV_i represents the net caloric value of fossil fuels (GJ/Gg), EF_i represents the carbon content (GgC/GJ), O_{ij} is the carbon oxidation factor (%), and 44/12 is the molecular weight ratio of CO_2 to C. These terms are listed in Table 3. The GHG emission coefficients of power and heat consumption are 0.604 ($kgCO_2$/kW·h) and 0.11 ($GgCO_2$/TJ), respectively [38]. The GHG emission parameters of external power transfer in Beijing and Shenzhen are 1.246 ($kgCO_2$/kW·h) and 0.714 ($kgCO_2$/kW·h), respectively, and the GHG emission parameter of heating is 0.11 ($GgCO_2$/TJ) [50].

Table 3. Accounting parameters of fossil fuel consumption.

Energy Type	NCV_i	EF_i	O_i
Raw coal	0.21	26.32	85
Cleaned coal	0.26	26.32	85
Other washed coal	0.15	26.32	85
Briquettes	0.18	26.32	90
Coke	0.28	31.38	93
Other gas	0.83	21.49	99
Other coking products	0.28	27.45	93
Crude oil	0.43	20.08	98
Gasoline	0.44	18.90	98
Kerosene	0.44	19.60	98
Diesel oil	0.43	20.20	98
Fuel oil	0.43	21.10	98
Liquefied petroleum gas	0.47	20.00	98
Refinery gas	0.43	20.20	98
Other petroleum products	0.51	17.20	98
Natural gas	3.89	15.32	99

2.3.2. GHG Emissions from Industrial Processes

GHG emissions from industrial processes refer to CO_2 emissions caused by physical and chemical reactions in production processes, rather than GHG emissions caused by industrial combustion. These emissions include the high-temperature decomposition process of ironmaking solvents and the decarbonization process in the production of steel, as well as the high-temperature calcination process of limestone in cement production [40,51].

The accounting formula of GHG emissions in the industrial production process (E, in $GgCO_2$) is shown in Formula (3) as follows:

$$E = \sum_{i} AD_i \times EF_i \quad (3)$$

where i refers to the ith industrial production process, AD refers to the product output (Gg), EF refers to the carbon emission factor ($GgCO_2/Gg$), and the emission factors of cement and steel are 0.538 and 0.265 ($GgCO_2/Gg$), respectively [40].

2.3.3. GHG Emissions from Waste Disposal

GHG emissions from waste disposal are calculated according to the methods recommended in the Provincial Greenhouse Gas Inventory Preparation Guidelines [38], including CH_4 and CO_2 emissions from solid waste landfill and incineration, as well as CH_4 and N_2O emissions from wastewater treatment.

GHG Emissions from Solid Waste Treatment

1. CH_4 emissions from landfill treatment

CH_4 emissions from landfill treatment (E_{CH_4}, in $GgCH_4$) were estimated using Formula (4):

$$E_{CH_4} = (MSW \times L_0) \times (1 - OX) \quad (4)$$

where MSW refers to the landfill treatment capacity (Gg/yr), L_0 represents the CH_4 generation potential ($GgCH_4$/Gg waste), and OX refers to the oxidation factor (%). The accounting parameters are listed in Table 4.

Table 4. Accounting parameters of waste disposal.

Accounting Parameter	Unit	Value [38]
CH_4 generation potential (L_0)	$GgCH_4$/Gg waste	0.03
Landfill oxidation factor (OX)	%	10
Total carbon content (CCW)	%	20
Fraction of fossil carbon in the total carbon (FCF)	%	39
Combustion efficiency of waste incinerator (EF)	%	95
Emission factor of domestic wastewater (EF)	$kgCH_4/kgBOD$	0.099
Values of BOD/COD in Beijing	—	0.45
Values of BOD/COD in Shenzhen	—	0.47
Emission factor of industrial wastewater (EF)	$kgCH_4/kgCOD$	0.025
Protein consumption per capita (Pr)	kg/person/year	35.22
N_2O emission factor for wastewater treatment (EF)	kgN_2O/kgN	0.0015

2. CO_2 emissions from incineration

CO_2 emissions from incineration (E_{CO_2}, in Gg) were estimated using Formula (5):

$$E_{CO_2} = \sum IW \times CCW \times FCF \times EF \times 44/12 \quad (5)$$

where IW refers to the waste incineration capacity ($GgCO_2$/yr), CCW is the total carbon content (%), FCF refers to the fraction of fossil carbon in the total carbon (%), EF is the combustion efficiency (%), and 44/12 is the conversion factor from C to CO_2; the accounting parameters are shown in Table 4.

GHG Emissions from Wastewater Treatment

1. Wastewater treatment CH_4 emissions

CH_4 emissions from wastewater treatment (E_{CH_4}, in $GgCH_4$) were estimated using Formula (6):

$$E_{CH_4} = \sum_i TOW_i \times EF_i \quad (6)$$

where i refers to domestic wastewater and industrial wastewater, E_{CH_4} refers to the total CH_4 emissions ($GgCH_4$/yr), TOW_i refers to organics in wastewater (kgBOD/yr; kgCOD/yr), and EF_i refers to the emission factor ($kgCH_4$/kgBOD; $kgCH_4$/kgCOD). The accounting parameters are shown in Table 4.

2. Wastewater Treatment N_2O Emissions

N_2O emissions from wastewater treatment (E_{N_2O}, in kgN_2O) were estimated using Formula (7):

$$E_{N_2O} = P \times P_r \times EF_E \times 44/28 \quad (7)$$

where P is the population, P_r is the annual per capita protein consumption (kg/person/year), EF_E is the N_2O emission factor (kgN_2O/kgN), and 44/28 is the transformation coefficient; the accounting parameters are shown in Table 4.

According to the global warming potential (GWP), CH_4 and N_2O were converted to CO_2 equivalents, and the GWP parameters of CH_4 and N_2O were 29 and 298, respectively.

2.3.4. GHG Emissions from Household Consumption

GHG emissions from household consumption can be divided into three categories: GHG emissions from clothing, from food, and from household articles [52,53]. To avoid repeat calculations, housing and transportation can be included in energy activities, waste disposal, and other sectors. GHG emissions from household consumption (E, in $GgCO_2$) were estimated using Formula (8):

$$E = \sum_i AD_i \times EF_i \quad (8)$$

where i represents clothing, food, and household articles and AD refers to the per capita expenditure on food, clothing, and household articles (CNY/year); these values are 0.120, 0.077, and 0.244 ($kgCO_2$/CNY), respectively [43].

2.3.5. GHG Emissions from Agricultural Activities

GHG emissions from agricultural activities are accounted for according to the methodology recommended by the provincial Greenhouse Gas Inventory Preparation Guidelines [38]; these emissions mainly include direct and indirect GHG emissions from cropland and CH_4 emissions from rice paddies, animal enteric fermentation, and animal manure management. According to the accounting results, CH_4 and N_2O emissions were converted into CO_2 equivalents.

GHG Emissions from Cropland

1. Direct emissions

The direct emissions come from the nitrogen fertilizer input, and the estimation formula for the direct emission sector (is E_{N_2O}, in GgN_2O) is shown in Formula (9):

$$E_{N_2O} = N_{N\ fertilizer} \times EF_{direct} \quad (9)$$

where $N_{N\ fertilizer}$ refers to the amount of nitrogen fertilizer applied (Gg) and EF is the emission factor of nitrogen input from cropland; the emission factors are 0.0057 and 0.0178 (kgN_2O/kgN) for Beijing and Shenzhen, respectively [38].

2. Indirect emissions

Indirect N_2O emissions come from atmospheric nitrogen deposition ($N_2O_{deposition}$, in GgN_2O) and leaching runoff ($N_2O_{leaching}$, in GgN_2O) [54], and the formulae are as follows:

$$N_2O_{deposition} = (N_{animal} \times 20\% + N_{input} \times 10\%) \times 0.01 \quad (10)$$

$$N_2O_{leaching} = N_{input} \times 20\% \times 0.0075 \quad (11)$$

$$N_{animal} = \sum_{i} \text{number of animals}_i \times \text{animal nitrogen excretion}_i \quad (12)$$

where N_{animal} represents animal manure emissions (Gg) and N_{input} represents cropland nitrogen inputs (Gg). According to the statistical yearbook data, Beijing's statistics include cattle, sheep, goats, pigs, and poultry, while the statistical data of Shenzhen include dairy cattle, other cattle, pigs, and poultry; all corresponding emission factors are shown in Table 5.

Table 5. Nitrogen excretion of animals.

Beijing animal	Poultry	Pig	Cattle	Sheep	Goat	Other
Nitrogen excretion (kg/head/year) [50]	0.6	16	50	12	2	40
Shenzhen animal	Poultry	Pig	Dairy cattle	Other cattle		
Nitrogen excretion (kg/head/year) [50]	0.6	16	60	40		

Methane (CH_4) Emissions from Rice Paddies

CH_4 emissions from rice paddies (E_{CH_4}, in $GgCH_4$) were estimated using Formula (13):

$$E_{CH_4} = AD \times EF \quad (13)$$

where AD is the sowing area (ha) and EF is the CH_4 emission factor ($kgCH_4\ ha^{-1}$); the EF values in Beijing and Shenzhen are 234 and 236.7 ($kgCH_4\ ha^{-1}$), respectively [38].

GHG Emissions from Animal Enteric Fermentation

CH_4 is produced as a byproduct in the process of animals' enteric digestion of feed, and CH_4 is excreted in the form of gas through the mouth, nose, and rectum of livestock. Ruminant livestock are the main emission sources of CH_4 produced by enteric fermentation, while non-ruminant livestock can be ignored because of their small CH_4 production. However, considering the large number of pigs in Beijing, the emission sources of CH_4 from enteric fermentation mainly include cattle, goats, sheep, and pigs [55]. CH_4 emissions from animal enteric fermentation (E_{CH_4}, in $kgCH_4$) were estimated using Formula (14):

$$E_{CH_4} = \sum_{i} EF_{CH_4} \times AP_i \times 10^{-7} \quad (14)$$

where i is the species of livestock, AP_i is the number of heads of livestock species (head), and EF_i is the CH_4 emission factor of the livestock population ($kgCH_4\ head^{-1}\ year^{-1}$); the values of each coefficient are shown in Table 6.

Table 6. CH_4 emission factors of animal enteric fermentation.

Beijing animal	Cattle	Sheep	Goat	Pig
Emission factors ($kgCH_4$ $head^{-1}$ $year^{-1}$) [38]	70.5	8.2	8.9	1
Shenzhen animal	Dairy cattle	Other cattle	Pig	
Emission factors ($kgCH_4$ $head^{-1}$ $year^{-1}$) [38]	88.1	52.9	1	

GHG Emissions from Animal Manure Management

Greenhouse gas emissions from animal manure management refer to the CH_4 and N_2O produced by the storage and treatment of animal manure prior to its application to the soil. GHG emissions from animal manure management (E_{CH_4}, in $kgCH_4$; E_{N_2O}, in kgN_2O) were estimated using Formula (15):

$$E_{CH_4(N_2O)} = \sum_i AP_i \times EF_i \tag{15}$$

where i refers to the livestock species, AP_i refers to the number of heads of livestock species (head), and EF_i is the CH_4 (N_2O) emission factor for the livestock population ($kgCH_4$ $head^{-1}year^{-1}$; kgN_2O $head^{-1}year^{-1}$). The values of each coefficient are shown in Table 7.

Table 7. Emission factors of CH_4 and N_2O from animal manure management.

Beijing animal	Cattle		Sheep		Goat		Pig		Poultry	
	CH_4	N_2O	CH_4	N_2O	CH_4	N_2O	CH_4	N_2O	CH_4	N_2O
Emission factors (kg $head^{-1}year^{-1}$) [38]	5.14	1.32	0.15	0.093	0.17	0.093	3.12	0.227	0.01	0.007
Shenzhen animal	Dairy cattle		Other cattle		Pig		Poultry			
	CH_4	N_2O	CH_4	N_2O	CH_4	N_2O	CH_4	N_2O		
Emission factors (kg $head^{-1}year^{-1}$) [38]	8.45	1.71	4.72	0.805	5.85	0.157	0.02	0.007		

2.4. Accounting for Carbon Sinks

The carbon sink mainly calculates the carbon sink of forest land, garden plots, cultivated land, grassland, and wetlands. According to the accounting standard of the Gross Ecosystem Product (Trial) and previous studies [46–48], the carbon sink rate method was adopted. Since grassland vegetation withers every year, and because fixed carbon is returned to the atmosphere or soil, only the soil carbon sink amount of grasslands is considered here. On the basis of the available data, the carbon emissions from cultivated land were calculated in the agricultural part. Therefore, to avoid repeated calculations, the carbon sink amount of cultivated lands was obtained mainly by calculating the soil carbon sink amount of agricultural fields applied with chemical fertilizer, and the formula is as follows:

2.4.1. Carbon Sink of Forestlands

The carbon sink of forestlands (Q, in $kgCO_2$ yr^{-1}) was estimated using Formula (16):

$$Q = (FVCSR + FSCSR) \times S \times 44/12 \tag{16}$$

where FVSCR is the carbon sink rate of forest vegetation (kgC ha^{-1} $year^{-1}$), FSCSR is the rate of soil carbon sink in forestlands (kgC ha^{-1} $year^{-1}$), and S is the area of forestlands (ha).

2.4.2. Carbon Sink of Garden Plots

The carbon sink of garden plots (Q, in $kgCO_2\ yr^{-1}$) was estimated using Formula (17):

$$Q = GCSR \times S \times 44/12 \quad (17)$$

where GSCR is the carbon sink rate of garden plots ((kgC ha^{-1} $year^{-1}$) and S is the area of garden plots (ha).

2.4.3. Carbon Sink of Cultivated Lands

The carbon sink of cultivated lands (Q, in $kgCO_2\ y^{r-1}$) was estimated using Formula (18):

$$Q = SCSR \times S \times 44/12 \quad (18)$$

$$\text{Beijing}: \ SCSR = 0.5286 \times TNF + 0.002 \quad (19)$$

$$\text{Shenzhen}: \ SCSR = 1.5339 \times TNF - 0.267 \quad (20)$$

$$TNF = NF/S \quad (21)$$

where SCSR is the carbon sink rate of cultivated lands (kgC ha^{-1} yr^{-1}), S is the area of cultivated lands (ha), TNF is the amount of chemical nitrogen fertilizer per unit area of cultivated lands (kg ha^{-1} $year^{-1}$), and NF is the amount of chemical nitrogen fertilizer applied (kg $year^{-1}$).

2.4.4. Carbon Sink of Grasslands

The carbon sink of grasslands (Q, in $kgCO_2$ $year^{-1}$) was estimated using Formula (22):

$$Q = GSCSR \times S \times 44/12 \quad (22)$$

where GSCSR is the carbon sink rate of grasslands (kgC ha^{-1} $year^{-1}$) and S is the area of grasslands (ha).

2.4.5. Carbon Sink of Wetlands

The carbon sink of wetlands (Q, in $kgCO_2\ yr^{-1}$) was estimated using Formula (23):

$$Q = SCSR \times SW \times 10^{-2} \times 44/12 \quad (23)$$

where SCSR is the carbon sink rate of wetlands (kgC ha^{-1} $year^{-1}$) and SW is the area of wetlands (ha). Each parameter is shown in Table 8.

Table 8. Carbon sink rate (kgC ha^{-1} $year^{-1}$).

	Forest Vegetation [46]	Forest Soil [46]	Garden Plot [47]	Grassland [46]	Wetland [48]
Beijing	551	586	1274	30	477
Shenzhen	554	118	1274	18	3305

2.5. Accounting of Net GHG Emissions from Urban Ecosystems

Net GHG emissions refer to the difference between the total GHG emissions and total carbon sinks ($E_{Net\ emission}$, in $kgCO_2$), as estimated by Formula (24). According to the accounting, the net GHG emissions of Beijing and Shenzhen during 2005–2020 can be determined as follows:

$$E_{Net\ emission} = E_{total\ emission} - E_{carbon\ sink} \quad (24)$$

where $E_{total\ emission}$ is the GHG emissions from the energy sector, industrial processes, agricultural activities, waste disposal, and household consumption, while $E_{Carbon\ sink}$ is the carbon sink from forestlands, garden plots, cultivated lands, grasslands, and wetlands.

2.6. Analysis Method of Influencing Factors of the GHG Budget

The STIRPAT model was developed from the IPAT model to examine the impacts on the environment [25,56], where I represents the influence of the environment, P represents the population size, A represents the affluence, and T represents the technological level. Dietz et al. built the STIRPAT model on the basis of the IPAT model [25]; the STIRPAT model can be expressed as follows:

$$I = P^{b} \times A^{c} \times T^{d} \times a \times e \quad (25)$$

where b, c, and d represent the index of each variable, a is the constant term, and e is the residual error term.

Since the model can add or decompose relevant influencing factors, in this paper, in combination with the urban development situation of China, the population factor is divided into three variables: the total population, household size, and urbanization rate. The GDP per capita and resident consumption level are used to reflect economic development, and the technical level is divided into two variables (the proportion of secondary industry and the energy intensity), with the formula of influencing factors of the GHG budget (I) expressed as follows:

$$I = P_1^{X_1} \times P_2^{X_2} \times P_3^{X_3} \times A_1^{X_4} \times A_2^{X_5} \times T_1^{X_6} \times T_2^{X_7} \times a \times e \quad (26)$$

The description of each independent variable is shown in Table 9. After logarithmic processing, the expression is as follows:

$$\begin{aligned} \ln I = X_1 \ln P_1 + X_2 \ln P_2 + X_3 \ln P_3 + X_4 \ln A_1 + X_5 \ln A_2 + X_6 \ln T_1 + X_7 \ln T_2 \\ + \ln e + \ln aa \end{aligned} \quad (27)$$

Table 9. Variable description.

Variable	Symbol	Define	Unit
Greenhouse gas budget	I	Greenhouse gas budget	$TgCO_2$ equivalents
Population	P_1	Number of permanent residents	10,000 persons
Household size	P_2	The ratio of registered population to registered households	Persons/household
Urbanization rate	P_3	The proportion of urban population to total population	%
GDO per capita	A_1	Ratio of GDP to population	CNY 10,000/person
Resident consumption level	A_2	Monthly consumption expenditure per person	CNY 100
Proportion of secondary industry	T_1	The proportion of secondary industry to GDP	%
Energy intensity	T_2	Ratio of energy consumption to GDP	kgce/CNY 1000

In view of the urban development of Shenzhen, the two indicators of the population and household size reflecting the population size were selected for practical applications, while the impact of the urbanization rate on the GHG budget was not selected. With the help of SPSS (Statistical Product and Service Solutions) software (IBM SPSS Statistics 26), factors influencing the total GHG emissions, carbon sinks, GHG budget, sectoral GHG budget, and categorical GHG budget in Beijing and Shenzhen were analyzed. Based on the STIRPAT extended model, serious multicollinearity was found among the variables when using the least-squares method for regression analysis. To solve this multicollinearity, the ridge regression estimation method was used. Ridge regression adds a K value [57,58] to the least-squares estimation and changes its estimated value to make the estimation result stable. The K value of the ridge parameter was selected with the help of programming in SPSS software, and the selection principle was to ensure that the regression coefficients were essentially stable.

3. Results

3.1. Comparison of the Patterns and Dynamics of the GHG Budgets of Beijing and Shenzhen

3.1.1. Pattern and Dynamics of Total GHG Emissions

Beijing's GHG emissions were always higher than Shenzhen's in 2005–2020 (Figure 1). On the whole, the GHG emissions in Beijing showed a relatively stable range of change. The GHG emissions increased from 160.3 $TgCO_2$ equivalents in 2005 to 209.1 $TgCO_2$ equivalents in 2020, with a growth rate of 30.5%. The GHG emissions in Shenzhen showed a gradual increasing trend, from 36.0 $TgCO_2$ equivalents in 2005 to 119.1 $TgCO_2$ equivalents in 2020, with a growth rate of 231.1%. Figure 2 shows the per capita and per unit GDP GHG emissions of Beijing and Shenzhen in 2005–2020. Beijing's per capita GHG emissions show an overall decreasing and fluctuating trend (decrease–increase–decrease), with the lowest per capita GHG emissions of 9.3 tons of CO_2 equivalents per person in 2015, and a slight increase from 2016 to 2019. The change in per capita GHG emissions in Beijing is related to both the promotion of low-carbon-emission efforts and the changes in population size, which began to decrease slightly in 2016. As shown in Figure 2, the per capita GHG emissions in Beijing were higher than those in Shenzhen. However, the per capita GHG emissions in Beijing decreased from 10.4 tons of CO_2 equivalents per person in 2005 to 9.6 tons of CO_2 equivalents per person in 2020, while the per capita GHG emissions in Shenzhen increased from 4.3 tons of CO_2 equivalents per person in 2005 to 6.8 tons of CO_2 equivalents per person in 2020. This indicates that Beijing has achieved certain results in reducing GHG emissions, but its emissions are still higher than those of Shenzhen. It is necessary to continue implementing emission reduction measures. Shenzhen needs to further strengthen low-carbon publicity, raise public awareness of emissions reduction, and reduce per capita GHG emissions. The GHG emissions per unit GDP in Beijing and Shenzhen decreased significantly from 2005 to 2020, and the degree of decrease in Beijing was greater than that in Shenzhen. The GHG emissions per unit GDP in Beijing decreased by 74.2%, from 2.2 tCO_2 equivalents/10^4 CNY GDP in 2005 to 0.6 tCO_2 equivalents/10^4 CNY GDP. Meanwhile, the greenhouse gas emissions per unit GDP in Shenzhen decreased by 39.7%, from 0.7 t CO_2 equivalents/10^4 CNY GDP in 2005 to 0.4 t CO_2 equivalents/10^4 CNY GDP in 2020. Although the GHG emissions per unit GDP in Beijing were higher than those in Shenzhen, their reduction was greater, and the gap between the two cities has clearly narrowed. This proves Beijing's efforts in optimizing industrial production structures, adjusting energy structures, vigorously introducing natural energy sources, and improving energy efficiency.

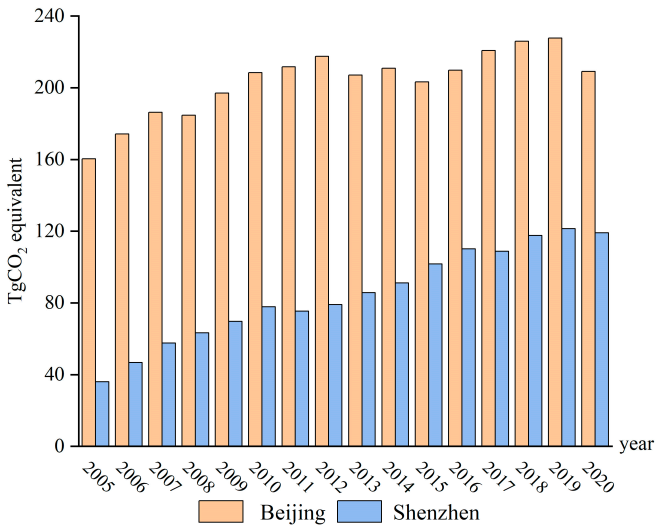

Figure 1. Total GHG emissions of Beijing and Shenzhen.

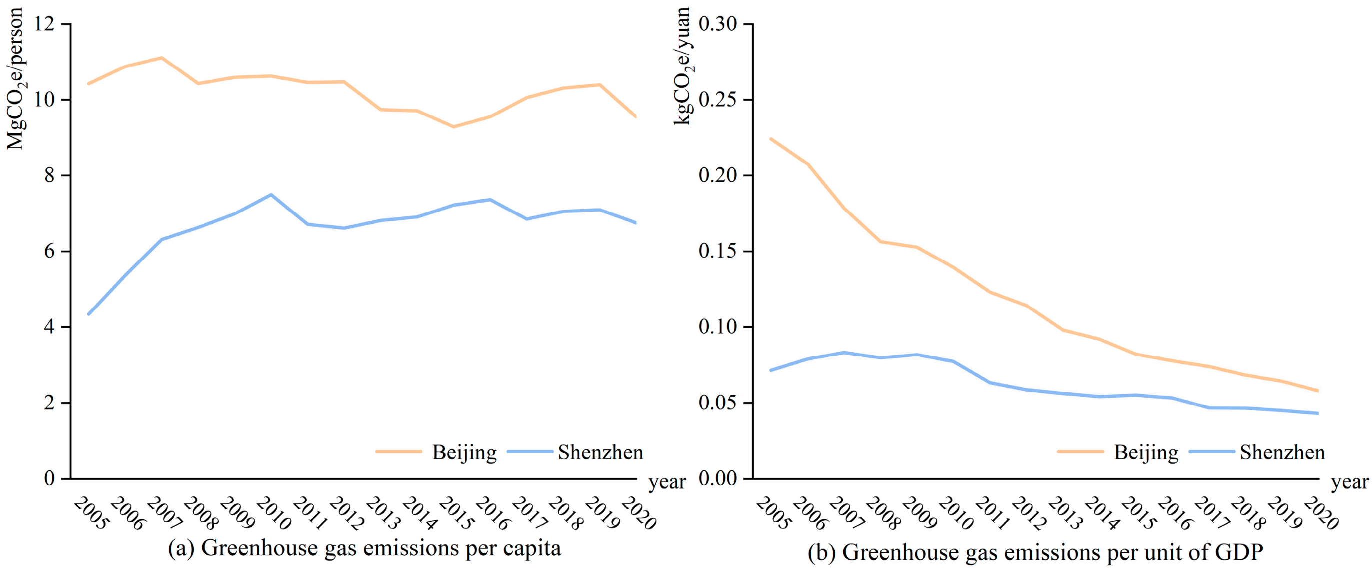

Figure 2. GHG emission intensities of Beijing and Shenzhen.

3.1.2. Characteristics of Sectoral GHG Emissions

Energy activities were still the main source of GHG emissions in Beijing and Shenzhen from 2005 to 2020 (Figures 3 and 4). Although the highest average proportion of GHG emissions from energy activities in Beijing was 82.5%, its emission structure changed significantly. The GHG emissions from energy consumption decreased by 4.0% (Figure 4a), while the GHG emissions from external energy transfer increased gradually, increasing by 93.8% in 2020 compared to 2005. Overall, the GHG emissions from energy activities in Shenzhen showed an increasing trend, increasing by 214.4% in 2020 compared to 2005, but the proportion of GHG emissions from energy activities in the total GHG emissions decreased slightly, from 75.9% in 2005 to 72.0% in 2020 (Figure 4b). In 2007, Shenzhen changed from energy transfer out to energy transfer in, and the amount of energy transfer in gradually increased; thus, the GHG emissions from energy transfer out increased from 710.2 $GgCO_2$ equivalents in 2007 to 11,778.8 $GgCO_2$ equivalents in 2020.

The greenhouse gas emissions from industrial production processes in Beijing have shown a significant downward trend, decreasing by 77.2% from 8.9 $TgCO_2$ equivalents in 2005 to 2.0 $TgCO_2$ equivalents in 2020 (Figure 4c); among these emissions, the GHG emissions from the cement and steel industries decreased by 75.8% and 80.9%, respectively.

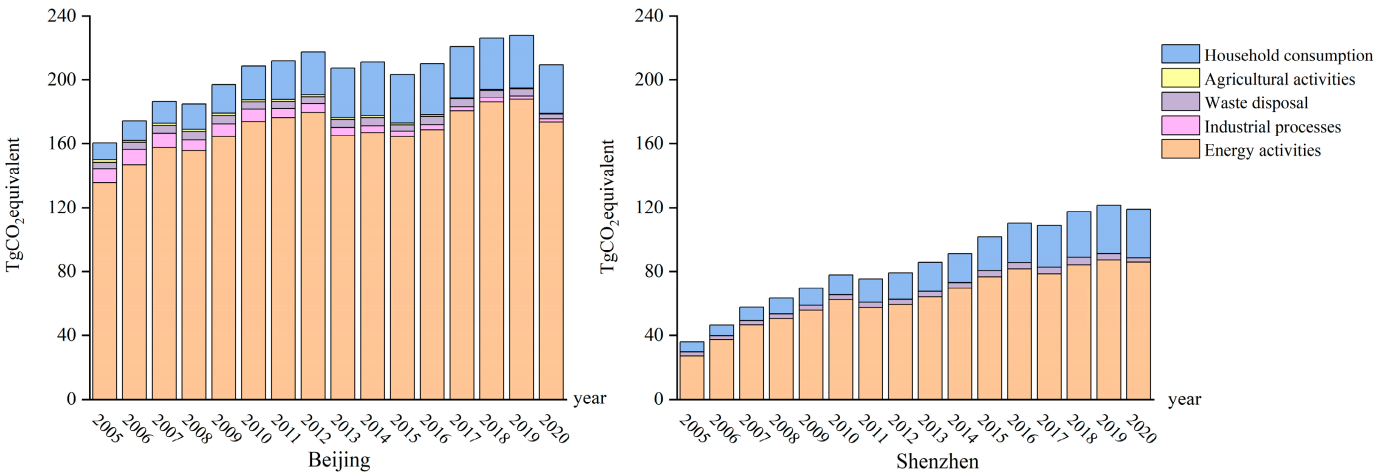

Figure 3. GHG emissions in Beijing and Shenzhen from 2005 to 2020.

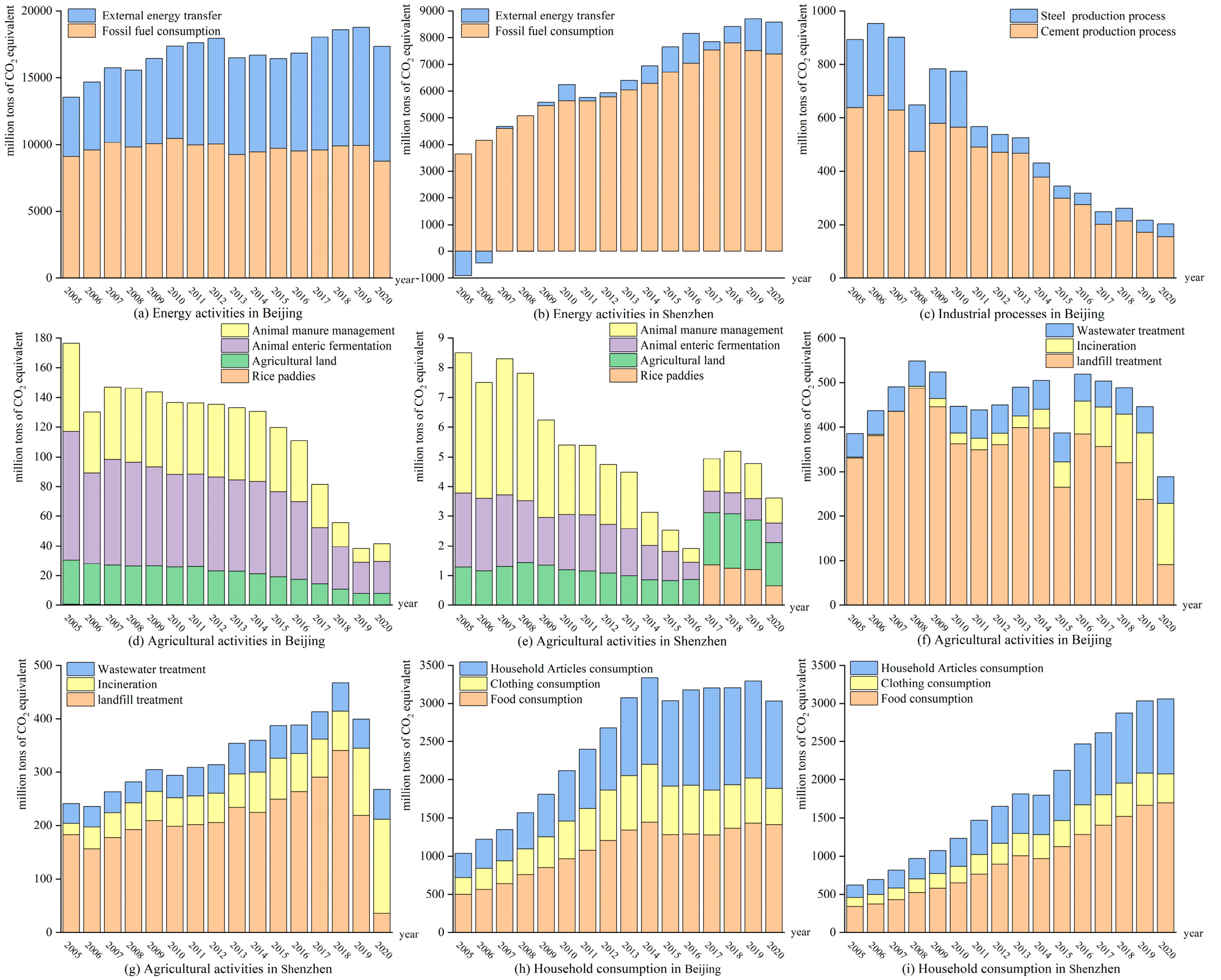

Figure 4. Sectoral GHG emissions in Beijing and Shenzhen from 2005 to 2020. Note: (**a**–**i**) refers to each department.

Overall, Beijing's waste disposal GHG emissions started to decrease gradually in 2008, increased slightly in 2013, and then gradually decreased again from 2016, with an overall decrease of 25.3% in 2020 compared to 2005 (Figure 4d). Shenzhen's waste disposal GHG emissions showed a trend of first increasing and then decreasing, with a 42.65% decrease in 2020 compared to 2018 (Figure 4e). The GHG emissions from waste disposal in Beijing and Shenzhen changed from the highest proportion corresponding to landfill disposal to the highest proportion corresponding to incineration disposal. The GHG emissions from incineration treatment in Beijing and Shenzhen increased from 20.1 and 213.5 $GgCO_2$ equivalents in 2005 to 1378 and 1759.9 $GgCO_2$ equivalents in 2020, respectively, and the GHG emissions from landfill treatment decreased from 3311.6 and 1825.5 $GgCO_2$ equivalents in 2005 to 907.8 and 356.0 $GgCO_2$ equivalents by 2020, respectively.

From 2005 to 2014, the GHG emissions from household consumption in Beijing significantly increased (Figure 4f), with an average annual growth rate of 13.9%. After 2016, the changes tended to flatten out, with an average annual growth rate of −1.57% in 2020 compared to 2016. The greenhouse gas emissions from household consumption in Shenzhen steadily increased (Figure 4g), with a growth rate of 394.3% in 2020 compared to 2005 and an average annual growth rate of 11.2%.

The GHG emissions from agricultural activities in Beijing generally showed a decreasing trend, with a decrease of 76.5% in 2020 compared to 2005 (Figure 4h). GHG emissions from agricultural activities in Shenzhen gradually decreased from 2005 to 2016 and increased significantly in 2017 (Figure 4i), mainly due to an increase in the area of rice paddies sown in Shenzhen in 2017, resulting in an increase in GHG emissions from agricultural activities.

3.1.3. Components of GHG Emissions

Both cities had the highest proportions of CO_2 emissions (Figures 5 and 6), at over 90%, followed by CH_4, and the lowest share of N_2O emissions, the GWP of which accounted for less than 1% of the GHG emissions; in addition, in both cities, the proportions of CO_2 gradually increased, while the proportions of CH_4 and N_2O showed decreasing trends year by year. The Beijing CO_2 emissions showed a fluctuating upward trend from 2005 to 2020, with an increase of 33.9% in 2020 compared to 2005, while the Shenzhen CO_2 emissions increased steadily during 2005–2020, with a growth rate of 250.7%.

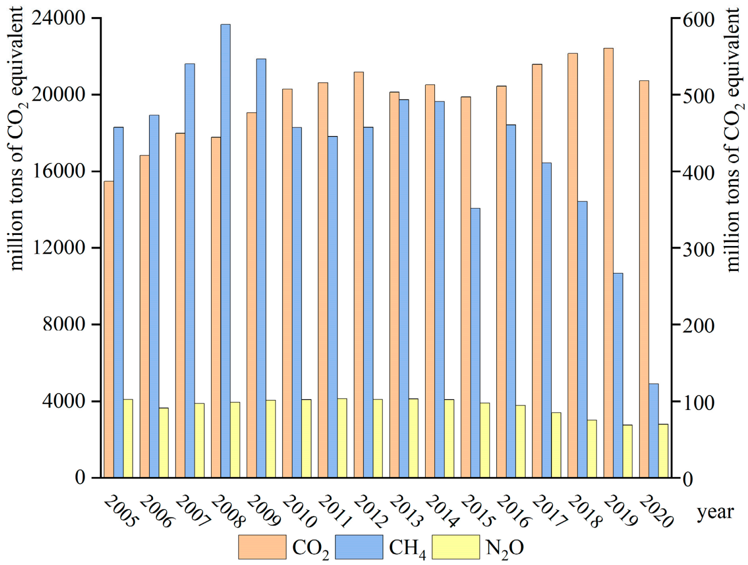

Figure 5. Emissions of CO_2, CH_4, and N_2O in Beijing from 2005 to 2020.

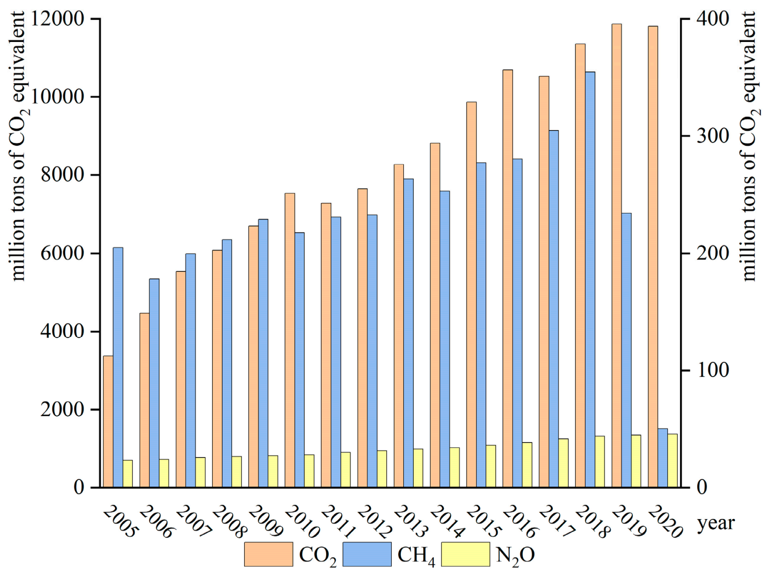

Figure 6. Emissions of CO_2, CH_4, and N_2O in Shenzhen from 2005 to 2020.

The CH_4 emissions in Beijing exhibited large changes, first decreasing by 28.4% in 2015 compared to 2014, and then rapidly decreasing from 2016. The Beijing People's Government introduced waste-treatment-related policies in 2013, requiring Beijing to reduce the amount of waste landfill disposal to less than 30% by the end of 2015 and, further, to build an industrial system of clean and circular development in the 13th Five-Year Plan period, thereby keeping the amount of disposed waste to a minimum and developing efficient and modern agriculture, through which CH_4 emissions could be gradually reduced. CH_4 emissions in Shenzhen showed a trend of first increasing and then decreasing. The increase was obvious in 2018, and the emissions decreased rapidly after 2018. The decrease in 2020 was 85.92% compared to 2018, possibly related to the waste disposal methods applied in Shenzhen, the increase in waste landfills in Shenzhen in 2018, and Shenzhen fully promoting the "waste-free city" construction pilot work in 2019 to achieve the full amount of domestic waste incineration and tend towards zero landfill, causing CH_4 emissions to be reduced.

The N_2O emission proportions of the two cities were the lowest, and their global warming potential was less than 1%. The average annual N_2O emissions in Beijing from 2005 to 2020 were 892.3 $GgCO_2$ equivalents, with a gradual decrease of 29.4%, and in Shenzhen from 2005 to 2020 they were 330.42 $GgCO_2$ equivalents, with an increasing trend of 96.2%. N_2O emissions were generated in the agricultural activity sector and the wastewater treatment sector. In recent years, Beijing has adopted measures such as fertilizer saving and pesticide saving to build new agricultural industries. The number of animal stocks in 2020 decreased by 74.6% compared to that in 2005, so the N_2O emissions decreased significantly. The N_2O emissions from agricultural activities in Shenzhen decreased by 35.9%, but overall, the N_2O emissions increased by 96.2%; the main reason for this is that the N_2O emissions from wastewater treatment in 2020 had increased by 113.0% compared to 2005.

3.1.4. Carbon Sinks in Beijing and Shenzhen

The carbon sink of Beijing increased from 3674.9 $GgCO_2$ in 2005 to 4698.1 $GgCO_2$ in 2020, among which the carbon sink of forestlands made the largest contribution to the GHG emission reduction (Figure 7), accounting for more than 77% of the total GHG absorption of the five land types, followed by the carbon sinks of garden plots, grasslands, cultivated lands, and wetlands, which contributed less to reducing the GHG emissions. The overall trend of the carbon sink of Shenzhen decreased and then increased, and it increased significantly in 2020, with a total carbon sink of 397.0~544.2 $GgCO_2$ equivalents, among which the carbon sinks of forestlands, wetlands, and garden plots in Shenzhen contributed the most to reducing the GHG emissions. The contributions of grasslands and cultivated lands to reducing the GHG emissions were small.

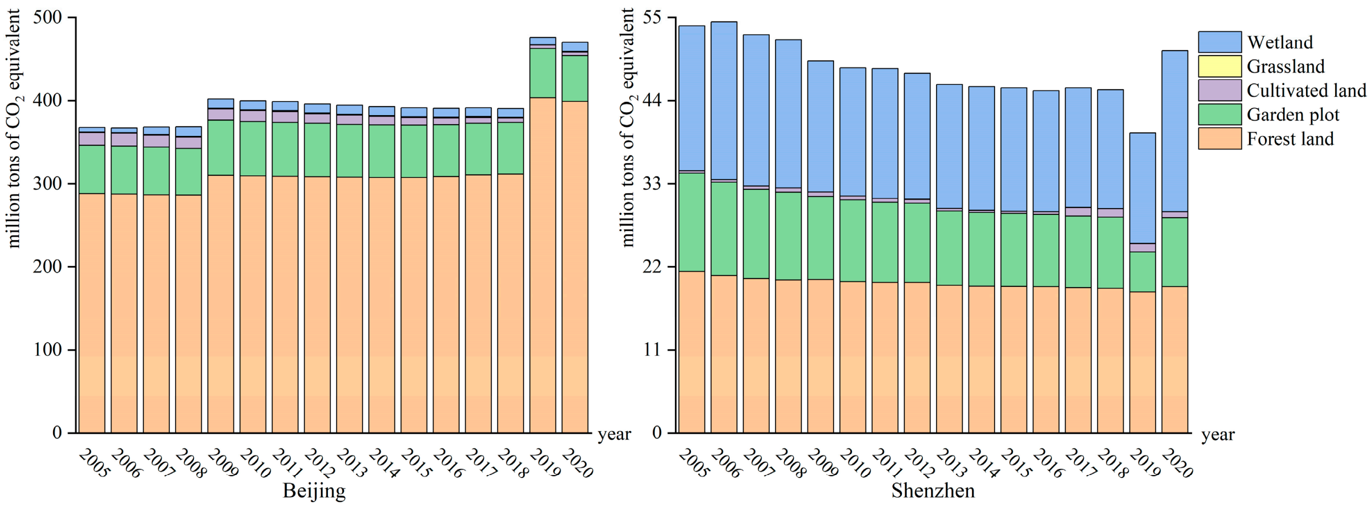

Figure 7. Carbon sinks in Beijing and Shenzhen from 2005 to 2020.

3.1.5. Net GHG Emissions in Beijing and Shenzhen

Net emissions are GHG emissions minus carbon sinks. The net emissions of GHGs in Beijing from 2005 to 2020 were 156.6~222.9 $TgCO_2$ equivalents, and the neutralization rates of carbon sinks to total GHG emissions ranged from 1.7% to 2.3% (Figure 8). Shenzhen's GHG emissions increased significantly from 2005 to 2020, but the growth rate showed a slowing trend. The net GHG emissions increased from 35.4 $TgCO_2$ equivalents in 2005 to 118.5 $TgCO_2$ equivalents in 2020—an increase of 234.7%. The neutralizing effect of carbon sinks on total GHG emissions declined overall, from 1.5% of GHG emissions in 2005 to 0.4% of GHG emissions in 2020.

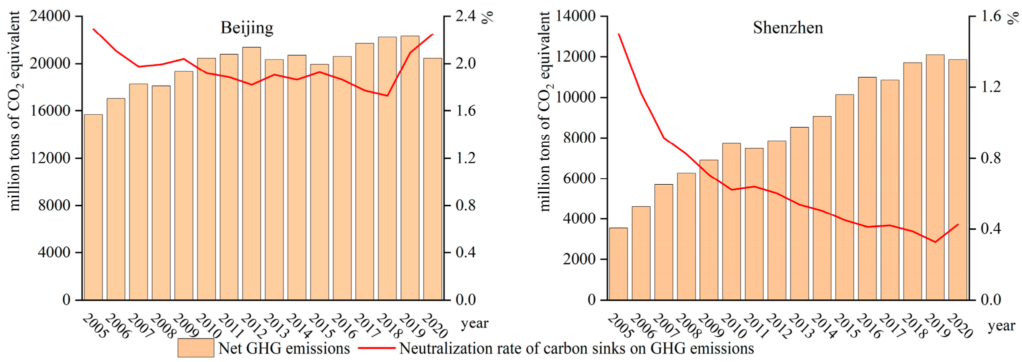

Figure 8. Net GHG emissions in Beijing and Shenzhen.

3.2. Influencing Factors on the GHG Budget in Beijing and Shenzhen

3.2.1. Multicollinearity Testing

A correlation analysis and ordinary least-squares (OLS) estimation were conducted based on the GHG emissions in Beijing and Shenzhen, and significant correlations were found between the emissions and a series of independent variables (Table 10). Secondly, multiple linear regression was performed using OLS, and the results showed that the variance inflation factor (VIF) for all independent variables was greater than 10 (Table 11). Based on these findings, it can be concluded that there was multicollinearity among the independent variables. Therefore, the analysis of the factors influencing greenhouse gas budgets adopted the ridge regression method.

Table 10. Correlation test results.

1. Beijing								
	lnI	lnP_1	lnP_2	lnP_3	lnA_1	lnA_2	lnT_1	lnT_2
lnI	1.000							
lnP_1	0.923 **	1.000						
lnP_2	−0.898 **	−0.850 **	1.000					
lnP_3	0.917 **	0.973 **	−0.892 **	1.000				
lnA_1	0.865 **	0.926 **	−0.891 **	0.970 **	1.000			
lnA_2	0.884 **	0.960 **	−0.864 **	0.979 **	0.987 **	1.000		
lnT_1	−0.845 **	−0.912 **	0.909 **	−0.950 **	−0.988 **	−0.970 **	1.000	
lnT_2	−0.795 **	−0.888 **	0.828 **	−0.941 **	−0.985 **	−0.973 **	0.962 **	1.000
2. Shenzhen								
	lnI	lnP_1	lnP_2	lnA_1	lnA_2	lnT_1	lnT_2	
lnI	1.000							
lnP_1	0.952 **	1.000						
lnP_2	0.938 **	0.979 **	1.000					
lnA_1	0.981 **	0.981 **	0.964 **	1.000				
lnA_2	0.966 **	0.995 **	0.978 **	0.986 **	1.000			
lnT_1	−0.970 **	−0.990 **	−0.977 **	−0.983 **	−0.993 **	1.000		
lnT_2	−0.937 **	−0.996 **	−0.969 **	−0.980 **	−0.988 **	0.981 **	1.000	

Notes: ** indicates significance at the 1% level.

Table 11. OLS results.

Variables	Unstandardized Coefficients	t-Statistic	Sig.	VIF
1. Beijing				
Constant	14.130	0.908	0.390	
$\ln P_1$	0.271	0.763	0.467	44.684
$\ln P_2$	−4.364	−2.252	0.054	10.617
$\ln P_3$	−1.479	−0.382	0.713	65.472
$\ln A_1$	0.623	2.013	0.079	349.091
$\ln A_2$	0.187	0.937	0.376	135.634
$\ln T_1$	0.951	2.750	0.025	67.323
$\ln T_2$	0.369	2.446	0.040	81.172
R^2	0.963			
F test	29.392			
Sig.	0.000			
2.Shenzhen				
Constant	−0.434	−0.061	0.953	
$\ln P_1$	2.074	2.337	0.044	528.617
$\ln P_2$	−1.134	−1.935	0.085	28.973
$\ln A_1$	1.481	6.915	0.000	45.535
$\ln A_2$	−0.128	−0.312	0.762	192.359
$\ln T_1$	−1.145	−1.400	0.195	90.131
$\ln T_2$	1.903	4.532	0.001	200.276
R^2	0.993			
F test	214.656			
Sig.	0.000			

3.2.2. Influencing Factors on the Total GHG Budget

In recent years, the land-use changes in Beijing and Shenzhen have been relatively small, resulting in relatively small changes in carbon sinks. The average annual growth rate of the carbon sinks in Beijing from 2005 to 2018 was 0.5%. The average annual decrease in the carbon sinks in Shenzhen from 2005 to 2020 was 0.4%, so the influence of various factors on the carbon sinks was not significant. Therefore, this paper analyzes the influence of each factor on the total and net GHG emissions in Beijing and Shenzhen (Table 12). The population promoted GHG emissions in both Beijing and Shenzhen, the urbanization rate promoted GHG emissions in Beijing, and the household size had opposing effects on GHG emissions in the two cities. The GDP per capita and resident consumption levels contributed to GHG emissions in Beijing and Shenzhen, with a greater impact observed in Shenzhen. The proportion of secondary industry and the energy intensity had more significant impacts in Shenzhen, where they were negatively correlated with GHG emissions.

Table 12. Results of the ridge regression analysis for Beijing and Shenzhen.

	Beijing		Shenzhen	
	Total GHG Emissions	**Net GHG Emissions**	**Total GHG Emissions**	**Net GHG Emissions**
$\ln P_1$ (population)	0.181 **	0.185 **	0.180 **	0.175 **
$\ln P_2$ (household size)	−2.083 **	−2.122 **	0.487 **	0.470 **
$\ln P_3$ (urbanization rate)	1.256 **	1.263 **	-	-
$\ln A_1$ (GDP per capita)	0.019 **	0.019 *	0.243 **	0.270 **
$\ln A_2$ (resident consumption level)	0.030 **	0.031 **	0.172 **	0.179 **
$\ln T_1$ (proportion of secondary industry)	−0.026	−0.025	−0.553 **	−0.591 **
$\ln T_2$ (energy intensity)	0.003	0.003	−0.110 **	−0.097 **
Constant	4.839	4.788	7.910	8.037
R^2	0.864	0.862	0.933	0.936
Sig	0.006	0.006	0.000	0.000

Note: ** and * indicate significance at the 5% and 10% levels, respectively.

3.2.3. Factors Influencing the Sectoral GHG Budget

In Beijing's energy activity sector, the population, urbanization rate, and household size had relatively great degrees of influence on GHG emissions, with the population and urbanization rate promoting GHG emissions and the household size playing a negative role (Table 13). In the industrial process sector, the urbanization rate, GDP per capita, residential consumption level, proportion of secondary industry, and energy intensity had relatively great influences on GHG emissions, with the increase in the urbanization rate, GDP per capita, and residential consumption level suppressing GHG emissions, while the proportion of secondary industry and the energy intensity played positive roles. In the household consumption sector, increases in the population, urbanization rate, GDP per capita, and residential consumption level promoted GHG emissions, while the proportion of secondary industry and the energy intensity played negative roles. In the agricultural activity sector, the population, proportion of secondary industry, and energy intensity promoted GHG emissions, the GDP per capita played a negative role in GHG emissions, and the household size, urbanization rate, and resident consumption level had less significant roles in affecting GHG emissions. The impact of each influencing factor on GHG emissions from the waste disposal sector in Beijing was not significant.

Table 13. Results of the analysis of influencing factors on GHG emissions by sector in Beijing.

	Energy Activities	Industrial Processes	Household Consumption	Agricultural Activities
$\ln P_1$ (population)	0.115 *	−0.127	0.837 **	1.054 **
$\ln P_2$ (household size)	−2.518 **	2.831	−1.934	6.119
$\ln P_3$ (urbanization rate)	1.074 **	−3.393 **	4.996 **	−1.834
$\ln A_1$ (GDP per capita)	0.018 *	−0.240 **	0.100 **	−0.296 **
$\ln A_2$ (resident consumption level)	0.019 *	−0.206 **	0.168 **	−0.107
$\ln T_1$ (proportion of secondary industry)	−0.028	0.636 **	−0.198 **	0.649 **
$\ln T_2$ (energy intensity)	0.007	0.290 **	−0.084 **	0.335 **
Constant	6.412	19.19	−19.296	−1.485
R^2	0.807	0.920	0.935	0.753
Sig	0.021	0.001	0.000	0.051

Note: ** and * indicate significance at the 5% and 10% levels, respectively.

In Shenzhen's energy activity sector, the population, GDP per capita, and residential consumption level had significant promoting effects on GHG emissions, while the proportion of secondary industry had a negative effect (Table 14). In the waste disposal sector, the population, GDP per capita, and residential consumption level played promoting roles, while the proportion of secondary industry and the energy intensity played negative roles. The GHG emissions of the household consumption sector increased with increasing population, household size, GDP per capita, and residential consumption level, while the proportion of secondary industry and the energy intensity had negative effects. The impact of each influencing factor on GHG emissions from the agricultural activity sector in Shenzhen was less significant.

Table 14. Results of the analysis of influencing factors on GHG emissions by sector in Shenzhen.

	Energy Activities	Waste Disposal	Household Consumption
$\ln P_1$ (population)	0.141 **	0.092 **	0.313 **
$\ln P_2$ (household size)	0.389 *	−0.053	0.840 **
$\ln A_1$ (GDP per capita)	0.264 **	0.137 **	0.313 **
$\ln A_2$ (resident consumption level)	0.158 **	0.126 **	0.259 **
$\ln T_1$ (proportion of secondary industry)	−0.564 **	−0.210 *	−0.734 **
$\ln T_2$ (energy intensity)	−0.063	−0.069 *	−0.237 **
Constant	8.143	5.174	4.945
R^2	0.888	0.633	0.988
Sig	0.001	0.096	0.000

Note: ** and * indicate significance at the 5% and 10% levels, respectively.

3.2.4. Influencing Factors of the Categorical GHG Budget

Ridge regression analysis showed that the influence of each factor on CH_4 emissions in Beijing and Shenzhen was not significant; therefore, this study analyzed the influence of each influencing factor on the CO_2 and N_2O budgets (Table 15).

Table 15. Influencing factors of the categorical GHG budgets in Beijing and Shenzhen.

	Beijing		**Shenzhen**	
	CO_2	**N_2O**	**CO_2**	**N_2O**
lnP_1 (population)	0.202 **	0.467 **	0.179 **	0.161 **
lnP_2 (household size)	−2.403 **	1.848	0.499 **	0.417 **
lnP_3 (urbanization rate)	1.471 **	0.274	-	-
lnA_1 (GDP per capita)	0.021 *	−0.087 **	0.278 **	0.090 **
lnA_2 (resident consumption level)	0.034 **	−0.018	0.181 **	0.112 **
lnT_1 (proportion of secondary industry)	−0.018	0.206	−0.610 **	−0.297 **
lnT_2 (energy intensity)	0.005	0.110 **	−0.098 **	−0.119 **
Constant	3.937	−2.253	7.986	2.191
R^2	0.890	0.637	0.934	0.987
Sig	0.003	0.174	0.000	0.000

Note: ** and * indicate significance at the 5% and 10% levels, respectively.

The analysis of the factors influencing the CO_2 budget in Beijing shows that the population, urbanization rate, GDP per capita, and resident consumption level played positive roles, the household size played a negative role, and the energy intensity and the proportion of secondary industry had no significant impact. The analysis results of the factors influencing N_2O emissions in Beijing indicate that the population and energy intensity played positive roles, the GDP per capita played a negative role, and the household size, urbanization rate, residential consumption level, and proportion of secondary industry were less significant.

The analysis of influencing factors in Shenzhen shows that each factor had a consistent effect on the CO_2 and N_2O emissions. The population, household size, GDP per capita, and residential consumption level all played roles in promoting the CO_2 budget and N_2O emissions, with the household size contributing most strongly. The proportion of secondary industry and the energy intensity both played negative roles in GHG emissions.

4. Discussion

4.1. Comparison of the Characteristics of the GHG Budgets in Beijing and Shenzhen

The main source of GHG emissions in both Beijing and Shenzhen is the energy activity sector. The GHG emissions from energy consumption in Beijing's energy activity sector decreased slightly over the study period, while the GHG emissions from external energy transfer gradually increased. This was due mainly to the various measures taken by Beijing in recent years, such as implementing the conversion of coal to electricity, vigorously introducing high-quality energy such as electricity and natural gas, and reducing residents' energy use [59]. At the same time, the traditional energy-consuming industries underwent a comprehensive transformation, resolutely eliminating high-energy-consuming production industries and introducing equipment with low consumption and lower emissions to high-tech industries to replace energy-intensive industries. This finding is consistent with the study by Xue et al. [58] on GHG emissions in Beijing.

GHG emissions from energy activities in Shenzhen showed an increasing trend overall. In 2007, the mode changed from energy transfer out to energy transfer in, and the amount of energy transfer gradually increased. Shenzhen has developed rapidly in recent years. On the one hand, due to its increasing urban population, energy consumption in transportation and energy consumption in life have increased significantly [60]; on the other hand, to cope with the air pollution problem in megacities, Shenzhen has carried out electrification reform of its manufacturing industry, and this has promoted the increasing demand for electricity; these findings are consistent with the study results of Liao et al. [61] obtained in Shenzhen.

The GHG emissions from industrial processes in Beijing decreased gradually from 2006 to 2008, increased slightly in 2009 and 2010, and continued to decrease from 2011; this change trend is consistent with the findings of Liu [50].

In Beijing and Shenzhen, the greatest proportion of GHG emissions from waste disposal changed from the landfill source to the incineration source, mainly because the two cities adjusted their waste treatment structures in recent years, thereby increasing their incineration rates and reducing their landfill rates. Beijing has accelerated the construction of waste incineration treatment plants in recent years and increased the incineration rates of household waste to more than 70%. In 2019, Shenzhen comprehensively promoted the pilot construction of a "waste-free city" and achieved the total incineration of household waste and near-zero landfill. As a result, the landfill disposal of waste in Beijing and Shenzhen decreased significantly. The above results are similar to the findings of Zhang et al. [62,63].

Beijing's GHG emissions from household consumption increased gradually from 2005 to 2014, with smaller changes observed from 2016 to 2020; Shenzhen's GHG emissions from household consumption increased gradually from 2005 to 2020, and the highest percentage of GHG emissions from household consumption in both cities was from food consumption. Studies have shown that [64–66] GHG emissions from household consumption are related mainly to the population size and income level. Beijing's population showed a gradual increasing trend from 2005 to 2014, and the increase in the urban population increased the demands for food and other consumer goods as well as increasing GHG emissions. From 2016 to 2020, Beijing's population showed a slight decreasing trend, so the change range of GHG emissions was small. With the continuous increase in the population of Shenzhen, the demands for clothing, food, and household articles have increased, resulting in an increase in GHG emissions, and with their increased incomes, people now have increasingly higher requirements for food quality, resulting in increasing indirect emissions.

The scale of agriculture in Beijing and Shenzhen has been decreasing in recent years; the sown area of rice paddies in Beijing decreased by 73.3%, while the stock of major animals decreased by 74.6%, and the stock of major animals in Shenzhen decreased by 69.8%. In recent years, both cities have carried out pollution control measures on large-scale breeding farms, improved their agricultural production technology, and developed a conservation-oriented agriculture that is resource-saving and land-saving, so their agricultural-activities-related GHG budget has decreased. Shenzhen's agricultural activities increased significantly in 2017, mainly due to the increase in the area of rice paddies sown in Shenzhen in 2017, resulting in an increase in GHG emissions from agricultural activities.

The total carbon sink of Beijing was larger than that of Shenzhen, and the neutralization rate of the carbon sink to GHG emissions was also higher than that of Shenzhen, partly because of the abundance of forestlands and other land resources in Beijing [67], and partly because of the larger growth of GHG emissions in Shenzhen. Forestlands contributed the most to the carbon sink in Beijing, while forestlands and wetlands contributed the most to the carbon sink in Shenzhen; these differences are mainly related to the geographical locations of Beijing and Shenzhen. Shenzhen is a coastal city with abundant wetland resources [68], so the carbon sink of wetlands is larger there than in Beijing.

4.2. Differences in the Influencing Factors of the GHG Budget in Beijing and Shenzhen

4.2.1. Population Size

The increasing populations have played a role in increasing GHG emissions in both Beijing and Shenzhen, with population growth leading to increased demands for energy and urban household consumer goods, thereby generating more GHG emissions. The increased urbanization rate has promoted GHG emissions in Beijing, and the migration of the rural population into cities, the growth of urban construction lands, and changes in people's consumption patterns all produce more GHG emissions, as has been proven by a large number of studies [32,69].

The household size had opposite influences on GHG emissions in Beijing and Shenzhen. The number of households in Beijing increased by 23.4% from 2005 to 2020, while the growth rate of the registered population was 18.6%. The registered population was smaller than the increase in the number of households, resulting in a constant decrease in the household size in Beijing. Meanwhile, the number of households in Shenzhen increased by 104.60% from 2005 to 2020. The growth rate of the registered population was 172.0%, and the registered population number was greater than the increase in the number of households, causing the household size in Shenzhen to increase continuously. It has been shown that an increase in the number of urban households and a decrease in the household size can cause increased emissions in terms of household energy and other aspects [70], and the household size in Beijing has been decreasing in recent years; thus, CO_2 emissions are expected to increase as the household size decreases. Significant increases in the number of households and the registered population of Shenzhen will bring more demands for energy and other resources, so an increase in the household size will increase Shenzhen's greenhouse gas emissions.

4.2.2. Economic Development

Using the GDP per capita and residential consumption level to represent the changes in urban economic development, the regression results show that economic development influenced GHG emissions to different degrees in the two cities, and that the degree of influence was greater for Shenzhen than for Beijing. Therefore, this paper further explores the relationship between economic development and GHG emissions using the Tapio decoupling model [71,72]. The Tapio decoupling model divides the decoupling status into three major categories and eight subcategories according to the decoupling index T (Table 16). The decoupling indices were calculated separately for Beijing and Shenzhen (Table 17). Beijing was in a decoupling state between GHG emissions and economic development from 2005 to 2020, indicating that Beijing's economic development was no longer at the cost of high GHG emissions. However, the relationship between GHG emissions and economic development in Shenzhen was mostly expansionary negative decoupling from 2005 to 2010, meaning that the growth rate of GHG emissions far exceeded the growth rate of the economy. From 2010 to 2020, the decoupling state was unstable, with three strong decoupling periods, five weak decoupling periods, and two expanding connection periods. This means that with the increase in the GDP per capita and the residents' consumption level, GHG emissions are increasing. From this point of view, seeking a balance between economic development and emission reductions will remain an important goal of Shenzhen's development in the future.

Table 16. Classification of the decoupling state between GHG emissions and economic development.

ΔGDP	ΔGHG	Decoupling Index T	Decoupling State		
>0	>0	0 < T < 0.8	Weak decoupling	GHG emissions growth rate is lower than that of economic growth	Decoupling
>0	<0	T < 0	Strong decoupling	GHG emissions decrease while GDP increases	
<0	<0	T > 1.2	Recessionary decoupling	GHG emissions decrease faster than economic decline	
>0	>0	T > 1.2	Expansionary negative decoupling	GHG emissions growth rate is faster than economic growth	Negative decoupling
<0	>0	T < 0	Strong negative decoupling	GHG emissions increase while GDP decreases	
<0	<0	0 < T < 0.8	Weak negative decoupling	GHG emissions decrease at a slower pace than economic decline	
>0	>0	0.8 < T < 1.2	Expansionary coupling	GHG emissions growth rate is close to that of economic growth	Coupling
<0	<0	0.8 < T < 1.2	Recessionary coupling	GHG emissions reduction rate is close to that of economic decline	

Table 17. Decoupling between GHG emissions and economic development in Beijing and Shenzhen.

Year	Beijing		Shenzhen	
	Decoupling Index T	**Decoupling State**	**Decoupling Index T**	**Decoupling State**
2005–2006	0.50	Weak decoupling	1.70	Expansionary negative decoupling
2006–2007	0.29	Weak decoupling	1.37	Expansionary negative decoupling
2007–2008	−0.06	Strong decoupling	0.67	Weak decoupling
2008–2009	0.72	Weak decoupling	1.39	Expansionary negative decoupling
2009–2010	0.36	Weak decoupling	0.64	Weak decoupling
2010–2011	0.10	Weak decoupling	−0.17	Strong decoupling
2011–2012	0.26	Weak decoupling	0.37	Weak decoupling
2012–2013	−0.43	Strong decoupling	0.65	Weak decoupling
2013–2014	0.22	Weak decoupling	0.61	Weak decoupling
2014–2015	−0.45	Strong decoupling	1.20	Expansionary coupling
2015–2016	0.35	Weak decoupling	0.68	Weak decoupling
2016–2017	0.50	Weak decoupling	−0.10	Strong decoupling
2017–2018	0.22	Weak decoupling	0.94	Expansionary coupling
2018–2019	0.11	Weak decoupling	0.48	Weak decoupling
2019–2020	−4.39	Strong decoupling	−0.78	Strong decoupling

4.2.3. Technical Level

The effects of the proportion of secondary industry and the energy intensity on GHG emissions differed between the two cities. The effects of the proportion of secondary industry and the energy intensity on GHG emissions in Beijing were less significant, while the effect on GHG emissions from industrial processes in Beijing was more significant. With decreases in the proportion of secondary industry and the energy intensity, the GHG emissions in Beijing's industrial production process decreased. The proportion of secondary industry and the energy intensity negatively affected GHG emissions in Shenzhen.

Secondary industry is usually regarded as a high-GHG-emission sector. In recent years, Beijing has adjusted its industrial structure and changed into a low-consumption production mode, shifting the traditional high-GHG-emission secondary industry to a green and low-carbon tertiary industry. Therefore, the reductions in the proportion of secondary industry and the energy intensity played a role in reducing GHG emissions. The proportion of secondary industry in Shenzhen decreased from 53.8% in 2005 to 37.8% in 2020. Although secondary industry continued to decrease, the GHG emissions brought by secondary industry increased by 12.2%. Therefore, although Shenzhen has followed the "321" industrial economic pattern in recent years, it still needs to further optimize its industrial structure.

The energy intensity denotes the technical level and energy-use efficiency of a city. During the study period, the energy intensity of Beijing and Shenzhen decreased year by year, but the energy intensity had opposite effects on GHG emissions from industrial processes in Beijing and on total GHG emissions in Shenzhen. Beijing reduced its raw coal consumption by 95.8% from 2005 to 2020 by adjusting its energy structure. Therefore, although energy consumption is still increasing, the growth rate slowed down significantly, and the reduction in the energy intensity played a role in reducing the GHG emissions. The energy intensity of Shenzhen played a negative role—on the one hand, because of the rapid economic development of Shenzhen, and on the other hand, because of the continuous increase in energy consumption in Shenzhen. Therefore, although the energy intensity was reduced, the total energy consumption and economic scale expanded, resulting in an increase in GHG emissions. Therefore, the energy structure should be further adjusted.

5. Conclusions

This study comprehensively accounted for the GHG budgets in Beijing and Shenzhen from 2005 to 2020 and investigated the factors affecting the GHG budgets. We found that the total GHG emissions of both cities showed an increasing trend from 2005 and peaked in 2019 before decreasing in 2020. The GHG emissions of Beijing, which increased from 160.3 TgCO_2 equivalents in 2005 to 209.1 TgCO_2 equivalents in 2020, were always greater than those of Shenzhen (36.0 TgCO2 equivalents in 2005 and 119.1 TgCO_2 equivalents in 2020). However, the growth rate of GHG emissions from Shenzhen (231.1%) was almost seven times larger than that of Beijing (30.5%). Energy activities in Beijing and Shenzhen have always been the main emission sectors of GHGs from 2005 to 2020, accounting for more than 70% of the total GHG emissions. Among the three GHGs, CO_2 contributed over 90% to the total emissions, followed by CH_4, (2.2% in Beijing, 3.0% in Shenzhen), while N_2O contributed the lowest proportion of global warming effect (less than 1%). The neutralization rate of carbon sinks on GHG emissions was greater in Beijing (1.7% to 2.3%) than in Shenzhen (0.3% to 1.5%), and the carbon neutrality rate of the ecosystem carbon sink in Shenzhen showed a decreasing trend overall. Forest alone contributed about 79% of Beijing's ecosystem carbon sink, while in Shenzhen, the carbon sink effect of forest, garden, and wetlands contributed 41.3%, 21.2%, and 36.3% of the total urban carbon sink, respectively. Population size, GDP per capita, and residents' consumption level were positively correlated with GHG emissions in both Beijing and Shenzhen. Meanwhile, household size had opposite effects on the two cities, with a decrease in household size and an increase in GHG emissions in Beijing, while there was a positive correlation between household size and GHG emissions in Shenzhen. The increase in the proportion of secondary industry and the energy intensity had more significant impacts on GHG emissions in Shenzhen, where they were negatively correlated with greenhouse gas emissions. Based on the above analysis, the following suggestions and insights are proposed:

1. Promote the high-quality development of urbanization: The rapid development of urbanization is accompanied by population growth and urban expansion, which promote increased GHG emissions. The populations of Beijing and Shenzhen will increase further in the future, so we should focus on the quality of urban development and develop a concentrated and compact urban spatial structure to reduce GHG emissions. At the same time, to reduce the GHG emissions caused by increasing populations, governments should strengthen the publicity of low-carbon consumption and guide residents' awareness of low-carbon consumption to achieve their GHG emission reduction goals.
2. Optimize the industrial structure and adjust the energy structure: Although Beijing and Shenzhen have followed the "321" industrial model, in the process of adjusting their industrial structures and gradually building industrial systems dominated by tertiary industry, attention should also be paid to the internal structure of the tertiary industry; this industry should gradually be transformed into a knowledge-intensive industry with low consumption and low emissions. At the same time, technological upgrading should be strengthened, low-carbon technologies should be developed, the close integration of industry, academia, and research should be promoted, the energy-utilization efficiency should be improved, and GHG emissions should be reduced. Shenzhen should further adjust its energy structure, focus on optimizing its energy structure and layout, reduce its coal consumption, and increase its development and utilization of clean energy and new energy.
3. Increase carbon sinks: Forestry is the main carbon sink resource, and the main countermeasures used to increase the carbon sink capacity include increasing the carbon sequestration capacity, improving the quality of forestland resources, focusing on the conservation of forest trees, expanding the area of forestlands, encouraging the development of unused lands, and giving priority to the conversion of cultivated lands, grasslands, and forestlands, reducing the construction occupation and increasing the area of public green spaces to increase the carbon sink.

Since the relevant activity-level data of Beijing and Shenzhen are not complete, applying different methods to calculate the urban GHG budgets and selecting different GHG emission coefficients would lead to differences in the GHG accounting results. The carbon sink accounting performed in this paper was based on previous studies, so the accounting standard had a certain universality, but because the actual environment of each city has some differences, the calculated results showed some deviation. Moreover, the data used in this paper were obtained from statistical data. There is no more detailed division of land use and vegetation types, and unused land was not considered in the accounting process. As a result, the calculated values were small. Therefore, we hope that in future research the standards and parameter values used to establish an urban GHG budget inventory can be refined to fully conform to the characteristics of Chinese cities and accurately calculate the GHG budgets at different urban scales. The GHG income and expenditure process contains very complex influencing factors that are not only affected by the population size, economic development, and technical level but are also related to many unquantifiable factors, such as climate change, geographic spatial differences, and living habits. Therefore, in future work, multidisciplinary and cross-disciplinary research should be combined with the actual situations of different cities to propose emission reduction measures.

Author Contributions: Conceptualization, K.L. and S.Y.; methodology, K.L., S.Y. and B.H. (Binbin Huang); software, K.L., S.Y. and C.S.; validation, K.L. and S.Y.; formal analysis, K.L., S.Y. and H.W. (Haoqi Wang); investigation, K.L., S.Y. and Z.C.; resources, K.L. and S.Y.; data curation, K.L., S.Y. and T.X.; writing—original draft preparation, K.L. and S.Y.; writing—review and editing, K.L., S.Y., C.X., B.H. (Baolong Han), H.W. (Haijun Wang) and F.L.; visualization, K.L. and S.Y.; supervision, K.L., S.Y., H.W. (Haijun Wang) and F.L.; project administration, K.L., S.Y., H.W. (Haijun Wang) and F.L.; funding acquisition, K.L., S.Y., H.W. (Haijun Wang) and F.L.; K.L. and S.Y. contributed equally to this work. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the National Natural Science Foundation of China (Grant 72174192), the National Key Research and Development Program of China (Grant 2022YFB3903701), the Carbon Peak Carbon Neutrality Eco-Environmental Technology Project of the Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences (Grants RCEES-TDZ-2021-8 and RCEES-TDZ-2021-16), the Major Research Program of Hebei Province (Grant 21373902D), and the Youth Innovation Promotion Association, Chinese Academy of Sciences (Grants 2013030 and 2014312).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data used to support the findings of this study are available from the author upon request.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. IPCC. *Climate Change 2021: The Physical Science Basis*; Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S.L., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M.I., Eds.; Cambridge University Press: Cambridge, UK; New York, NY, USA, 2021.
2. Yang, T.; Fang, L.; Wang, H.L. Total Carbon Emission Accounting and the Determination of Carbon Peak at the District and County Scale. *J. Energy Conserv. Environ. Prot.* **2021**, *8*, 37–39.
3. Zhang, Y.; Lu, H.J.; Zheng, H.M. Progress in the study of nitrogen cycling and nitrogen metabolism under the influence of multi-scale human activities. *Chin. J. Popul. Resour. Environ.* **2016**, *26*, 417–422.
4. Cai, B.; Wang, J.; Yang, S.; Mao, X.; Cao, L. Carbon dioxide emissions from cities in China based on high resolution emission gridded data. *Chin. J. Popul. Resour. Environ.* **2017**, *15*, 58–70. [CrossRef]
5. Gurney, K.R.; Kılkış, Ş.; Seto, K.C.; Lwasa, S.; Moran, D.; Riahi, K.; Keller, M.; Rayner, P.; Luqman, M. Greenhouse gas emissions from global cities under SSP/RCP scenarios, 1990 to 2100. *Glob. Environ. Change* **2022**, *73*, 102478. [CrossRef]
6. Zhao, H.X. *Research on the Relationship between Chinese Urbanization Development and Carbon Emissions*; Jilin University: Changchun, China, 2015.
7. Cai, M.M.; Zhao, M.; Wu, K.Y. Impact of urbanization on carbon emission in Shanghai. *J. Anhui Agric. Univ.* **2017**, *44*, 81–86.
8. Shan, Y.; Guan, D.; Hubacek, K.; Zheng, B.; Davis, S.J.; Jia, L.; Liu, J.; Liu, Z.; Fromer, N.; Mi, Z.; et al. City-level climate change mitigation in China. *Sci. Adv.* **2018**, *4*, eaaq0390. [CrossRef] [PubMed]

9. Zhang, M.; Huang, X.J.; Chuai, X.W. Research on China's urban carbon emission accounting and influencing factors. *Ecol. Econ.* **2019**, *35*, 13–19+74.
10. Huang, R.Q.; Zeng, Q. Research on the dynamic evolution and grade assessment of carbon emission in Xi'an. *Environ. Sci. Sur.* **2023**, *42*, 1–8.
11. Mutlu, V.; Cindoruk, Y.O.; Cindoruk, S.S. Evaluation of Bursa metropolitan greenhouse Gas inventory and reduction targets. *Urban Clim.* **2020**, *34*, 100717. [CrossRef]
12. Liu, J.B.; Xu, X.Y.; Li, S.W. Lifecycle carbon footprint analysis of China's power industry. *Chin. J. Popul. Resour. Environ.* **2022**, *32*, 31–41.
13. Markolf, S.A.; Matthews, H.S.; Azevedo, I.L.; Hendrickson, C. An integrated approach for estimating greenhouse gas emissions from 100 U.S. metropolitan areas. *Environ. Res. Lett.* **2017**, *12*, 024003. [CrossRef]
14. Castrejón-Godínez, M.L.; Sánchez-Salinas, E.; Rodríguez, A.; Ortiz-Hernández, M.L. Analysis of solid waste management and greenhouse gas emissions in Mexico: A study case in the central region. *J. Environ. Prot.* **2015**, *6*, 146. [CrossRef]
15. Guo, Y.J.; Gong, Y.P.; Zou, Y.F.; Ying, Z.; Jiangdu, L.; Xinyi, Z. Temporal variation characterstics and influencing factors of carbon emissions from municipal solid waste treatment in Tianjin. *J. Environ. Engr. Technol.* **2022**, *12*, 834–842.
16. Hachaichi, M.; Baouni, T. Virtual carbon emissions in the big cities of middle-income countries. *Urban Clim.* **2021**, *40*, 100986. [CrossRef]
17. Guo, Z. *Analysis on the Characteristics and Influence Factors of Carbon Emission Urban Typical with Household Consumption in Beijing*; University of Chinese Academy of Sciences: Beijing, China, 2015.
18. Carpio, A.; Ponce-Lopez, R.; Lozano-García, D.F. Urban form, land use, and cover change and their impact on carbon emissions in the Monterrey Metropolitan area, Mexico. *Urban Clim.* **2021**, *39*, 100947. [CrossRef]
19. Wang, W.J.; Lu, F.; Ou Yang, Z.Y. Spatial identification of territory space ecological conservation and restoration: A case study of Beijing. *Acta Ecol. Sin.* **2022**, *42*, 2074–2085.
20. Zheng, Y.; Lu, F.; Liu, J.R.; Wang, X.K. Comparative study on CO_2 emissions from fossil energy consumption and its influencing factors in typical of China. *Acta ecol. Sin.* **2020**, *40*, 3315–3327.
21. Xu, G.Q.; Liu, Z.Y.; Jiang, Z.H. Decomposition model and empirical study of carbon emissions for China, 1995–2004. *Chin. J. Popul. Resour. Environ.* **2006**, *6*, 158–161.
22. Wang, Y.; Chen, W.; Kang, Y.; Li, W.; Guo, F. Spatial correlation of factors affecting CO_2 emission at provincial level in China: A geographically weighted regression approach. *J. Clean. Prod.* **2018**, *184*, 929–937. [CrossRef]
23. Ang, B.W.; Zhang, F.G.; Choi, K.-H. Factorizing changes in energy and environmental indicators through decomposition. *Energy* **1998**, *23*, 489–495. [CrossRef]
24. Ehrlich, P.; Holdren, J. Impact of population growth. *Popul. Resour. Environ.* **1972**, *3*, 365–377.
25. Dietz, T.; Rosa, E.A. Effects of population and affluence on CO_2 emissions. *Proc. Natl. Acad. Sci. USA* **1997**, *94*, 175–179. [CrossRef]
26. Zhou, Y.; Shan, Y.; Liu, G.; Guan, D. Emissions and low-carbon development in Guangdong-Hong Kong-Macao Greater Bay Area cities and their surroundings. *Appl. Energy* **2018**, *228*, 1683–1692. [CrossRef]
27. Svirejeva-Hopkins, A.; Schellnhuber, H.J. Urban expansion and its contribution to the regional carbon emissions: Using the model based on the population density distribution. *Ecol. Model.* **2008**, *216*, 208–216. [CrossRef]
28. Strohbach, M.W.; Haase, D. Above-ground carbon storage by urban trees in Leipzig, Germany: Analysis of patterns in a European city. *Landscape Urban Plan.* **2012**, *104*, 95–104. [CrossRef]
29. Pataki, D.E.; Alig, R.J.; Fung, A.S.; Golubiewski, N.E.; Kennedy, C.A.; McPherson, E.G.; Nowak, D.J.; Pouyat, R.V.; Romero Lankao, P. Urban ecosystems and the North American carbon cycle. *Glob. Chang. Biol.* **2006**, *12*, 2092–2102. [CrossRef]
30. Creutzig, F.; Baiocchi, G.; Bierkandt, R.; Pichler, P.P.; Seto, K.C. Global typology of urban energy use and potentials for an urbanization mitigation wedge. *Proc. Natl. Acad. Sci. USA* **2015**, *112*, 6283–6288. [CrossRef]
31. Croci, E.; Melandri, S.; Molteni, T. Determinants of cities' GHG emissions: A comparison of seven global cities. *Int. J. Clim. Chang Str.* **2011**, *3*, 275–300. [CrossRef]
32. Li, Z.; Deng, X.Z.; Peng, L. Uncovering trajectories and impact factors of CO_2 emissions: A sectoral and spatially disaggregated revisit in Beijing. *Technol. Forecast. Soc. Chang.* **2020**, *158*, 120124. [CrossRef]
33. Zhou, Y.; Li, Y.P.; Huang, G.H. Planning sustainable electric-power system with carbon emission abatement through CDM under uncertainty. *Appl. Energy* **2015**, *140*, 350–364. [CrossRef]
34. Energy Statistics Division, National Bureau of Statistics. *China Energy Statistical Yearbook*; China Statistics Press: Beijing, China, 2011.
35. Guangdong Provincial Bureau of Statistics, National Bureau of Statistics. *Guangdong Statistical Yearbook*; China Statistics Press: Beijing, China, 2006.
36. Shenzhen Municipal Bureau of Statistics. *Shenzhen Statistical Yearbook*; China Statistics Press: Beijing, China, 2006.
37. Shan, Y.; Guan, D.; Zheng, H.; Ou, J.; Li, Y.; Meng, J.; Mi, Z.; Liu, Z.; Zhang, Q. China CO_2 emission accounts 1997–2015. *Sci. Data.* **2018**, *5*, 170201. [CrossRef] [PubMed]
38. Department of Climate Change of the National Development and Reform Commission. *Provincial Greenhouse Gas Inventory Preparation Guidelines (Trial)*; Department of Climate Change of the National Development and Reform Commission: Beijing, China, 2011.
39. Beijing Municipal Bureau of Statistics. *Beijing Statistical Yearbook*; China Statistics Press: Beijing, China, 2006.

40. Liu, H.Q.; Fu, J.X.; Liu, S.Y.; Xie, X.Y.; Yang, X.Y. Calculation methods and application of carbon dioxide emission during steel-making process. *Iron Steel* **2016**, *51*, 74–82.
41. National Bureau of Statistics. *China Statistical Yearbook on Environment*; China Statistics Press: Beijing, China, 2006.
42. Shenzhen Municipal Bureau of Ecology and Environment. Information Announcement on Prevention and Control of Environmental Pollution by Solid Wastes Shenzhen. Available online: http://meeb.sz.gov.cn/xxgk/qt/tzgg/content/post_2085853.html (accessed on 5 January 2022).
43. Liu, L.; Qu, J.; Zhang, Z.; Zeng, J.; Wang, J.; Dong, L.; Pei, H.; Liao, Q. Assessment and determinants of per capita household CO_2 emissions (PHCEs) based on capital city level in China. *J. Geogr. Sci.* **2018**, *28*, 1467–1484. [CrossRef]
44. Beijing Municipal Commission of Planning and Natural Resources. Land change survey in Beijing. Available online: http://ghzrzyw.beijing.gov.cn/zhengwuxinxi/sjtj/tdbgdctj/201912/t20191213_1159087.html (accessed on 16 January 2022).
45. Shenzhen Municipal Bureau of Planning and Natural Resources. Bulletin of the Main Data Results of the Land Change Survey. Available online: http://pnr.sz.gov.cn/xxgk/sjfb/tjsj/index_17.html (accessed on 16 January 2022).
46. National Development and Reform Commission, National Bureau of Statistics. *Accounting Standards of Gross Ecosystem Product (Trial)*; Department of Climate Change of the National Development and Reform Commission: Beijing, China, 2022.
47. Yu, T.R.; Lu, F.; Yang, S.S. Greenhouse gas budget and net carbon sequestration of different afforestation types used in grain for green project—A case study in central south and east China. *Bull. Soil Water Conserv.* **2022**, *42*, 337–347+59.
48. Zhang, X.D.; Zu, J.H.; Kang, X.M. An overview of greenhouse gas inventory in the Chinese wetlands. *Acta Ecol. Sin.* **2022**, *42*, 9417–9430.
49. IPCC. *IPCC Guidelines for National Greenhouse Gas Inventories*; IPCC: Geneva, Switzerland, 2006.
50. Liu, R. *Research on Greenhouse Gas Emission in Beijing*; Beijing University of Civil Engineering and Architecture: Beijing, China, 2016.
51. Sun, Y.G. *Characteristics and Driving Forces of Carbon Emissions of 50 Chinese Cities During 2000–2015*; Nanjing University: Nanjing, China, 2019.
52. Long, Y.; Jiang, Y.; Chen, P.; Yoshida, Y.; Sharifi, A.; Gasparatos, A.; Wu, Y.; Kanemoto, K.; Shigetomi, Y.; Guan, D. Monthly direct and indirect greenhouse gases emissions from household consumption in the major Japanese cities. *Sci. Data* **2021**, *8*, 301. [CrossRef]
53. Wu, Y.; Wang, X.K.; Lu, F. The carbon footprint of food consumption in Beijing. *Acta Ecol. Sin.* **2012**, *32*, 1570–1577.
54. Xian, C.F.; Ouyang, Z.Y. Urban ecosystem nitrogen metabolism: Research progress. *Chin. J. Ecol.* **2014**, *33*, 2548–2557.
55. Li, N. *Study on Energy Consumption and GHG Emissions of Agriculture in China*; Dalian University of Technology: Dalian, China, 2014.
56. Shuai, C.; Chen, X.; Wu, Y.; Tan, Y.; Zhang, Y.; Shen, L. Identifying the key impact factors of carbon emission in China: Results from a largely expanded pool of potential impact factors. *J. Clean Prod.* **2018**, *175*, 612–623. [CrossRef]
57. Xiong, C.H.; Chen, S.; Huang, R. Extended STIRPAT model-based driving factor analysis of energy-related CO_2 emissions in Kazakhstan. Environ. *Sci. Pollut. Res.* **2019**, *26*, 15920–15930. [CrossRef]
58. Xue, Y.X.; Xie, J.C.; Huai, C.P. Decomposition Analysis of Influencing Factors of Energy Related Carbon Emission in Beijing. *J. Build. Energy Effic.* **2022**, *50*, 128–132.
59. Tang, B.J.; Zhou, B.J.; Feng, C. Analysis on influence factors of energy consumption and research on energy saving and emission reduction in Beijing: Based on the industrial perspective. *J. Chongqing Univ. Tech.* **2015**, *29*, 19–27+67.
60. Li, F.; Mao, H.W.; Lai, Y.P. Greenhouse Gas Inventory and Emission Accounting of Shenzhen. *Urban Dev. Stud.* **2013**, *20*, 136–139+43.
61. Liao, S.; Wang, D.; Ren, T.; Liu, X. Heterogeneity and Decomposition Analysis of Manufacturing Carbon Dioxide Emissions in China's Post-Industrial Innovative Megacity Shenzhen. *Int. J. Env. Res. Public Health* **2022**, *19*, 15529. [CrossRef] [PubMed]
62. Wang, A.; Zhao, T.Z. Greenhouse Gas Emission Characteristics of Municipal Waste Management in Beijing. *Environ. Monit. China* **2017**, *33*, 68–75. [CrossRef]
63. Zhang, J.F.; Fang, H.; Ma, B.F.; You, H. Study on Carbon Emissions from Municipal Solid Waste in Shenzhen. In Proceedings of the 2015 International Symposium on Energy Science and Chemical Engineering, Guangzhou, China, 12–13 December 2015; He, Y., Ed.; Atlantis Press: Paris, France, 2015; Volume 45, pp. 232–235.
64. Wang, Y.; Li, F.; Chen, X.C. Characteristics and influencing factors of carbon emission from typical community household consumption: A case of Beijing. *Acta Ecol. Sin.* **2019**, *39*, 7840–7853.
65. Li, W.L. *The Research of Driving Forces of CO_2 Emission from Household Consumption in Beijing*; Beijing Institute of Technology: Beijing, China, 2018.
66. Zhang, G.; Li, L.; Huang, C.; Huang, H.; Chen, M.; Chen, C.; Zhou, N. Carbon emissions of the household living in Shanghai using Urban-R AM model. *Acta Sci. Circumstantiae* **2014**, *34*, 457–465.
67. Liu, A.Y.; Ke, S.F.; Wang, Y. The Land Resources Endowment and Carbon Sinks Volume of Beijing. *For. Econ.* **2015**, *37*, 94–98+128.
68. Zeng, H.; Gao, Q.; Chen, X.; Li, G. Changes of the wetland landscape in Shenzhen city from 1988 to 2007 and the driving force analysis. *Acta Ecol. Sin.* **2010**, *30*, 2706–2714.
69. Su, K.; Wei, D.Z.; Lin, W.X. Influencing factors and spatial patterns of energy-related carbon emissions at the city-scale in Fujian province, Southeastern China. *J. Clean. Prod.* **2020**, *244*, 118840. [CrossRef]
70. Wen, L.; Zhang, Z.Q. Probing Energy-Related CO_2 Emissions in the Beijing-Tianjin-Hebei Region Based on Ridge Regression Considering Population Factors. *Pol. J. Environ. Stud.* **2020**, *29*, 2413–2427. [CrossRef]

71. Song, X.C.; Du, S.; Shen, P. Analysis of Decoupling Relationship Between Economy and CO_2 from Manufacturing Industry of China. *Environ. Sci. Technol.* **2022**, *45*, 201–208.
72. Su, M. *Decoupling Effect of Carbon Emissions and Economic Growth and Its Driving Forces in Shandong Province*; China University of Petroleum (East China): Qingdao, China, 2019.