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Analysis of Characteristics of Urban Greenhouse Gas Emissions in Yunnan Province

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Abstract As a typical province in China's low-latitude plateau, Yunnan Province is vulnerable to climate change driven by extreme weather events, which poses a severe threat to regional economic development and urban security. Based on data on greenhouse gas emissions from 16 major cities in Yunnan Province in 2005, 2010, 2015 and 2020, this paper systematically quantified emission characteristics, compared emission levels across cities, and identified the emission structure of typical industrial sectors. The results indicate that the greenhouse gas emissions of all cities fluctuated throughout the study period, and no city reached its emission peak; both carbon dioxide emissions per unit GDP and per capita emissions were high in Qujing, Honghe and Yuxi and low in Nujiang, Diqing, Xishuangbanna, and other regions; for industrial cities represented by Qujing, the combined emissions from industrial energy consumption and industrial processes accounted for 88% – 95% of total emissions, constituting the dominant emission sources. This study suggests that strategies for the mitigation of urban greenhouse gas in Yunnan Province should prioritize improving industrial energy efficiency and regulating industrial processes, while differentiated pathways for emission reduction should be formulated in light of local conditions. This paper provides a scientific basis and decision-making reference for the construction of low-carbon cities in Yunnan.

Key words Greenhouse gas, Emission characteristics, Urban scale, Yunnan Province, Industrial emissions

0 Introduction

The Sixth Assessment Report of the Intergovernmental Panel on Climate Change (*IPCC*) clearly states that anthropogenic greenhouse gas emissions are the primary driver of global warming since the Industrial Revolution, and the frequency and intensity of extreme weather events have increased significantly[1]. As agglomerations of population and economic activities, cities contribute approximately 70% of global energy-related greenhouse gas emissions[2]. With the continuous advancement of global urbanization, especially the rapid growth of urban populations and energy consumption in developing countries, the total amount of urban greenhouse gas emissions and their share in global emissions are expected to keep rising. Against this backdrop, cities have become core arenas for global efforts to mitigate climate change. An increasing number of cities have set carbon neutrality and low-carbon development goals and actively explored emission reduction pathways compatible with their respective development stages[3].

At the international level, methodologies for urban greenhouse gas accounting have evolved from general frameworks to refined and localized systems. Institutions including the Institute for Global Environmental Strategies (IGES) and the C40 Urban Climate Leadership Group jointly developed the Global Protocol for Community – Scale Greenhouse Gas Emission Inventories (GPC), laying a foundation for cross-city comparability[4]. Major cities in developed European and American countries (*e.g.*, New York, London, and Tokyo) established long-term continuous emission inventory systems at an early stage, and relevant research has shifted focus from total emission accounting to sectoral mitigation potential assessment and carbon neutrality pathway simulation[5]. In recent years, China has made substantial progress in research on urban greenhouse gas emission accounting[6]. Institutions such as the National Center for Climate Change Strategy and International Cooperation have released multiple editions of guidelines for compiling provincial and municipal greenhouse gas inventories. Numerous scholars have conducted emission accounting and characteristic analyses for cities at various administrative levels across China based on energy balance tables and statistical yearbook data[6]. Existing studies generally conclude that urban emissions in China exhibit prominent regional disparities and industrial concentration: the emission intensity of industry-dominated cities is far higher than that of service-oriented cities, and carbon emissions per unit GDP in central and western cities are generally higher than those in eastern coastal cities[7]. Nevertheless, most existing research focuses on economically developed urban agglomerations, including the Beijing – Tianjin – Hebei Region, the Yangtze River Delta, and the Pearl River Delta, while cities in the southwest plateau have received insufficient research attention.

Located on China's low-latitude plateau, Yunnan Province features fragile ecological environments and complex climatic systems, rendering it particularly sensitive to the impacts of global climate change. In recent years, frequent extreme weather events such as droughts and heavy rainstorms have posed substantial threats to agricultural production, water resource supply, and urban infrastructure safety across the province[8]. Meanwhile, Yunnan is undergoing accelerated industrialization and urbanization,

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accompanied by rising energy consumption and greenhouse gas emissions. Compared with developed eastern provinces, research on urban greenhouse gas inventories in Yunnan started late and is hampered by inadequate basic data. Besides, a standardized unified evaluation indicator system for urban greenhouse gas emissions remains absent, leading to a lack of systematic comparisons of emission levels across cities and ambiguous industrial emission structures. This impedes precise support for the formulation of differentiated emission reduction strategies.

Against the above background, this paper quantified the greenhouse gas emissions of 16 major cities in Yunnan Province, systematically compared total urban emissions, carbon emissions per unit GDP, and per capita emissions across four time cross-sections (2005, 2010, 2015, and 2020), identified the emission structure and contributions of typical sectors, and analyzed the emission characteristics of industrial cities represented by Qujing. This research aims to fill the gap in research on urban greenhouse gas emissions and provide scientific evidence and decision support for advancing low-carbon and green urban development in Yunnan Province.

1 Data sources and research methods

1.1 Study area and time scope The 16 prefecture-level administrative regions of Yunnan Province, namely Kunming City, Qujing City, Yuxi City, Baoshan City, Zhaotong City, Lijiang City, Pu'er City, Lincang City, Chuxiong Yi Autonomous Prefecture, Honghe Hani and Yi Autonomous Prefecture, Wenshan Zhuang and Miao Autonomous Prefecture, Xishuangbanna Dai Autonomous Prefecture, Dali Bai Autonomous Prefecture, Dehong Dai and Jingpo Autonomous Prefecture, Nujiang Lisu Autonomous Prefecture, and Diqing Tibetan Autonomous Prefecture, were studied. To reveal the temporal evolution of urban greenhouse gas emissions, four typical years (2005, 2010, 2015, and 2020) were selected as research cross-sections, covering the 11th Five-Year Plan to the 13th Five-Year Plan periods.

1.2 Data sources Greenhouse gas emission data used in this study were derived from the China Urban Greenhouse Gas Database (https://www.cityghg.com/toCauses?id=4). The dataset of urban greenhouse gas emissions in Yunnan Province was extracted from the database, with detailed information as follows. (i) Research scope. Research objects: 16 major regions in Yunnan (Kunming, Qujing, Yuxi, Baoshan, Zhaotong, Lijiang, Pu'er, Lincang, Chuxiong, Honghe, Wenshan, Xishuangbanna, Dali, Dehong, Nujiang, and Diqing). Research period: four key time nodes (2005, 2010, 2015, and 2020), covering critical stages of China's low-carbon policy implementation. (ii) Core data types. Basic statistical data: the data of GDP (for calculating carbon emissions per unit total GDP) and permanent resident population (for calculating per capita emissions) in each city were sourced from urban energy balance tables, statistical yearbooks, data on activity levels of industrial processes, and provincial greenhouse gas inventory outputs of Yunnan Province[9-10]. Energy consumption data were categorized by coal, oil, gas, electricity, and other fuel types; industrial process emissions covered major manufacturing processes, including cement production, iron and steel smelting, and non-ferrous metal smelting. Population and GDP data were obtained from the *Yunnan Statistical Yearbook* and national economic and social development statistical bulletins of each city[10]. GDP was calculated at current prices, and the nominal GDP of each city in the corresponding year is adopted for analyzing emissions per unit GDP. (iii) Data on greenhouse gas emissions: carbon dioxide emissions were the core indicator, including total emissions (10 000 t), direct emissions, and indirect emissions, and covering nine major sectors such as agriculture, services, industrial energy consumption, and industrial processes. (iv) Standard gas and accounting data: emissions were calculated based on unified accounting standards; key emission parameters referred to relevant national standards and industrial accounting specifications to ensure data comparability. (v) Key data. Urban emission data included total emissions, carbon dioxide emissions per unit total GDP, per capita emissions, and sectoral emission data. Total emissions: total carbon dioxide emissions of each city from 2005 to 2020 (*e.g.*, 55.28 million t in Qujing, 36.34 million t in Honghe, and 1.91 million t in Nujiang in 2020). Carbon dioxide emissions per unit total GDP: it ranged from 0 to 12 t/10^4 yuan; high-emission cities were concentrated in Qujing, Honghe, and Yuxi, while low-emission cities included Nujiang, Kunming, Xishuangbanna, *etc.* Per capita emissions: they range from 0 to 12 t/person; Yuxi, Qujing, and Honghe consistently were among the top three, whereas Nujiang, Lincang, and Xishuangbanna form the low-emission tier. Sectoral emission data: Qujing was a typical case, and the emission proportion of nine major sectors was subdivided (*e.g.*, industrial energy consumption 74%, industrial processes 16%, and road transportation 5% in 2020); Honghe, Yuxi, and other cities display similar sectoral emission structure.

1.3 Emission accounting method Referring to the methodological frameworks of the *Guidelines for Compiling Provincial Greenhouse Gas Inventories* (*2025 Edition*) issued by the Ministry of Ecology and Environment in 2026[9], the 2006 *IPCC Guidelines for National Greenhouse Gas Inventories*, and its 2019 revised version[11], this study adopted the emission factor method to calculate sectoral greenhouse gas emissions of each city in Yunnan Province. Compared with the 2011 trial version, the updated guidelines comprehensively revised accounting boundaries and methodologies: the number of covered industrial sectors in industrial production processes and product use expanded from 12 to 24; carbon capture, transportation and geological storage were newly incorporated into energy activity inventories; global warming potential (GWP) values are updated to those from the *Fifth Assessment Report of the IPCC*, providing more solid methodological support for the compilation of scientific and standardized inventories. Total carbon dioxide emissions consisted of direct emissions and indirect emissions. Direct emissions refer to emissions generated by fossil fuel combustion and industrial processes, while indirect emissions represent upstream power generation emissions associated with purchased electricity consumed within cities. The accounting boundary covered nine sectors: agriculture, industrial energy consumption, industrial processes, services, urban residential consumption, rural residential consumption, road transportation, railway transportation, and air transportation. Emission factors prioritized locally measured or regionally recommended values in Yunnan; national default factors were adopted when local data were unavailable. Indirect power emission factor was calculated based on the average emission factor of regional power grids in Southern China in each year.

1.4 Evaluation indicators Three indicators were selected to comprehensively characterize urban greenhouse gas emissions, including total emissions, carbon dioxide emissions per unit GDP ($t/10^4$ yuan) and per capita emissions (t/person)[12]. Carbon dioxide emissions per unit GDP reflect the decoupling degree between economic growth and carbon emissions, while per capita emissions embody emission responsibility and levels at the individual level. Complementary to one another, the three indicators facilitate comprehensive comparisons of emission disparities across cities from the dimensions of economic efficiency and per capita carbon burden.

2 Results and analysis

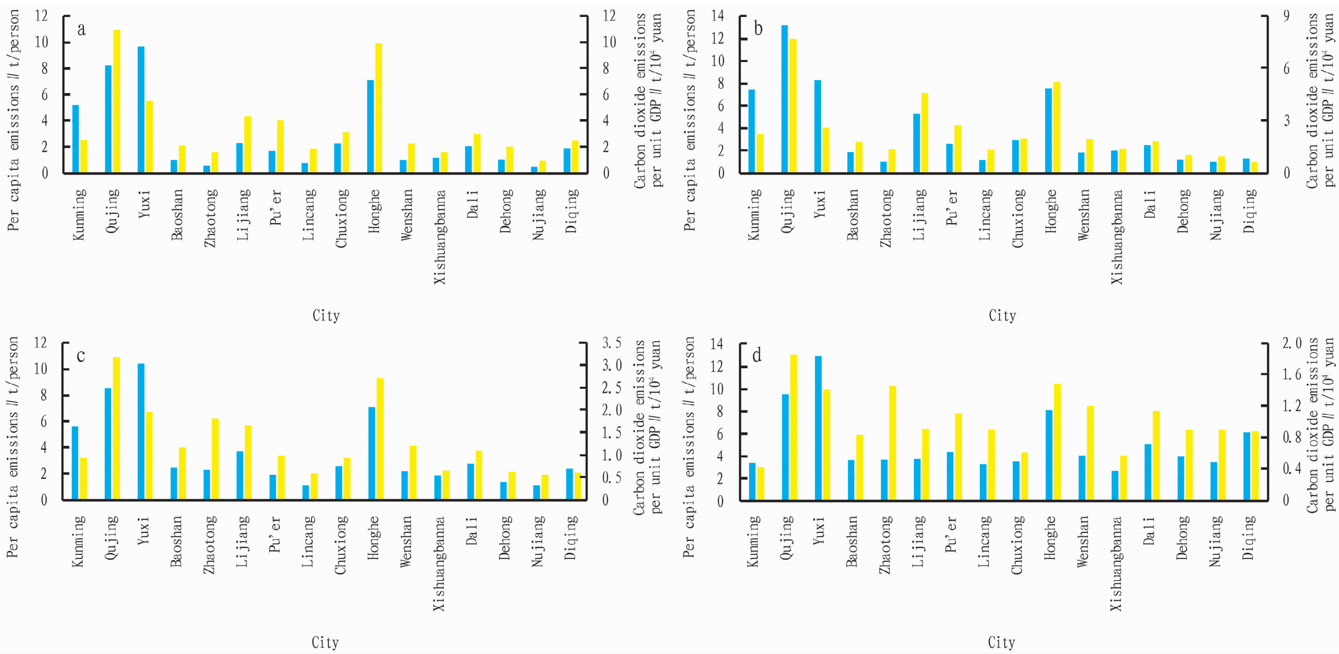
2.1 Comparison of total urban emissions From the perspective of total emissions, greenhouse gas emissions varied significantly across the 16 regions in Yunnan Province, presenting a highly spatially concentrated pattern. In 2005, the top three cities by total emissions were Qujing (48.29 million t), Honghe (30.56 million t), and Kunming (26.30 million t), while those of Nujiang (0.22 million t), Diqing (0.69 million t), and Dehong (1.16 million t) were the lowest, and the maximum was approximately 220 times the minimum. In 2010, total emissions in all cities rose generally. Qujing (77.46 million t), Kunming (47.46 million t), and Honghe (33.92 million t) still occupied the top three positions, while Diqing (0.47 million t), Nujiang (0.52 million t), and Dehong (1.47 million tons) remained at the bottom. Emissions in Qujing increased by 60.4% relative to 2005. In 2015, Qujing (52.34 million t), Honghe (33.41 million t), and Yuxi (24.81 million t) ranked the top three; Nujiang (0.66 million t), Diqing (1.01 million t), and Dehong (1.86 million t) remained low-emission cities. Notably, emissions in Qujing dropped by 32.4% compared with 2010, showing obvious volatility. In 2020, Qujing (55.28 million t), Honghe (36.34 million t), and Yuxi (29.17 million t) stayed at the forefront, while Nujiang (1.91 million t), Diqing (2.38 million t), and Xishuangbanna (3.51 million t) recorded the lowest emissions. Qujing's emissions rebounded slightly by 5.6% relative to 2015. In word, Qujing, Honghe, and Yuxi consistently accounted for over 60% of the province's total emissions, whereas western cities, including Nujiang, Diqing, and Dehong, maintained extremely low emission levels, forming a distinct spatial pattern of "high emissions in the east and low emissions in the west"[7]. It is worth noting that the emissions in all cities fluctuated to varying degrees across the four research years with the adjustment of economic cycles and industrial structure.

2.2 Comparison of carbon dioxide emissions per unit GDP

Carbon dioxide emissions per unit GDP reflect the carbon emission efficiency of economic growth. As shown in Fig. 5, the three cities with the highest emissions per unit GDP were Qujing, Honghe and Yuxi, while Nujiang, Xishuangbanna and Zhaotong recorded the lowest values in 2005. In 2010, Qujing, Honghe and Lijiang ranked the top three, and Diqing, Nujiang and Dehong had the lowest emissions per unit GDP. In 2015, the top three regions were Qujing, Honghe and Yuxi, and the minimums appeared in Nujiang, Lincang and Diqing. In 2020, Qujing, Honghe and Zhaotong occupied the top three positions, with Kunming, Xishuangbanna and Chuxiong at the bottom. Across all four years, Qujing and Honghe consistently ranked first and second in carbon dioxide emissions per unit GDP, indicating that economic growth in these two cities still relied heavily on energy-intensive industries. The emissions per unit GDP in Kunming (the provincial capital) gradually declined from the medium level in 2005 to the provincial minimum in 2020, reflecting positive outcomes from industrial restructuring toward service industries[6]. Lijiang's emissions per unit GDP surged to third place in 2010 due to the phased commissioning of large-scale industrial projects in the region, followed by a decline to the medium range in subsequent years. Low-emission cities could be divided into two categories: Diqing and Xishuangbanna which are dominated by tourism and ecological functions, as well as economically underdeveloped regions with small industrial scales including Nujiang and Dehong.

2.3 Comparison of per capita emissions Per capita emissions measure the emission level from an individual perspective[13]. In 2005 (Fig. 1), Yuxi, Qujing, and Honghe ranked the top three in terms of per capita emissions, while Nujiang, Zhaotong, and Lincang had the lowest per capita emissions. In 2010, Qujing, Yuxi, and Honghe ranked first to third, with Nujiang, Zhaotong, and Lincang at the bottom. In 2015, Yuxi, Qujing, and Honghe remained the top three, and Nujiang, Lincang, and Dehong had the lowest values. In 2020, Yuxi, Qujing, and Honghe still took the top three positions, while Xishuangbanna, Lincang, and Kunming recorded the lowest per capita emissions. Yuxi, Qujing, and Honghe persistently occupied the top three positions across all four years, with Yuxi ranking first in 2005, 2015, and 2020. This result is highly consistent with total emissions and emissions per unit GDP, further confirming the high-emission characteristics of industrial cities in central and eastern

Yunnan. Notably, Kunming's per capita emissions dropped from the medium level in 2015 to the provincial minimum in 2020, demonstrating that the provincial capital effectively controlled emission growth amid continuous population agglomeration and took a leading position in low-carbon development. Nujiang, Lincang, and Xishuangbanna had low per capita emissions and were characterized by weak industrial foundations, low population density, and strong carbon sequestration capacity of terrestrial ecosystems.



NOTE a. 2005; b. 2010; c. 2015; d. 2020.

Fig. 1 Per capita emissions and carbon dioxide emissions per unit GDP of cities in Yunnan Province in 2005, 2010, 2015 and 2020

2.4 Analysis of sectoral emission structure In terms of sectoral emission structure, urban greenhouse gas emissions in Yunnan Province were highly concentrated in the industrial sector (Fig. 2 – Fig. 5 display the distribution and proportion of sectoral emissions in each city in 2005, 2010, 2015, and 2020, respectively). Qujing, a representative industrial city, is taken as an example to analyze sectoral emission structure. In 2005 (Fig. 2), the direct emissions of Qujing were 48.29 million t, and its indirect emissions were 0; sectoral proportions were as follows: agriculture 1%, services 0%, industrial energy consumption 91%, industrial processes 3%, urban residential consumption 0%, rural residential consumption 3%, road transportation 2%, railway transportation 0%, and air transportation 0%. Combined emissions from industrial energy consumption and industrial processes reached as high as 94%. In 2010 (Fig. 3), Qujing's direct emissions hit 77.46 million t, without indirect emissions; industrial energy consumption and industrial processes accounted for 89% and 6%, with a combined share of 95%, slightly higher than that in 2005. In 2015 (Fig. 4), Qujing's direct emissions stood at 50.79 million t, and indirect emissions increased to 1.55 million t (accounting for 3% of total emissions). Industrial energy consumption and industrial processes took up 79% and 9%, and their combined proportion fell to 88%, but they still held an absolutely dominant position. In 2020 (Fig. 5), Qujing's direct emissions were 54.72 million t, and indirect emissions increased to 0.56 million t; industrial energy consumption and industrial processes occupied 74% and 16%, with a combined proportion of 90%.

Column charts showing sectoral proportions in Fig. 2 – Fig. 5 intuitively reflect temporal changes in emissions from various sectors: the share of emissions from industrial energy consumption gradually decreased from 91% to 74%, while the proportion of emissions from industrial processes rose from 3% to 16%. This indicates that the proportion of emissions from fuel combustion declined alongside clean energy substitution and energy efficiency improvement, yet emissions from industrial processes such as cement and steel manufacturing increased due to rising outputs. The proportion of emissions from road transportation grew slowly from 2% to 5%, consistent with the expansion of motor vehicle ownership. Combined emissions from agriculture, urban and rural residential consumption accounted for less than 5% of total emissions throughout the study period, and emissions from railway and air transportation were nearly negligible. Yuxi and Honghe exhibited highly similar sectoral emission structure to Qujing, and the total emissions from industrial energy and industrial processes exceeded 85%. This reveals that the industrial sector, especially energy-intensive heavy industries, acted as the core driving factor of urban greenhouse gas emissions in Yunnan Province.

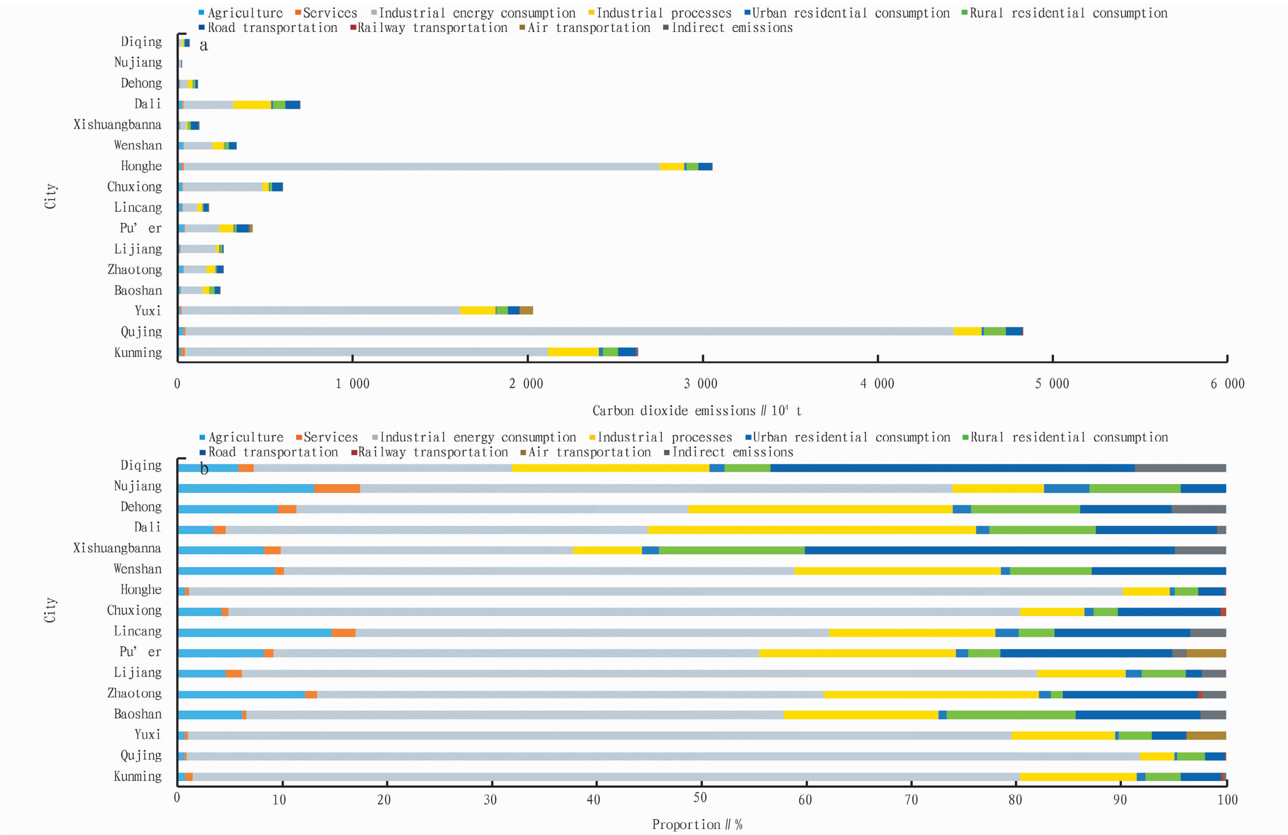


Fig. 2 Sectoral structure and proportion of greenhouse gas emissions in cities in Yunnan Province in 2005

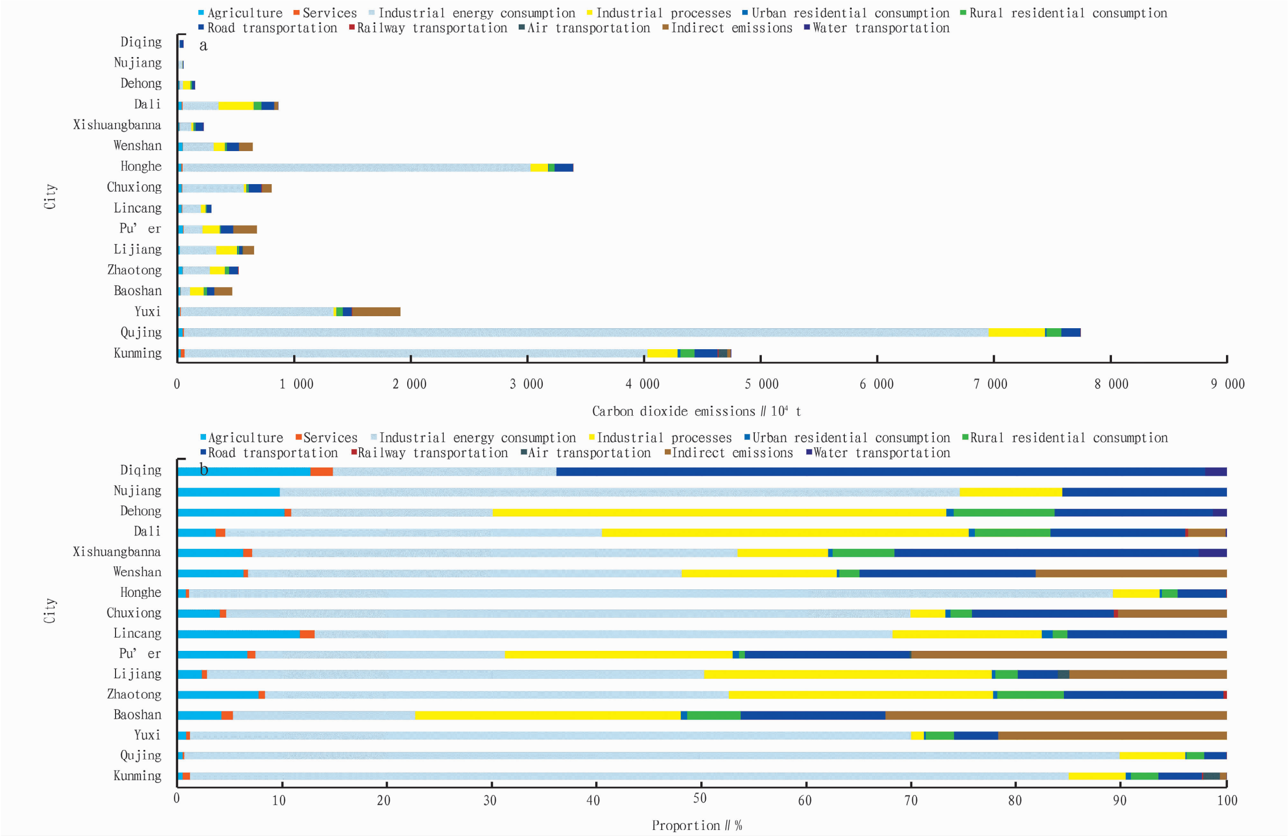


Fig. 3 Sectoral structure and proportion of greenhouse gas emissions in cities in Yunnan Province in 2010

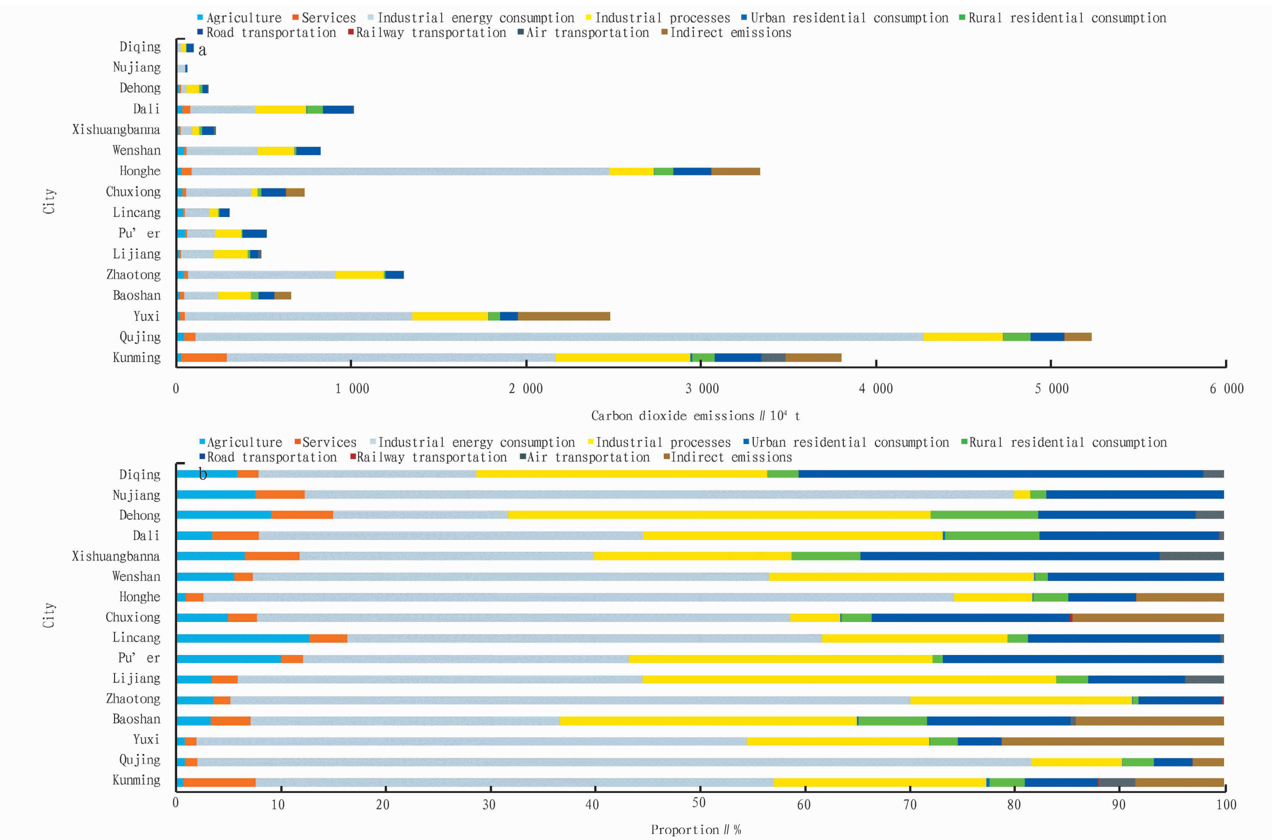


Fig. 4 Sectoral structure and proportion of greenhouse gas emissions in cities in Yunnan Province in 2015

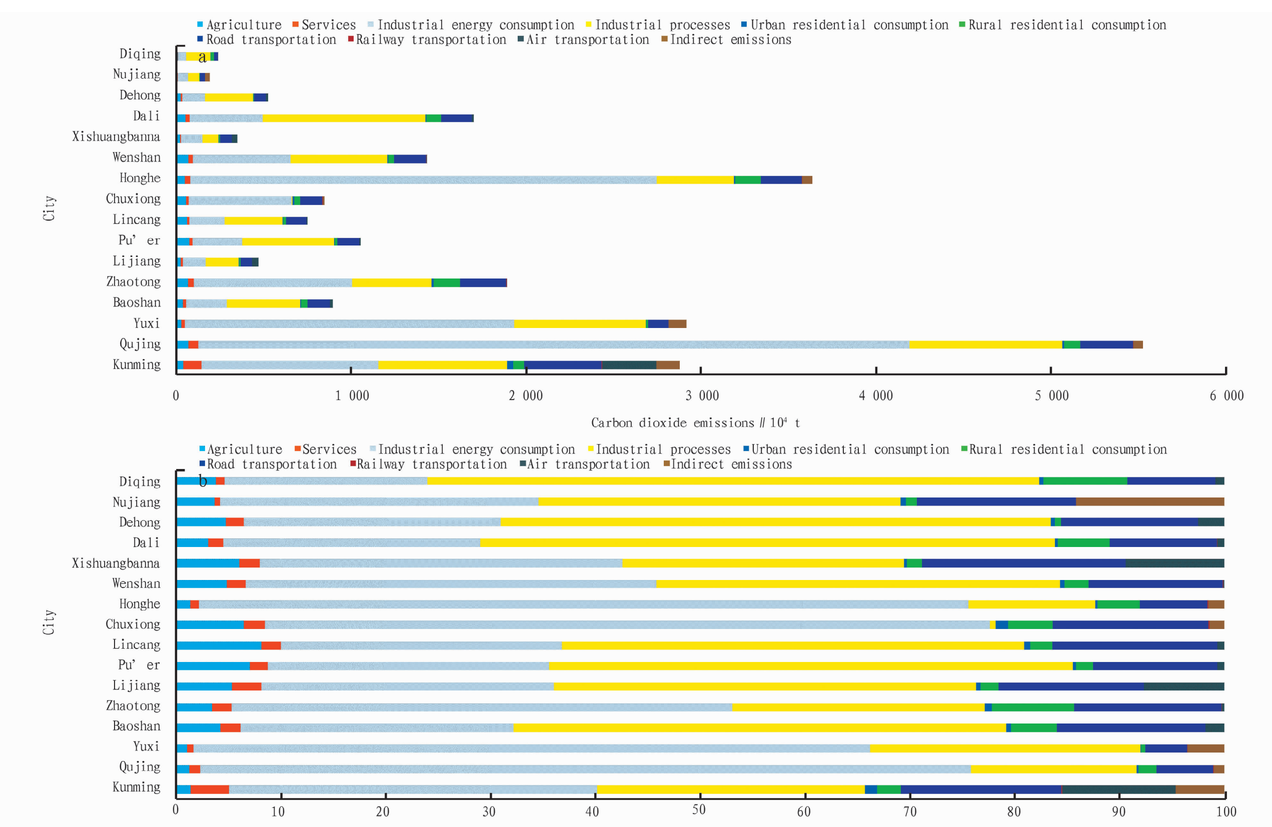


Fig. 5 Sectoral structure and proportion of greenhouse gas emissions in cities in Yunnan Province in 2020

3 Conclusions

(i) Total urban greenhouse gas emissions in Yunnan Province fluctuated from 2005 to 2020. The urban greenhouse gas emissions of Qujing, Honghe, and Yuxi consistently ranked the top three, contributing over 60% of total urban emissions across the province. Western cities such as Nujiang, Diqing, and Dehong maintained ultra-low emission levels, forming a remarkable spatial pattern of "high emissions in the east and low emissions in the west".

(ii) From the perspectives of emission efficiency and per capita carbon burden, Qujing and Honghe persistently took the first two positions in emissions per unit GDP, featuring high-carbon economic growth. Yuxi, Qujing, and Honghe were the top three cities in per capita emissions. Benefiting from industrial structure optimization, Kunming achieved the lowest emissions per unit GDP and per capita emissions in the province by 2020, emerging as a pioneer of low-carbon transformation in Yunnan.

(iii) Sectoral emissions were highly concentrated in the industrial sector. For industrial cities represented by Qujing, the combined proportion of emissions from industrial energy consumption and industrial processes was up to 88% – 95% across the four research years. The proportion of emissions from industrial energy consumption declined from 91% to 74%, while emissions from industrial processes increased significantly from 3% to 16%. Yuxi and Honghe presented identical characteristics. The industrial sector constitutes the core driver of urban greenhouse gas emissions in Yunnan Province, so emission reduction strategies should focus on improving industrial energy efficiency and regulating industrial production processes.

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