Humanities & Social Sciences Communications

ARTICLE

https://doi.org/10.1057/s41599-023-02100-3 OPEN

Check for updates

The impact of the digital economy on inter-city carbon transfer in China using the life cycle assessment model

Bingjiang Luan[1]✉, Hanshuo Yang[2]✉, Hong Zou[2] & Xi Yu[2]

The haven paradise hypothesis has been widely supported in the international carbon transfer, but there is still a lack of inter-city evidence. The emergence of the digital economy in recent years has introduced unprecedented opportunities and challenges for carbon emissions reduction and carbon transfer. As the world's largest carbon emitter and a major player in the digital economy, exploring whether the pollution haven hypothesis exists among cities in China and how the digital economy affects inter-city carbon transfer is crucial for countries to optimize their domestic carbon reduction structures. To this end, this paper employs the 2012 and 2015 Chinese Urban Household Survey data alongside input-output tables based on the life cycle assessment method to quantify the inter-city carbon transfer. In addition, the impact and mechanisms of the digital economy on inter-city carbon transfer are explored using the two-way fixed effects model. The results show that 54% of Chinese cities' carbon emissions come from outside, with third-tier cities bearing high carbon transfer pressures, indicating the presence of the pollution haven hypothesis. The digital economy exacerbates inter-city carbon transfer by promoting market integration and facilitating industrial transfer, and it mainly promotes the transfer of high-intensity carbon emissions to third-tier cities. Considering carbon emission reduction targets, mandatory environmental regulations have strengthened the effect of the digital economy on carbon transfer. Therefore, the Chinese government needs to properly address carbon transfer by improving the collaborative carbon reduction system, enhancing carbon emission reduction efficiency, and accelerating the equitable progress of the digital economy.

[1] Institute of Western China Economic Research, Southwestern University of Finance and Economics, Chengdu, China. [2] School of Economics, Southwestern University of Finance and Economics, Chengdu, China. ✉email: luanbingjiang@swufe.edu.cn; yhs7777@163.com

Introduction

With the globalization of the economy, the problem of carbon transfer caused by inter-regional trade has become increasingly prominent (Kim et al., 2019; Wang et al., 2022a). The pollution paradise hypothesis holds that developed regions transfer carbon emissions generated by high-polluting and high-emission industries to less developed or less environmentally regulated regions (Li et al., 2022; Liu et al., 2022). This has resulted in a series of undesirable outcomes including global carbon imbalances (Xu et al., 2022a), heightened environmental pollution in developing countries (Essandoh et al., 2020), and carbon market failure (Xu et al., 2022b). Some countries and regions have already paid more attention to the environmental externalities of regional carbon transfer (Lu et al., 2020; Zhang et al., 2020), such as the implementation of carbon tax and subsidy policies in Sweden (Runst and Thonipara, 2020) and the carbon border adjustment in the EU (Tagliapietra and Wolff, 2021). However, there is still a lack of literature on operationalizing carbon quotas at the local level and domestic inter-regional carbon transfers, especially in developing countries.

As the world's largest emitter of carbon, China has announced at the United Nations General Assembly that its CO_2 emissions would peak by 2030 and strive for carbon neutrality by 2060. During the 13th Five-Year Plan period, numerous provinces in China established mandatory emission reduction targets (Shao et al., 2018). In the 14th Five-Year Plan, China explicitly proposed to reduce CO_2 emissions by 18%[1], and implemented carbon quota allocation policies in many provinces (see Table S1). The central government has also included carbon emissions reduction in the annual performance evaluation index of local governments, which effectively reduces regional carbon emissions through green investment and carbon trading (Chen and Lin, 2021; Qin et al., 2023). However, the geographical carbon emissions reduction responsibility allocation system ignores the carbon transfer problem caused by inter-regional trade. Under the pressure of high-intensity carbon reduction, local governments may accomplish local carbon reduction targets through carbon transfer (Monica and Neha, 2021). This strategy has the potential to convert less developed or poorly regulated environmental regions into pollution havens, thereby significantly undermining the inter-regional carbon reduction structure and accelerating carbon market failure (Li et al., 2022; Liu et al., 2022). According to statistics, the carbon emissions driven by out-of-province consumption demand account for ~57% of the province's overall carbon emissions in China, while the share of out-of-province carbon emissions in developed coastal provinces is up to 80% (Feng et al., 2013; Duan et al., 2018). Thus, it is essential to compensate the inter-regional responsibility allocation system from the demand side. Without policy attention to carbon transfer, developed regions will further achieve local carbon reduction targets through carbon transfer, while less developed regions will be relegated to pollution havens. It will greatly hinder the achievement of global long-term carbon reduction goals (Li et al., 2022; Yuan et al., 2022).

The rapid growth of the digital economy has received widespread attention for its impact on all aspects of society, including the potential impact on carbon emissions and transfer. On the one hand, the digital economy can improve energy efficiency and promote industrial innovation (Pan et al., 2022; Ma et al., 2022), reduce production costs and affect regional industrial structure (Zhang et al., 2022), and stimulate industry transfer (Li and Wang, 2022; Wang et al., 2022b), subsequently impacting inter-regional carbon transfer. On the other hand, the digital economy breaks down trade barriers among regions and facilitates market integration (Niu et al., 2023), while also changing the traditional consumption patterns of households and enterprises. Households and enterprises can obtain high-quality goods from other places at lower costs (Li et al., 2019a; Niu et al., 2023), thereby facilitating carbon transfer among regions. Furthermore, under the pressure of high-intensity carbon emissions reduction targets and environmental regulation, Chinese local governments have the motivation to reduce carbon emissions through carbon transfer (Wu and Cao, 2021; Pu and Fu, 2018). The digital economy offers an effective means for local governments to transfer carbon emissions. Regions with advanced digital economies can more easily transfer carbon emissions reduction pressure to regions with poorer digital economies. Existing studies have generally explored the carbon transfer caused by trade among regions (Peters et al., 2011; Essandoh et al., 2020), and investigated the effects of the digital economy on carbon emissions from production (Wang et al., 2022b) and consumption (Li et al., 2019b; Xue et al., 2022). However, as far as we know, there is a scarcity of studies examining the effect of the digital economy on carbon transfer among cities.

This study verifies the existence of the pollution haven paradise hypothesis among domestic cities using the life cycle assessment method and investigates the effect and specific mechanisms of the digital economy on inter-city carbon transfer with the two-way fixed effects model. The potential research contributions are as follows: First, existing studies mainly discuss the influencing factors of carbon transfer from the perspectives of carbon tax (Chen, 2022), economic structure (Duan et al., 2018), climate policies (Grubb et al., 2022) and green finance (Tong et al., 2022). In this paper, the impact and mechanism of the digital economy on inter-regional carbon transfer are investigated for the first time, and the inconsistent conclusions of the digital economy on carbon emission in the literature are explained from the perspective of carbon transfer. Second, the existing literature is generally based on macro or meso data to explore international (Essandoh et al., 2020; Wang et al., 2022a) and domestic provincial carbon transfer (Yang et al., 2020; Yuan et al., 2022), there is scant evidence of carbon transfer among cities and at the micro level. In this study, comprehensive household consumption data combined with city-level multi-region input-output tables, are used to measure inter-city carbon transfer in China and demonstrate the pollution paradise hypothesis among cities. Third, this paper investigates the effects of the digital economy on carbon transfer, grounded in the principle of consumption responsibility allocation. The empirical evidence provided in this paper will help the government to formulate carbon emission policies and promote balanced development between regional economic and environmental development.

The remainder of this paper is structured as follows: "Literature review and research hypothesis" reviews the relevant literatures on the digital economy and carbon transfer, and subsequently presents the research hypothesis. "Data and methods" describes the data sources, the variables and the identification strategy of the empirical model. "Empirical results" shows the empirical results. "Conclusions and policy implications" presents the related conclusions and policy implications.

Literature review and research hypothesis

Measurement and research status of carbon emissions and transfer. Existing research on measuring regional carbon emissions mainly includes the production-based accounting method and the consumption-based accounting method. The production-based accounting method measures carbon emissions generated by domestic regional production, which does not consider where the commodity is utilized (Shan et al., 2018; Moran et al., 2018). Chen et al. (2021) employed satellite nighttime light data to measure regional carbon emissions, while Yu et al. (2020) utilized regional energy consumption based on the IPCC method to measure regional carbon emissions. It has been widely applied in the Kyoto Protocol and the United Nations Framework Convention on Climate Change (Mi et al., 2016). However, this method ignores carbon leakage among regions, disrupting the equitable allocation of carbon emissions responsibilities (Meng et al., 2018; Yang et al., 2020). Consequently, the consumption-based accounting method offers a more equitable and rational approach, which can address the allocation of carbon responsibility for both production and consumption dimensions by tracing the entire process of product production, transportation, and purchase (Duan et al., 2018). It has been increasingly employed in policy research (Yuan et al., 2022; Long et al., 2021).

The input-output table method is the principal consumption-based accounting method to measure regional carbon emissions and carbon transfer. In previous studies, single-region input-output tables are often employed to measure regional consumption-side carbon emissions (Long et al., 2021; Li et al., 2019b). However, due to the limitations in identifying inter-regional differences in production efficiency and technology, potential biases may arise in the results (Meng et al., 2018). Consequently, multi-region input-output tables, which incorporate more extensive information, have been widely used to examine regional consumption-side carbon emissions (Long et al., 2021) and carbon transfer among regions (Wu and Cao, 2021; Yuan et al., 2022).

In the process of exploring carbon transfer, numerous studies have explored inter-regional carbon transfer at the global (Zhang et al., 2020; Wang et al., 2022a) and regional levels (Chen et al., 2019a; Yuan et al., 2022). These studies generally found that developed regions tend to transfer carbon emissions generated by low-efficiency, high-polluting sectors to less developed or environmentally lenient regions through international trade and industrial relocation (Chen et al., 2019a; Yuan et al., 2022), corroborating the existence of the pollution haven hypothesis (Monica and Neha, 2021). The economic structure, income, consumption patterns, capacity to benefit, and differences in fuel mix among regions are essential causes of inter-regional carbon transfer (Duan et al., 2018; Shan et al., 2018). In contrast, carbon trading mechanisms, carbon quotas and carbon taxes can have a significant dampening effect on inter-regional carbon transfer (Tong et al., 2022; Moosavian et al., 2021). However, due to the absence of multi-region input-output tables at the city level, only a few literature employing single-region input-output tables have discussed carbon transfer in specific cities, such as cities within Brussels (Athanassiadis et al., 2018), China's Heilongjiang province (Chen et al., 2019a), 13 cities of China (Mi et al., 2016), and 52 major cities in Japan (Long et al., 2021). These studies do not address inter-city carbon linkages on a national scale and the production heterogeneity among cities, which may lead to under- or overestimation of carbon emissions (Chen et al., 2019b).

Moreover, the life cycle assessment method is frequently employed as a complement to the consumption-based accounting methods and is extensively employed to measure indirect carbon emissions at the micro-household level (Yuan et al., 2019; Mi et al., 2019). This method typically requires careful combination and cross-mapping of consumption inventories and input-output tables to ensure accurate estimations of indirect emissions. Nevertheless, as available micro-household data generally contain fewer consumption categories than the number of input-output table sectors, there may be some bias in the estimations (Long et al., 2021).

Accordingly, this paper combines the life cycle assessment method with the inter-city multi-region input-output table to measure inter-city carbon transfer from the micro-household perspective, addressing the gap in inter-city carbon transfer. In addition, this paper matches the multi-region input-output table with monthly household consumption data of 218 commodities based on the authoritative consumption database in China, which further improves the accuracy of household carbon emissions and carbon transfer.

The impact of the digital economy on carbon emissions. The existing literature primarily examines the effects of the digital economy on carbon emissions from the production side and the consumption side. In terms of carbon emissions on the production side, scholars have generally found that the digital economy can contribute to reducing carbon emissions by improving the energy usage structure of industries (Li and Wang, 2022; Zhang et al., 2022), enhancing technological innovation (Pan et al., 2022; Ma et al., 2022), and optimizing the efficient distribution of energy (Kloppenburg and Boekelo, 2019; Chen and Lin, 2021). However, the impact of the digital economy on carbon emissions is also subject to the Jevons paradox (Fich et al., 2022). Although the digital economy can improve energy use efficiency, it concurrently stimulates a rise in industrial energy demand (Lange et al., 2020), which in turn promotes an increase in carbon emissions. In addition, some scholars found heterogeneous effects of the digital economy on carbon emissions across different industries (Wang et al., 2022b) and regions (Usman et al., 2021; Zhang et al., 2022). For instance, Wang et al. (2022b) found that digital economy has a carbon-reducing effect on digital industries and a carbon-increasing effect on industries that use digital technologies indirectly. Usman et al. (2021) found that the digital economy has a decarbonization effect only for countries with less pollution.

There is little literature on the effects of digital economy on consumer-side carbon emissions and no consensus has been reached. Li et al. (2019a) found that the digital economy can promote consumption expansion and consumption upgrading through payment convenience and wage premiums, which in turn increases household carbon emissions. However, some scholars found that the digital economy can promote green consumption by raising residents' environmental awareness, ultimately leading to a reduction in household carbon emissions (Li et al., 2019b; Meng et al., 2023).

As far as we know, no existing literature directly examines the impact of the digital economy on inter-city carbon transfer. Inter-regional carbon transfer is of great significance in the equitable allocation of carbon reduction responsibilities and the realization of global environmental sustainability. Especially in the context of the information age, the digital economy, as an essential production factor, is likely to have an impact on inter-regional carbon transfer. Therefore, exploring the effects and underlying mechanisms of the digital economy on inter-regional carbon transfer holds great significance.

Research hypothesis. In contemporary society, the accelerated growth of the digital economy influences numerous domains worldwide, including inter-regional carbon transfer. Drawing upon existing research and theoretical frameworks, the following hypotheses are proposed in this paper:

Hypothesis 1: Digital economy facilitates inter-regional carbon transfer.

As the prevalence and adoption of digital technology advance, the dissemination of information and resource allocation have been significantly improved. Enterprises can more easily expand their production operations in other regions with digital platforms and virtual services. This results in the carbon footprints of goods generated in the production process involving more regions. As a consequence, this paper proposes that the digital economy may aggravate the inter-regional carbon transfer.

Hypothesis 2: Digital economy exerts a greater effect on the carbon emissions transfer from developed cities, and mainly promotes the transfer of carbon emissions from secondary industries in developed cities to undeveloped cities.

According to the pollution haven hypothesis, inter-regional differences in environmental regulations, production costs, and resource endowments may lead carbon-intensive industries in developed regions to transfer to weaker environmental regulations or less developed regions. The digital economy allows enterprises in developed cities to more easily transfer carbon emissions to other cities by facilitating cross-regional business expansion and reducing information transfer costs. Meanwhile, carbon-intensive industries are mainly concentrated in secondary industries, such as petrochemicals, iron and steel, and cement. Therefore, this paper proposes that the digital economy exerts a greater effect on the carbon emissions transfer from developed cities, and mainly promotes the transfer of carbon emissions from secondary industries in developed cities to undeveloped cities.

Hypothesis 3: Mandatory environmental regulations exacerbate the positive effects of the digital economy on carbon transfer.

To address global climate change and environmental challenges, countries around the world have implemented a series of environmental regulatory measures. For instance, China has set mandatory carbon emission reduction targets for each province and integrated these objectives into the performance assessment systems of local governments. However, under the pressure of stringent carbon reduction targets and performance assessments, local governments may be inclined to use the digital economy to transfer the pressures of carbon emissions reduction pressures to regions with more lenient environmental regulations, thereby achieving their carbon reduction targets. Consequently, this paper proposes that the mandatory environmental regulations may exacerbate the facilitative effects of the digital economy in carbon transfer.

Hypothesis 4: The digital economy primarily facilitates inter-regional carbon transfer by promoting market integration and relocation of carbon-intensive industries. The digital economy breaks inter-regional trade barriers and promotes the integration of domestic markets. In this case, enterprises and residents can obtain raw materials and commodities from other regions more rapidly and economically. The strengthening of inter-regional trade inevitably leads to an increase in inter-regional carbon transfer. Thus, the digital economy may facilitate inter-regional carbon transfer by promoting domestic market integration. Moreover, there exist significant disparities in regional factor endowments and economic development in China. Digital economy, through cross-border e-commerce and information dissemination, facilitates the global distribution of production processes for enterprises, leading to the transfer of carbon-intensive industries to regions with lower production costs. Consequently, this paper proposes that the digital economy may promote inter-regional carbon transfer by facilitating the relocation of carbon-intensive industries.

Data and methods

Data. The household consumption data are obtained from the Urban Household Survey of the National Bureau of Statistics of China for 2012 and 2015. The Urban Household Survey provides detailed information on the basic characteristics of urban households and their members, as well as the income and consumption expenditure of these households. It covers 57 prefecture-level cities in Liaoning, Shanghai, Guangdong, and Sichuan provinces, representing the different geographical locations and different levels of economic development in northeastern, eastern, southern, and southwestern China. A notable strength of this database is that it comprehensively records the monthly consumption expenditure for more than 200 goods and services for ~20,000 urban households per year. As one of the most detailed and authoritative consumption databases in China, the Urban Household Survey has been widely used to examine household energy demand (Zhou and Teng, 2013), social inequality (Tan et al., 2014), and household consumption behavior (Yu et al., 2019).

The city-level multi-region input-output tables used to measure inter-city carbon transfers are derived from the China Emissions Accounts and Datasets for the years 2012 and 2015 [2]. The China Emissions Accounts and Datasets provide a multi-regional input-output table for China, including detailed information on emissions and economic activities at the city level. The dataset includes 313 administrative units in China, accounting for over 95% of the population and more than 97% of its GDP. It has been widely used to explore environmental issues resulting from inter-regional economic relationships (Zhu et al., 2023) and the evolution of industrial structures (Han et al., 2020). The multi-region input-output table comprises 42 socioeconomic sectors and 5 final consumption categories, consistent with the national-scale input-output table published by the National Bureau of Statistics of China (Zheng et al., 2021).

To estimate carbon emissions, this study employs Socio Economic Accounts and Environment Accounts from the World Input-Output Database [3]. It provides comprehensive records of total output, value-added, energy consumption, and carbon emissions for various sectors across countries, providing a valuable resource for exploring trade globalization (Liu and Wang, 2022) and sustainable development (Yang et al., 2022).

Constructions of the variables

Carbon transfer. The life cycle assessment method has been widely used to measure household carbon emissions (Li et al., 2019b; Long et al., 2021). Referring to Miller and Blair (1985), the relationship between household final consumption demand and the output of corresponding sectors can be represented as follows:

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

where $X = (x_1, x_2, \ldots x_{42})^T$ denotes the 42-sector total output vector; I is the unit matrix; A denotes the direct consumption coefficient matrix, $(I\text{-}A)^{-1}$ denotes the Leontief inverse matrix (Yuan et al., 2019; Long et al., 2021), $Y = (y_1, y_2, \ldots y_{42})^T$ denotes the 42-sector final consumption demand vector of households.

The sectoral direct carbon emissions intensity vector is denoted as $D = (d_1, d_2, \ldots d_{42})$, where the direct carbon emissions intensity d_k of sector k is determined by the rate of annual carbon emissions ek to the annual output of corresponding sector x_k.

$$d_k = \frac{e_k}{x_k} \tag{2}$$

Then the household carbon footprint E can be expressed as the product of the increase in output X of the corresponding sector guided by household consumption demand and the carbon emissions intensity D of the corresponding sector (Bin and Dowlatabadi, 2005).

$$E = D(I - A)^{-1} Y \tag{3}$$

In this study, We harmonize the household consumption data from the Urban Household Survey, multi-region input-output tables and energy intensity data from the World Input-Output Database, the household carbon emissions are calculated by the above formula. Furthermore, the carbon footprints are divided

Table 1 Measure variables of the digital economic index.

Dimension	Variable	Expectation	Data source
Digital industry	Proportion of employees in computer services and software	+	City statistical yearbook
	The proportion of fixed investment in information transmission	+	China statistical yearbook
	Logarithm of software business income	+	China statistical yearbook
Digital users	Total telecom business per capita	+	City statistical yearbook
	Total postal business per capita	+	City statistical yearbook
	Logarithm of e-commerce turnover	+	Electronic business statistics yearbook
	Number of Internet users per 100 people	+	City statistical yearbook
	Number of mobile phone users per hundred people	+	City statistical yearbook
Digital environment	Inclusive finance index	+	Institute of Digital Finance, Peking University
	Optical cable length	+	City statistical yearbook
Digital platform	Logarithm of number of domain names	+	CSMAR
	Logarithm of number of websites	+	CSMAR
	Logarithm of number of netizens	+	CSMAR
Digital innovation	Logarithm of electronic invention patent	+	CCAD
	Logarithm of 5G patent	+	CCAD
	Logarithm of industrial internet patents	+	CCAD

Source: Authors.

into local and non-local carbon emissions according to whether the carbon emissions occur in the city where the household is located. To minimize the impact of outliers, we truncate the household's carbon emissions by 1% for 20,427 households. The detailed methodologies for data matching and calculation can be found in supplementary information.

Digital economy. Principal component analysis has been extensively employed for the measurement of multidimensional composite metrics (Lever et al., 2017; Louf et al., 2023). In this paper, we construct a comprehensive evaluation framework for the digital economy based on existing literature on digital economy measurement (Li and Wang, 2022; Zhang et al., 2022), including 5 dimensions and 16 indicators. These dimensions include digital industry, digital user, digital environment, digital platform, and digital innovation. The detailed indicators and data sources are listed in Table 1. According to the principle of eigenvalue >1 (Lever et al., 2017), the method of principal component analysis is used to standardize the above indicators and then downscale the dimensions to obtain a comprehensive index of the digital economy for cities.

We further examined the validity of digital economy indicators. The Kaiser-Meyer-Olkin test and Bartlett's sphericity test are effective methods for comparing simple and partial correlation coefficients between variables and are frequently employed to determine the suitability of variables for principal component analysis (Li et al., 2021; Zeng et al., 2021). In general, if the Kaiser-Meyer-Olkin value is >0.7 and Bartlett's sphericity test with a p-value not greater than 0.01, it indicates that these indicators are appropriate for factor analysis (Kaiser and Rice, 1974). The test results show that the digital economy indicators in this study are appropriate for principal component analysis (Kaiser-Meyer-Olkin value $= 0.867 > 0.7$, $p = 0.000 < 0.01$). Moreover, the factor analysis results of the principal component analysis revealed that the common factors account for 73.62% of the total variance, indicating that the index has strong construct validity for the digital economy.

Control variables. To more accurately identify the impact of the digital economy on inter-regional carbon transfer, individual, household, and city-level characteristics that may affect household carbon emissions are controlled in our empirical model. Specifically, the individual characteristics include age, gender, marital status, and education level of the head of household. Some literature shows that the age of the head of household has a positive effect on household emissions (Zhou and Teng, 2013). Meanwhile, the gender of the household head, marital status, and education level also have an impact on household carbon emissions (Li et al., 2019b; Zhou and Teng, 2013). For example, female, highly educated, and married households tend to have a higher consumption desire and demand, which may lead to an increase in household carbon emissions.

Household characteristics such as household size, proportion of elderly, proportion of children, and total household income may also affect household consumption behavior and carbon emissions. To be specific, household income and household size are closely related to household consumption and thus have a positive effect on household carbon emissions (Zhu et al., 2023; Zhou and Teng, 2013). Moreover, household structure also has an impact on household carbon emissions (Li et al., 2019b). For example, products consumed by children and the elderly (e.g., imported health products, medical devices, etc.) tend to involve more expenses and longer product chains, and thus a higher proportion of elderly or children may lead to higher carbon emissions. In this paper, household structure is measured by two indicators: the proportion of children under 16 and the proportion of elderly over 60.

Referring to existing literature, some city characteristics such as GDP per capita (Usman et al., 2021), urbanization rate (Li and Wang, 2022), industrial structure (Zhang et al., 2022), financial development (Pan et al., 2022), and openness (Xue et al., 2022) are included in our model as control variables. In particular, the financial development level is represented by the year-end ratio of total loans from financial institutions to the city's GDP, the industrial structure is expressed as the proportion of the tertiary industry to the city's GDP, and the degree of city openness is quantified as the ratio of import and export trade to the city's GDP. The specific variable descriptions, sources, expectations, and citations are shown in Table 2.

Descriptive statistic. The descriptive statistics of variables are reported in Table 3. The average annual carbon emissions of each household are 5493.8 kg. About 54% (3014.48 kg) of household carbon emissions come from other cities, which shows that intercity carbon transfer in China is widespread and serious. The considerable standard deviation of the digital economy indicates that there are significant differences in the digital economy among Chinese cities.

Table 2 Variable Description.

Variable	Description	Source	Expectation	Citations
Dependent variables:				
Total carbon emissions	Carbon emissions from household consumption	UHS, CEADS and WIOD		Li et al., 2019b; Long et al., 2021; Bin and Dowlatabadi, 2005
Local carbon emissions	Local carbon emissions from household consumption			
Non-local carbon emissions	Non-local carbon emissions from household consumption			
Independent variables:				
Digital economy	Digital economy development level	Table 1	+	Li and Wang, 2022; Zhang et al., 2022
Control variables:				
Householder age	Age of householder	UHS	+/−	Li et al., 2019b; Zhou and Teng, 2013; Zhu et al., 2023
Householder gender	Female equals 1; male equals 0	UHS	+	
Householder marriage	Married equals 1, unmarried equals 0	UHS	+	
Householder education	Number of years of education for the householder	UHS	+	
Proportion of children	Proportion of family members under 16 years of age	UHS	+	
Proportion of the elderly	Proportion of family members aged 60 and above	UHS	+	
Family size	Number of family members	UHS	+	
Family income	Annual household income	UHS	+	
Per capita GDP	Per capita GDP of the city	City statistical yearbook	+/−	Li and Wang, 2022; Zhang et al., 2022; Xue et al., 2022; Pan et al., 2022; Usman et al., 2021
Financial development	the year-end ratio of total loans from financial institutions to the city's GDP	City statistical yearbook	+/−	
Openness	Proportion of import and export trade to the city's GDP	City statistical yearbook	+/−	
Industrial structure	Proportion of the tertiary industry to the city's GDP	City statistical yearbook	+/−	
Urbanization rate	Proportion of urban population to the city's total population	City statistical yearbook	+/−	

Source: Authors.

Figure 1 shows the distribution of household carbon footprints by city development level, revealing that household carbon emissions in first-tier cities (6842 kg) are higher than those in second- (6158 kg) and third-tier cities (4756 kg). However, ~58% of these emissions are derived from other cities, and this proportion is notably higher than observed in second- (50%) and third-tier cities (50%). Compared with second and third-tier cities, first-tier cities exhibit a greater degree of carbon transfer.

Figure 2 explores the sources of non-local carbon emissions based on the target cities and industries for carbon transfer. The carbon emissions transferred to third-tier cities account for ~67% of non-local carbon emissions, while the carbon emissions from the secondary industry account for ~86% of non-local carbon emissions. Figure 2 suggests that underdeveloped third-tier cities in China primarily bear the burden of inter-city carbon transfer, most of which is carried out through carbon-intensive secondary industries. The above conclusions indicate the existence of the pollution haven hypothesis among Chinese cities.

Identification strategy. This study employs a two-way fixed effects model to explore the impact of the digital economy on household carbon emissions. This model minimizes the endogeneity issues arising from omitted variables to the greatest extent possible (Zhang et al., 2022; Li and Wang, 2022). The basic estimation model is as follows:

$$E_{ict} = \beta_0 + \beta_1 Dig_{ct} + \beta_2 X_{ict} + \delta_t + \mu_c + \varepsilon_{ict} \qquad (4)$$

where E_{ict} denotes the carbon footprints of household i, including logarithm of total household carbon emissions, the logarithm of local household carbon emissions, and the logarithm of non-local household carbon emissions. Dig_{ct} denotes the digital economic level of city c where households are located in year t. X_{ict} denotes the control variables. μ_c and δ_t respectively control the city and year fixed effects, and ε_{ict} denotes the random disturbance term.

Empirical results

Benchmark regression results. Table 4 reports the benchmark regression results of the digital economy on household carbon emissions. The result in column (1) reveals that the relationship between the digital economy and household carbon emissions is positive and statistically significant ($\beta = 0.298$, $p = 0.000$). With every unit added to the digital economy, household carbon emissions increase by 29.8% compared to the average (5494 kg). In column (3), the regression coefficient of the digital economy's impact on non-local household carbon emissions is also positive and statistically significant ($\beta = 0.578$, $p = 0.000$). This result implies that the digital economy intensifies inter-city carbon transfer, and the coefficient indicates that for every unit added to the digital economy, non-local household carbon emissions increase by 57.8% relative to their mean (3014 kg). Consequently, while the digital economy overall increases carbon emissions, it also facilitates the transfer of emissions to other cities, thus reducing local emissions. Hypothesis 1 is validated, and the above results provide a plausible explanation for the inconsistent conclusions in existing literature regarding the impact of the digital economy on carbon emissions.

The estimation results of other control variables on household carbon emissions are consistent with expectations. However, GDP per capita ($\beta = -1.002$, $p = 0.000$), financial development ($\beta = -0.396$, $p = 0.000$), openness ($\beta = -0.212$, $p = 0.000$) and

Table 3 Descriptive statistic results.

Variable	Obs	Mean/%	Standard deviation	Min	Max
Total carbon emissions	20,427	5493.80	3600.26	614.06	47,378.13
local carbon emissions	20,427	2479.32	1443.29	54.16	21,433.19
Non-local carbon emissions	20,427	3014.48	2535.40	235.07	29,359.68
Digital economy	20,427	0.58	0.82	−0.76	2.75
Householder age	20,427	51.46	12.83	19.00	96.00
Householder gender	20,427	0.30	0.46	0.00	1.00
Householder marriage	20,427	0.89	0.30	0.00	1.00
Householder education	20,427	11.64	3.25	0.00	19.00
Proportion of children	20,427	0.10	0.15	0.00	0.71
Proportion of the elderly	20,427	0.15	0.30	0.00	1.00
Family size	20,427	2.89	1.02	1.00	11.00
Family income	20,427	95,573.03	85,402.50	64.000	3,169,231.00
Per capita GDP	20,427	70,494.84	35,657.82	11,802.04	149,034.30
Financial development	20,427	1.23	0.61	0.28	2.13
Openness	20,427	0.59	0.62	0.01	2.27
Industrial structure	20,427	46.24	14.27	20.66	67.77
Urbanization rate	20,427	63.54	21.91	23.93	100.00

Source: Authors.

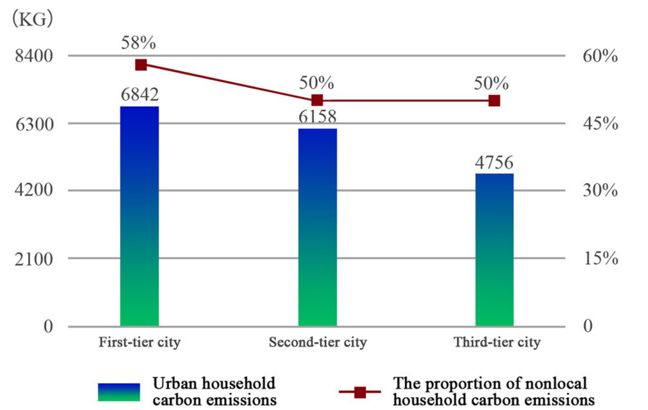

Fig. 1 Carbon emissions of urban household. Note: The classification of cities at different levels of development refers to the "2016 China City Commercial Attraction Ranking" published by the New First Line City Institute. For easy understanding, we combine the new first-tier cities and second-tier cities into second-tier cities, and the third-tier cities and below are uniformly classified as third-tier cities. Source: Authors.

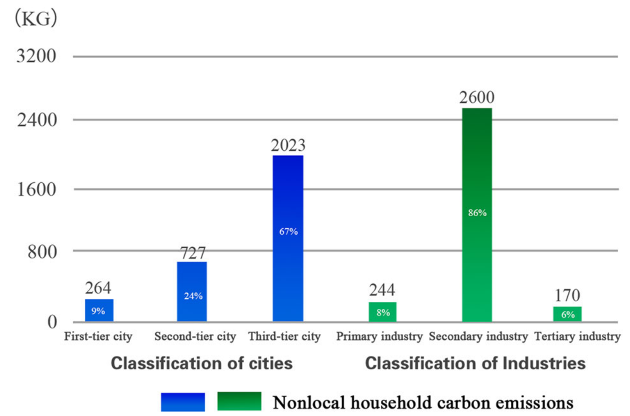

Fig. 2 Sources of non-local carbon emissions. Note: The secondary industry includes extractive industries, manufacturing, water, electricity, steam, hot water, gas, and construction. Source: Authors.

industrial structure ($\beta = -0.012$, $p = 0.000$) are negatively correlated with household carbon emissions, which may result from the carbon-reducing effect of urban agglomeration (Han et al., 2018).

Heterogeneity analysis

City development level. The level of city development has an impact on the production behavior of enterprises and the consumption habits of residents. Consequently, the effect of the digital economy on carbon transfer may exhibit heterogeneity across different development levels of cities where households are located. Thus, we construct city development-level dummy variables based on city development levels and interact them with the digital economy for regression analysis. Table 5 reports the results of the digital economy's effect on household carbon emissions in cities with varying development levels. The results reveal that the digital economy primarily increases household carbon emissions in second-tier cities ($\beta = 0.251$, $p = 0.000$). The increase in household carbon emissions is less noticeable for first- ($\beta = 0.116$, $p = 0.257$), which may be attributed to the agglomeration effect of carbon reduction in first-tier cities (Holian and Kahn, 2015).

Columns (2) in Table 5 show that the digital economy significantly reduces local carbon emissions in first-tier cities ($\beta = -0.400$, $p = 0.001$) and third-tier cities ($\beta = -0.15$, $p = 0.098$), while notably increasing non-local carbon emissions across all city tiers. The estimated results suggest digital economy facilitates carbon transfer across all city tiers. From the difference of coefficients, the digital economy's impact on both local and non-local carbon emissions is stronger in first-tier cities than in second- and third-tier cities, indicating that the digital economy primarily fosters the transfer of carbon emissions from first-tier cities to other cities. Hypothesis 2 is validated.

Non-local carbon emissions sources. To verify whether the effect of the digital economy on carbon transfer may differ across various destination cities, we explore the heterogeneous effects of the digital economy on carbon transfer by categorizing destination cities. We further conduct a detailed analysis of the carbon-intensive secondary industry. Columns (1)–(3) in Table 6 report the effect of the digital economy on carbon transfer in cities at different tiers, revealing a significant promotional effect on carbon emissions transfer to all level cities. The coefficients suggest that, compared to first ($\beta = 0.217$, $p = 0.003$) and second-tier cities ($\beta = 0.257$, $p = 0.001$), the digital economy more

Table 4 Benchmark regression results.

Variable	Total carbon emissions (1)	Local carbon emissions (2)	Non-local carbon emissions (3)
Digital economy	0.298*** (0.06)	−0.042 (0.06)	0.578*** (0.07)
Householder age	0.001*** (0.00)	0.003*** (0.00)	−0.000 (0.00)
Householder education	0.013*** (0.00)	0.011*** (0.00)	0.015*** (0.00)
Householder gender	0.028*** (0.01)	0.033*** (0.01)	0.025*** (0.01)
Householder marriage	0.035*** (0.01)	0.055*** (0.01)	0.026** (0.01)
Proportion of children	0.109*** (0.02)	0.075*** (0.02)	0.158*** (0.02)
Proportion of the elderly	0.015 (0.01)	0.009 (0.01)	0.024* (0.01)
Family size	0.046*** (0.00)	0.075*** (0.00)	0.022*** (0.00)
Logarithm of family income	0.544*** (0.01)	0.380*** (0.01)	0.684*** (0.01)
Logarithm of GDP per capita	−1.002*** (0.13)	−0.938*** (0.15)	−1.036*** (0.14)
Financial development	−0.396*** (0.09)	−0.724*** (0.11)	−0.086 (0.10)
Openness	−0.212*** (0.06)	−0.477*** (0.06)	−0.041 (0.07)
Urbanization	0.019*** (0.00)	−0.018*** (0.00)	0.047*** (0.00)
Industrial structure	−0.012*** (0.00)	−0.011*** (0.00)	−0.008** (0.00)
Constant	13.382*** (1.53)	16.402*** (1.85)	9.165*** (1.76)
City_fe	YES	YES	YES
Year_fe	YES	YES	YES
R-squared	0.575	0.468	0.576
Observations	20,427	20,427	20,427

Note: The values in parentheses are standard deviations of regression coefficients, where *** is $p < 0.01$, ** is $p < 0.05$ and * is $p < 0.1$ respectively.
Source: Authors.

Table 5 Heterogeneity of city development levels.

Variable	Total carbon emissions (1)	Local carbon emissions (2)	Non-local carbon emissions (3)
Digital economy* First-tier cities	0.116 (0.10)	−0.400*** (0.12)	0.635*** (0.12)
Digital economy* Second-tier cities	0.251*** (0.06)	−0.107 (0.07)	0.564*** (0.07)
Digital economy* Third-tier cities	0.134* (0.08)	−0.150* (0.09)	0.414*** (0.10)
Control	YES	YES	YES
City_fe	YES	YES	YES
Year_fe	YES	YES	YES
R-squared	0.575	0.469	0.576
Observations	20,427	20,427	20,427

Note: The values in parentheses are standard deviations of regression coefficients, where *** is $p < 0.01$ and * is $p < 0.1$ respectively.
Source: Authors.

prominently contributes to carbon emissions transfer to less developed third-tier cities ($\beta = 0.525$, $p = 0.000$).

Columns (4)–(6) in Table 6 report the effects of the digital economy on carbon transfer in the carbon-intensive secondary industry across different city tiers. The findings indicate that the digital economy significantly promotes the transfer of carbon emissions from carbon-intensive secondary industries to other cities. Examining the coefficients, the digital economy primarily fosters the transfer of carbon emissions from carbon-intensive secondary industries to third-tier cities ($\beta = 0.470$, $p = 0.000$), as compared to first- ($\beta = 0.132$, $p = 0.074$) and second-tier cities ($\beta = 0.281$, $p = 0.000$). These results substantiate Hypothesis 2.

Environmental regulations. We presume that mandatory environmental regulations may prompt local governments to leverage the digital economy for carbon transfer to achieve their carbon reduction goals. To test this hypothesis, referring to Domazlicky and Weber (2004), a composite index of various pollutant emissions (wastewater, sulfur dioxide, and particulate matter) is used as a proxy for the intensity of mandatory environmental regulation in cities. Considering that environmental regulations may inherently produce emissions reduction effects by lowering carbon emissions intensity, it becomes difficult to identify the increase in non-local carbon emissions caused by carbon transfer in absolute terms. Therefore, we also adopt the proportion of non-local carbon emissions in total carbon emissions as a measure of carbon transfer, Table 7 shows the estimated results of the interaction between the digital economy and environmental regulation.

Table 7 demonstrates that the effect of mandatory environmental regulations on both non-local carbon emissions ($\beta = 0.224$, $p = 0.000$) and the proportion of non-local carbon emissions ($\beta = 0.065$, $p = 0.000$) is significantly positive. Local governments facing high-intensity mandatory environmental regulations may transfer carbon emissions to other cities to achieve their carbon reduction targets. The interaction term's coefficient for non-local carbon emissions is positive but not statistically significant ($\beta = 0.085$, $p = 0.281$), which may be due to the confounding effect of carbon reduction caused by environmental regulations. Further investigation of the interaction term's effect on the proportion of non-local carbon emissions reveals a significantly positive coefficient ($\beta = 0.116$, $p = 0.000$), confirming that mandatory environmental regulations amplify the digital economy's role in promoting carbon transfer. These results support Hypothesis 3.

Table 6 Heterogeneity of non-local carbon emissions sources.

Variable	Source of non-local carbon emissions			Source of non-local carbon emissions in secondary industry		
	First-tier city	Second-tier city	Third-tier city	First-tier city	Second-tier city	Third-tier city
	(1)	(2)	(3)	(4)	(5)	(6)
Digital economy	0.217*** (0.07)	0.257*** (0.08)	0.525*** (0.07)	0.132* (0.07)	0.281*** (0.08)	0.470*** (0.07)
Control	YES	YES	YES	YES	YES	YES
City_fe	YES	YES	YES	YES	YES	YES
Year_fe	YES	YES	YES	YES	YES	YES
R-squared	0.753	0.584	0.580	0.740	0.592	0.569
Observations	20,427	20,427	20,427	20,427	20,427	20,427

Note: The values in parentheses are standard deviations of regression coefficients, where *** is $p < 0.01$ and * is $p < 0.1$ respectively.
Source: Authors.

Table 7 Heterogeneity of environmental regulations.

Variable	The value of non-local carbon emissions	The proportion of non-local carbon emissions
	(1)	(2)
Digital economy	0.597*** (0.07)	0.151*** (0.01)
Mandatory environmental regulation	0.224*** (0.08)	0.065*** (0.02)
Digital economy *Mandatory environmental regulation	0.085 (0.08)	0.116*** (0.02)
Control	YES	YES
City_fe	YES	YES
Year_fe	YES	YES
R-squared	0.576	0.306
Observations	20,427	20,427

Note: The digital economy index and the command environment regulation in the interaction term have been decentralized. The values in parentheses are standard deviations of regression coefficients, where *** is $p < 0.01$.
Source: Authors.

Robustness test. The carbon emissions at the household level are unlikely to significantly affect the digital economy at the city level, so the issue of reverse causality in this study may not exist. However, considering the potential endogeneity problems arising from measurement errors and omitted variables, we employ instrument variables, alternative variables, and additional control variables to assess the robustness of our findings.

Instrumental variable. We employ the interaction term between the number of post offices in cities in 1984 and the share of online retail sales in total retail sales in the previous year as an instrument variable for the digital economy in cities. Before the digital economy era, postal services were the primary means of communication. Consequently, the number of post offices in a city can, to some extent, reflect the city's level of information development. The distribution of post offices can also influence subsequent internet access, technology dissemination, and internet usage habits in different regions, thereby affecting the popularity and evolution of the Internet. It satisfies the correlation requirement of the instrumental variable.

Furthermore, with the rapid evolution of digital technologies including the internet and big data, the historical influence of the number of post offices on production and consumption behaviors is diminishing. The number of post offices in 1984 is unlikely to affect current household carbon emissions and inter-regional carbon transfer, meeting the instrument variable's excludability requirement. However, the historical number of post offices cannot capture time-varying trends. Therefore, drawing on Nunn and Qian (2014), an interaction term between the number of post offices in cities in 1984 and the share of online retail sales in total retail sales in the previous year is used as an instrument variable for the regional digital economy. The regression results are presented in Table 8.

Column (1) in Table 8 reports the first-stage regression result, indicating a significant positive correlation between the instrument variable and the digital economy ($\beta = 0.006$, $p = 0.000$), which is consistent with the expectation. The F-statistic value of 14,838.6 suggests that there is no weak instrument variable issue. Columns (2)–(7) in Table 8 report the two-stage least squares (2SLS) estimation results after introducing the instrument variable. Columns (2)–(4) results show the digital economy significantly increases household total carbon emissions ($\beta = 0.283$, $p = 0.000$) and non-local carbon emissions ($\beta = 0.643$, $p = 0.000$), while reducing local carbon emissions ($\beta = -0.158$, $p = 0.057$). Columns (4)–(6) reveal that compared to first- ($\beta = 0.258$, $p = 0.008$) and second-tier cities ($\beta = 0.152$, $p = 0.128$), the digital economy still exhibits a more pronounced effect on promoting carbon transfer to third-tier cities ($\beta = 0.587$, $p = 0.000$). The conclusions drawn in the previous analysis remain robust.

Substitution of dependent variable. The generation of household carbon emissions is fundamentally rooted in household energy consumption, implying that energy consumption transfer among cities can reflect the transfer of environmental pressures to some extent. In this study, we measure household energy consumption based on sectoral energy intensity data from the World Input-Output Database, and examine the effect of the digital economy on environmental pressure transfer by substituting household energy consumption for household carbon emissions. The regression results are reported in Table 9.

The results in columns (1) and (3) in Table 9 indicate that the digital economy significantly increases household total energy consumption ($\beta = 0.415$, $p = 0.000$) and non-local energy consumption ($\beta = 0.546$, $p = 0.000$). Columns (4) to (6) reveal that,

Table 8 The results of the instrumental variable.

Variable	First stage regression	Total carbon emissions	Local carbon emissions	Non-local carbon emissions	Source of non-local carbon emissions		
					First-tier city	Second-tier city	Third-tier city
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Digital economy		0.283*** (0.08)	−0.158* (0.08)	0.643*** (0.09)	0.258*** (0.10)	0.152 (0.10)	0.587*** (0.09)
Post offices * the proportion of online retail sales in previous year	0.006*** (0.00)						
F	14,838.6						
Control	YES	YES	YES	YES	YES	YES	YES
City_fe	YES	YES	YES	YES	YES	YES	YES
Year_fe	YES	YES	YES	YES	YES	YES	YES
R-squared	0.998	0.575	0.467	0.577	0.754	0.584	0.582
Observations	20,427	20,427	20,427	20,427	20,427	20,427	20,427

Note: The values in parentheses are standard deviations of regression coefficients, where *** is $p < 0.01$ and * is $p < 0.1$ respectively.
Source: Authors.

Table 9 The results of energy consumption.

Variable	Total energy consumption	Local energy consumption	Non-local energy consumption	Source of non-local energy consumption		
	(1)	(2)	(3)	First-tier city	Second-tier city	Third-tier city
				(4)	(5)	(6)
Digital economy	0.415*** (0.06)	0.265*** (0.06)	0.546*** (0.07)	0.310*** (0.07)	0.184** (0.08)	0.558*** (0.07)
Control	YES	YES	YES	YES	YES	YES
City_fe	YES	YES	YES	YES	YES	YES
Year_fe	YES	YES	YES	YES	YES	YES
R-squared	0.588	0.498	0.580	0.746	0.549	0.591
Observations	20,427	20,427	20,427	20,427	20,427	20,427

Note: The values in parentheses are standard deviations of regression coefficients, where *** is $p < 0.01$ and ** is $p < 0.05$ respectively.
Source: Authors.

compared to first ($\beta = 0.310$, $p = 0.000$) and second-tier cities ($\beta = 0.184$, $p = 0.018$), the digital economy has more pronounced effect on promoting non-local energy consumption from third-tier cities ($\beta = 0.558$, $p = 0.000$). These suggest that the previous empirical results are robust.

Substitution of the independent variable. The digital economy used in this paper may have some potential measurement errors. Therefore, the financial inclusiveness index measured by Peking University is used as a robustness analysis to substitute for the digital economy. The regression results are reported in Table 10. The results in Columns (2) and (3) indicate that the financial inclusion index significantly increases non-local household carbon emissions ($\beta = 0.85$, $p = 0.000$) and reduces local household carbon emissions $\beta = -1.11$, $p = 0.000$). The conclusion that the digital economy promotes the transfer of household carbon emissions to other cities remains robust. The results in columns (4)–(6) demonstrate that the digital economy exhibits the most prominent effect on promoting carbon emissions from the second ($\beta = 1.00$, $p = 0.000$) and third-tier cities ($\beta = 0.658$, $p = 0.001$). These results support the conclusion that the digital economy drives the transfer of carbon emissions pressures to less developed cities.

Add control variable. Since the 12th Five-Year Plan, China has implemented a series of carbon emission reduction policies to mitigate emissions such as the three batches of low-carbon city pilots since 2010, the carbon trading emission rights pilot since 2013, and the change of environmental protection fees to taxes since 2018, etc. The combined effects of these policies may affect carbon emissions and carbon transfer. During the sample period, the primary carbon reduction policies implemented in China include the carbon emissions trading pilot policy and the low-carbon city pilot policy. We incorporate these pilot policies as the control variables to eliminate potential endogeneity impacts. The regression results are presented in Table S2. Columns (1)–(3) in Table S2 demonstrate that after controlling for China's carbon reduction policies, the digital economy significantly increases household total carbon emissions ($\beta = 0.293$, $p = 0.000$) and non-local carbon emissions ($\beta = 0.575$, $p = 0.000$). Columns (4)–(6) reveal that compared to first ($\beta = 0.210$, $p = 0.004$) and second-tier cities ($\beta = 0.255$, $p = 0.001$), the digital economy still has the most pronounced effect on promoting non-local carbon emissions from third-tier cities ($\beta = 0.521$, $p = 0.000$). These results confirm the robustness of the previous empirical results.

Mechanism analysis. To determine the causal relationship between the digital economy and carbon transfer among cities, this paper investigates the mechanisms of market integration and industrial transfer.

Table 10 The results of the inclusive finance index.

Variable	Total carbon emissions	Local carbon emissions	Non-local carbon emissions	Source of non-local carbon emissions		
				First-tier city	Second-tier city	Third-tier city
	(1)	(2)	(3)	(4)	(5)	(6)
Inclusive finance	−0.046 (0.16)	−1.110*** (0.20)	0.850*** (0.19)	−0.010 (0.21)	1.000** (0.20)	0.658*** (0.19)
Control	YES	YES	YES	YES	YES	YES
City_fe	YES	YES	YES	YES	YES	YES
Year_fe	YES	YES	YES	YES	YES	YES
R-squared	0.574	0.469	0.575	0.753	0.584	0.579
Observations	20,427	20,427	20,427	20,427	20,427	20,427

Note: The values in parentheses are standard deviations of regression coefficients, where *** is $p < 0.01$ and ** is $p < 0.05$ respectively.
Source: Authors.

Table 11 Mechanisms of market integration and industrial transfer.

Variable	Market integration		Industrial transfer	
	Proportion of non-local consumption	Market segmentation index	Relative output	Relative employment rate
	(1)	(2)	(3)	(4)
Digital economy	0.262*** (0.01)	−0.021*** (0.01)	−0.178** (0.08)	−0.059*** (0.02)
Control	YES	YES	YES	YES
City_fe	YES	YES	YES	YES
Year_fe	YES	YES	YES	YES
R-squared	0.660	0.168	0.068	0.026
Observations	20,427	969	2168	2153

Note: The values in parentheses are standard deviations of regression coefficients, where *** is $p < 0.01$ and ** is $p < 0.05$ respectively.
Source: Authors.

Market integration. We presume that the digital economy may promote inter-city carbon transfer by facilitating domestic market integration. To test this hypothesis, we calculate the ratio of non-local household consumption to total household consumption and use it as a proxy variable for household-level market integration. Furthermore, referring to Parsley and Wei (2001), the market segmentation index constructed based on the consumer price index of Chinese cities is used as a proxy variable for market integration at the city level. The regression results are reported in Table 11.

Column (1) in Table 11 demonstrates that the digital economy significantly increases the proportion of non-local consumption expenditure ($\beta = 0.262$, $p = 0.000$), and the result in Column (2) reveals digital economy significantly breaks down inter-regional market segmentation among cities ($\beta = -0.021$, $p = 0.004$). These findings provide evidence that the digital economy facilitates inter-city carbon transfer through the promotion of market integration, thereby confirming Hypothesis 4.

Industrial transfer. We presume that the digital economy may promote inter-city carbon transfer by facilitating the shift of carbon-intensive industries. To test this hypothesis, we draw from Dou and Han (2019) and use the relative output and employment rates of the secondary industry to identify the transfer of carbon-intensive industries. The regression results are reported in columns (3) and (4) of Table 11.

The regression results show that there is a significant negative relationship between the relative output value ($\beta = -0.178$, $p = 0.018$) and the relative employment rate ($\beta = -0.059$, $p = 0.001$) of the local secondary industry. This preliminarily confirms that the digital economy facilitates inter-city carbon transfer by promoting the shift of local carbon-intensive industries to the outside, thus validating Hypothesis 4.

Conclusions and policy implications

Conclusions. This paper measures the inter-city carbon transfer in China based on city-level multi-region input-output tables and micro-household consumption data, and further explores the effects and mechanisms of the digital economy on inter-city carbon transfer. Our research reveals that carbon transfer is widespread among Chinese cities, with third-tier cities primarily bearing the burden of high-intensity carbon transfer pressures, which supports the pollution haven hypothesis. Second, the digital economy exacerbates the inter-regional carbon transfer by promoting market integration and facilitating industrial relocation. Compared to first and second-tier cities, the digital economy primarily promotes the transfer of high-intensity carbon emissions to third-tier cities. Third, the more developed the local city, the stronger the promoting effect of the digital economy on carbon transfer. Mandatory environmental regulations incentivize governments to use the digital economy for carbon transfer to achieve local carbon emission reduction targets. These conclusions still hold after robustness tests using instrumental variables, replacing measurement variables, and excluding relevant policies.

We compared our findings with other literature. Feng et al. (2013) found that ~57% of carbon emissions in Chinese provinces originate from other provinces, while Hasegawa et al. (2015) estimated that carbon leakage among 47 prefectures in Japan accounts for 51.7% of total emissions. These results are similar to our calculated outcome of 54%, lending credibility to our findings.

The impact of the digital economy on carbon transfer is thought-provoking. As found in this paper, the digital economy promotes the development of an integrated domestic market, which makes the division of labor more specialized across regions. In addition, the regional industrial structure may change due to a more specialized division of labor, increasing the share of the Secondary sector of the economy in the industrial developed regions. Regions with developed digital economies may also attract more foreign direct investment for further development due to their technological advantages. Although this process increases inter-regional carbon transfer, this will certainly promote economic growth to a certain extent (Pan et al., 2022). Meanwhile, the carbon-reducing effect of the scale of regional specialization will also promote China to achieve carbon neutrality (Han et al., 2018). However, without the right supporting environmental regulation policies, it is easy to lead the less developed or carbon-intensive industrial regions to become pollution havens, thereby undermining the long-term economic and environmental development of the regions.

With the largest carbon emitter and a major digital economy developer in the world, investigating the effects of China's digital economy on inter-regional carbon transfer holds international significance for striking a balance between environmental and economic benefits. It provides valuable insights for countries around the world, especially developing countries, to better understand and address carbon transfer issues in the process of digital transformation. Consequently, we propose the following policy recommendations.

Policy implications

Improving inter-regional synergistic carbon reduction systems. The aforementioned analysis highlights the inadequacy of the central government in setting carbon emissions reduction targets solely for local governments. High-intensity mandatory environmental regulations could potentially exacerbate inter-regional carbon transfer, rendering it crucial to enhance the regional cooperative carbon reduction system. In response, local governments should proactively measure and publicly report inter-regional carbon transfer data to establish a foundation for jointly taking responsibility for inter-regional carbon emissions. Building upon this foundation, the establishment of an inter-regional carbon quota trading market can mitigate the negative environmental externalities caused by carbon transfer. Furthermore, drawing upon the development trajectory of China's urban agglomeration, such as the Yangtze River Delta urban agglomeration, a "pairing" approach can be adopted for regions with frequent carbon transfer. This strategy facilitates overall carbon emissions reduction through the optimization of inter-regional industrial structures, thereby preventing third-tier cities from becoming pollution havens for more developed cities.

Accelerating the fair progression of the digital economy. The advancement of the digital economy ought to be linked to the current dual-carbon goal development vision, emphasizing the low-carbon environmental effect of the digital economy and strengthening regulation. The disparities in the digital economy across regions and industries significantly affect the coordination of carbon reduction efforts among regions. Therefore, digital economy development strategies should be tailored to favor undeveloped regions and high-carbon industries, ensuring equitable growth of the digital economy in second and third-tier cities and across various industries. By doing so, the economic benefits and low-carbon effects brought by the digital economy to second and third-tier cities can be fully realized.

Improving regional carbon reduction efficiency. China's carbon emissions reduction policies cannot be handled in a "one-size-fits-all" manner but rather be tailored to the development levels of cities. Contrasting with first-tier cities that primarily focus on high-value-added and low-carbon industries, third-tier cities mainly bear the carbon emissions generated by carbon-intensive industries. The government should augment support for green production in third-tier cities, such as providing guidance on green technologies, offering green finance loans to enterprises, and granting subsidies for green production. These measures not only facilitate the green transformation of third-tier cities, but also enable them to share the carbon emissions burden of first-tier cities sustainably.

There are inevitable limitations to the above study. Although this paper has made every effort to improve the accuracy of the data, it has assumed the carbon intensity of the same industry is consistent across cities. The carbon intensity of undeveloped cities may be higher due to technological backwardness, and thus the carbon transfer to these areas may be underestimated.

Data availability

The Urban Household Survey dataset that support the findings of this study are available from Urban Survey Office of the National Bureau of Statistics, but restrictions apply to the availability of these data, which were used under licence for the current study, and so are not publicly available. Data are however available from the authors upon reasonable request and with permission of Urban Survey Office of the National Bureau of Statistics.

Received: 9 January 2023; Accepted: 6 September 2023;
Published online: 18 September 2023

Notes

1 http://www.gov.cn/xinwen/2021-03/13/content_5592681.htm.
2 https://www.ceads.net.cn/.
3 https://www.rug.nl/ggdc/valuechain/wiod/?lang=en.

References

Athanassiadis A, Christis M, Bouillard P, Vercalsteren A, Crawford RH, Khan AZ (2018) Comparing a territorial-based and a consumption-based approach to assess the local and global environmental performance of cities. J Cleaner Prod 173:112–123. https://doi.org/10.1016/j.jclepro.2016.10.068

Bin S, Dowlatabadi H (2005) Consumer lifestyle approach to US energy use and the related CO_2 emissions. Energy Policy 33(2):197–208. https://doi.org/10.1016/S0301-4215(03)00210-6

Chen G, Shan Y, Hu Y, Tong K, Wiedmann T, Ramaswami A, Guan D, Shi L, Wang Y (2019b) Review on city-level carbon accounting. Environ Sci Technol 53(10):5545–5558. https://doi.org/10.1021/acs.est.8b07071

Chen J, Gao M, Cheng S, Liu X, Hou W, Song M, Li D, Fan W (2021) China's city-level carbon emissions during 1992–2017 based on the inter-calibration of nighttime light data. Sci Rep 11(1). https://doi.org/10.1038/s41598-021-81754-y

Chen S (2022) The inequality impacts of the carbon tax in China. Humanit Soc Sci Commun 9(1). https://doi.org/10.1057/s41599-022-01285-3

Chen W, Lei Y, Wu S, Li L (2019a) Opportunities for low-carbon socioeconomic transition during the revitalization of northeast China: Insights from Heilongjiang province. Sci Total Environ 683:380–388. https://doi.org/10.1016/j.scitotenv.2019.05.232

Chen X, Lin B (2021) Towards carbon neutrality by implementing carbon emissions trading scheme: Policy evaluation in China. Energy Policy 157:112510. https://doi.org/10.1016/j.enpol.2021.112510

Domazlicky BR, Weber WL (2004) Does environmental protection lead to slower productivity growth in the chemical industry? Environ Resource Econ 28(3):301–324. https://doi.org/10.1023/B:EARE.0000031056.93333.3a

Dou J, Han X (2019) How does the industry mobility affect pollution industry transfer in China: Empirical test on Pollution Haven Hypothesis and Porter Hypothesis. J Clean Prod 217:105–115. https://doi.org/10.1016/j.jclepro.2019.01.147

Duan C, Chen B, Feng K, Liu Z, Hayat T, Alsaedi A, Alsaedi B (2018) Interregional carbon flows of China. Appl Energy 227:342–352. https://doi.org/10.1016/j.apenergy.2018.01.028

Essandoh OK, Moinul I, Makoto K (2020) Linking international trade and foreign direct investment to CO_2 emissions: any differences between developed and

developing countries? Sci Total Environ 712(11):136437. https://doi.org/10.1016/j.scitotenv.2019.136437
Feng K, Davis SJ, Sun L, Li X, Guan D, Liu W, Liu Z, Hubacek K (2013) Outsourcing CO_2 within China. Proc Natl Acad Sci USA 110(28):11654–11659. https://doi.org/10.1073/pnas.1219918110
Fich LE, Viola S, Bentsen NS (2022) Jevons paradox: sustainable development goals and energy rebound in complex economic systems. Energies 15(16):5821. https://doi.org/10.3390/en15165821
Grubb M, Jordan ND, Hertwich E, Neuhoff K, Das K, Bandyopadhyay KR, van Asselt H, Sato M, Wang R, Pizer WA, Oh H (2022) Carbon leakage, consumption, and trade. Annu Rev Environ Resour 47(1):753–795. https://doi.org/10.1146/annurev-environ-120820-053625
Han F, Xie R, Lu Y, Fang J, Liu Y (2018) The effects of urban agglomeration economies on carbon emissions: evidence from Chinese cities. J Clean Prod 172:1096–1110. https://doi.org/10.1016/j.jclepro.2017.09.273
Han P, Lin X, Zeng N, Oda T, Zhang W, Liu D, Cai Q, Crippa M, Guan D, Ma X, Janssens-Maenhout G, Meng W, Shan Y, Tao S, Wang G, Wang H, Wang R, Wu L, Zhang Q, Zhao F (2020) Province-level fossil fuel CO_2 emission estimates for China based on seven inventories. J Clean Prod 277:123377. https://doi.org/10.1016/j.jclepro.2020.123377
Hasegawa R, Kagawa S, Tsukui M (2015) Carbon footprint analysis through constructing a multi-region input-output table: a case study of Japan. J Econ Struct 4(1). https://doi.org/10.1186/s40008-015-0015-6
Holian MJ, Kahn ME (2015) Household carbon emissions from driving and center city quality of life. Ecol Econ 116:362–368. https://doi.org/10.1016/j.ecolecon.2015.05.012
Kaiser HF, Rice J (1974) Little Jiffy, Mark Iv. Educ Psychol Meas 34:111–117. https://doi.org/10.1177/001316447403400115
Kim DH, Suen YB, Lin SC (2019) Carbon dioxide emissions and trade: evidence from disaggregate trade data. Energy Econ 78:13–28. https://doi.org/10.1016/j.eneco.2018.08.019
Kloppenburg S, Boekelo M (2019) Digital platforms and the future of energy provisioning: promises and perils for the next phase of the energy transition. Energy Res Soc Sci 49:68–73. https://doi.org/10.1016/j.erss.2018.10.016
Lange S, Pohl J, Santarius T (2020) Digitalization and energy consumption. Does ICT reduce energy demand? Ecol Econ 176:106760. https://doi.org/10.1016/j.ecolecon.2020.106760
Lever J, Krzywinski M, Altman N (2017) Points of significance: Principal component analysis. Nat Methods 14:641–642. https://go.gale.com/ps/i.do?id=GALE%7CA497319735&sid=googleScholar&v=2.1&it=r&linkaccess=abs&issn=15487091&p=AONE&sw=w&userGroupName=anon%7Ecca57e0e&aty=open-web-entry
Li B, Li RYM, Wareewanich T (2021) Factors influencing large real estate companies' competitiveness: a sustainable development perspective. Land 10(11):1239. https://doi.org/10.3390/land10111239
Li J, Zhang D, Su B (2019b) The impact of social awareness and lifestyles on household carbon emissions in China. Ecol Econ 160:145–155. https://doi.org/10.1016/j.ecolecon.2019.02.020
Li J, Wu Y, Xiao J (2019a) The impact of digital finance on household consumption: evidence from China. Econ Model 86. https://doi.org/10.1016/j.econmod.2019.09.027
Li W, Qiao Y, Li X, Wang Y (2022) Energy consumption, pollution haven hypothesis, and environmental Kuznets curve: Examining the environment-economy link in belt and road initiative countries. Energy 239:122559. https://doi.org/10.1016/j.energy.2021.122559
Li Z, Wang J (2022) The dynamic impact of digital economy on carbon emission reduction: evidence city-level empirical data in China. J Clean Prod 351:131570. https://doi.org/10.1016/j.jclepro.2022.131570
Liu H, Wang X (2022) Spillover effects of foreign direct investment on export sophistication: evidence from Chinese domestic manufacturing firms. J Dev Stud 1–16. https://doi.org/10.1080/00220388.2022.2094254
Liu Y, Sadiq F, Ali W, Kumail T (2022) Does tourism development, energy consumption, trade openness and economic growth matters for ecological footprint: testing the environmental Kuznets curve and pollution haven hypothesis for Pakistan. Energy 123208. https://doi.org/10.1016/j.energy.2022.123208
Long Y, Jiang Y, Chen P, Yoshida Y, Sharifi A, Gasparatos A, Wu Y, Kanemoto K, Shigetomi Y, Guan D (2021) Monthly direct and indirect greenhouse gases emissions from household consumption in the major Japanese cities. Sci Data 8(1). https://doi.org/10.1038/s41597-021-01086-4
Louf T, Gonçalves B, Ramasco JJ, Sánchez D, Grieve J (2023) American cultural regions mapped through the lexical analysis of social media. Human Soc Sci Commun 10(1):1–11. https://doi.org/10.1057/s41599-023-01611-3
Lu Q, Fang K, Heijungs R, Feng K, Li J, Wen Q, Li Y, Huang X (2020) Imbalance and drivers of carbon emissions embodied in trade along the belt and road initiative. Appl Energy 280:115934. https://doi.org/10.1016/j.apenergy.2020.115934
Ma Q, Tariq M, Mahmood H, Khan Z (2022) The nexus between digital economy and carbon dioxide emissions in China: The moderating role of investments in research and development. Technol Soc 68:101910. https://doi.org/10.1016/j.techsoc.2022.101910
Meng F, Liu G, Hu Y, Su M, Yang Z (2018) Urban carbon flow and structure analysis in a multi-scales economy. Energy Policy 121:553–564. https://doi.org/10.1016/j.enpol.2018.06.044
Meng W, Yuan G, Sun Y (2023) Expansion of social networks and household carbon emissions: evidence from household survey in China. Energy Policy 174:113460. https://doi.org/10.1016/j.enpol.2023.113460
Mi Z, Zhang Y, Guan D, Shan Y, Liu Z, Cong R, Yuan XC, Wei YM (2016) Consumption-based emission accounting for Chinese cities. Appl Energy 184:1073–1081. https://doi.org/10.1016/j.apenergy.2016.06.094
Mi Z, Zheng J, Meng J, Zheng H, Li X, Coffman D, Woltjer J, Wang S, Guan D (2019) Carbon emissions of cities from a consumption-based perspective. Appl Energy 235:509–518. https://doi.org/10.1016/j.apenergy.2018.10.137
Miller RE, Blair PD (1985) Input-output analysis: Foundations and extensions. Prentice Hall, Englewood Cliffs, NJ
Monica S, Neha S (2021) Demystifying pollution haven hypothesis: role of FDI. J Bus Res 123:516–528. https://doi.org/10.1016/j.jbusres.2020.10.007
Moosavian SF, Zahedi R, Hajinezhad A (2021) Economic, environmental and social impact of carbon tax for Iran: a computable general equilibrium analysis. Energy Sci Eng. https://doi.org/10.1002/ese3.1005
Moran D, Kanemoto K, Jiborn M, Wood R, Többen J, Seto KC (2018) Carbon footprints of 13,000 cities. Environ Res Lett 13(6):064041. https://doi.org/10.1088/1748-9326/aac72a
Niu Y, Wen W, Wang S, Li S (2023) Breaking barriers to innovation: the power of digital transformation. Finance Res Lett 51:103457. https://doi.org/10.1016/j.frl.2022.103457
Nunn N, Qian N (2014) US food aid and civil conflict. Am Econ Rev 104(6):1630–1666. https://doi.org/10.1257/aer.104.6.1630
Pan W, Xie T, Wang Z, Ma L (2022) Digital economy: an innovation driver for total factor productivity. J Bus Res 139:303–311. https://doi.org/10.1016/j.jbusres.2021.09.061
Parsley DC, Wei SJ (2001) Limiting currency volatility to stimulate goods market integration: a price based approach. IMF Working Pape n, 2001, 197. https://www.nber.org/papers/w8468
Peters GP, Minx JC, Weber CL, Edenhofer O (2011) Growth in emission transfers via international trade from 1990 to 2008. Proc Natl Acad Sci 108(21):8903–8908. https://doi.org/10.1073/pnas.1006388108
Pu Z, Fu J (2018) Economic growth, environmental sustainability and China mayors' promotion. J Clean Prod 172:454–465. https://doi.org/10.1016/j.jclepro.2017.10.162
Qin M, Zhang X, Li Y, Badarcea RM (2023) Blockchain market and green finance: the enablers of carbon neutrality in China. Energy Econ 118:106501. https://doi.org/10.1016/j.eneco.2022.106501
Runst P, Thonipara A (2020) Dosis facit effectum why the size of the carbon tax matters: evidence from the Swedish residential sector. Energy Econ 91:104898. https://doi.org/10.1016/j.eneco.2020.104898
Shan Y, Guan D, Zheng H, Ou J, Li Y, Meng J, Mi Z, Liu Z, Zhang Q (2018) China CO_2 emission accounts 1997–2015. Sci Data 5:170201. https://doi.org/10.1038/sdata.2017.201
Shao L, Li Y, Feng K, Meng J, Shan Y, Guan D (2018) Carbon emission imbalances and the structural paths of Chinese regions. Appl Energy 215(C):396–404. https://doi.org/10.1016/j.apenergy.2018.01.090
Tagliapietra S, Wolff GB (2021) Form a climate club: United States, European Union and China. Nature 591(7851):526–528. https://doi.org/10.1038/d41586-021-00736-2
Tan Y, Liu X, Hugo G (2014) Exploring relationship between social inequality and adaptations to climate change: Evidence from urban household surveys in the Yangtze River delta, China. Popul Environ 36(4):400–428. https://doi.org/10.1007/s11111-014-0223-2
Tong J, Yue T, Xue J (2022) Carbon taxes and a guidance-oriented green finance approach in China: path to carbon peak. J Clean Prod 367:133050. https://doi.org/10.1016/j.jclepro.2022.133050
Usman A, Ozturk I, Ullah S, Hassan A (2021) Does ICT have symmetric or asymmetric effects on carbon emissions? Evidence from selected Asian economies. Technol Soc 67:101692. https://doi.org/10.1016/j.techsoc.2021.101692
Wang J, Dong X, Dong K (2022b) How digital industries affect China's carbon emissions? Analysis of the direct and indirect structural effects. Technol Soc 68:101911. https://doi.org/10.1016/j.techsoc.2022.101911
Wang Y, Xiong S, Ma X (2022a) Carbon inequality in global trade: evidence from the mismatch between embodied carbon emissions and value added. Ecol Econ 195:107398. https://doi.org/10.1016/j.ecolecon.2022.107398
Wu M, Cao X (2021) Greening the career incentive structure for local officials in China: Does less pollution increase the chances of promotion for Chinese

local leaders? J Environ Econ Manag 107:102440. https://doi.org/10.1016/j.jeem.2021.102440
Xu D, Li Y, Zhao M, Wang X, Zhang Y, Chen B, Yang Z (2022a) Spatial characteristics analysis of sectoral carbon transfer path in international trade: a comparison of the United States and China. Appl Energy 323:119566. https://doi.org/10.1016/j.apenergy.2022.119566
Xu D, Zhang Y, Li Y, Wang X, Yang Z (2022b) Path analysis for carbon transfers embodied in China's international trade and policy implications for mitigation targets. J Clean Prod 334:130207. https://doi.org/10.1016/j.jclepro.2021.130207
Xue Y, Tang C, Wu H, Liu J, Hao Y (2022) The emerging driving force of energy consumption in China: does digital economy development matter? Energy Policy 165:112997. https://doi.org/10.1016/j.enpol.2022.112997
Yang X, Xu H, Su B (2022) Factor Decomposition for Global and National Aggregate Energy Intensity Change during 2000–2014. Energy 254:124347. https://doi.org/10.1016/j.energy.2022.124347
Yang Y, Qu S, Cai B, Liang S, Wang Z, Wang J, Xu M (2020) Mapping global carbon footprint in China. Nat Commun 11(1). https://doi.org/10.1038/s41467-020-15883-9
Yu J, Shi X, Laurenceson J (2019) Will the Chinese economy be more volatile in the future? Insights from urban household survey data. Int J Emerg Mark 15(4):790–808. https://doi.org/10.1108/IJOEM-04-2019-0290
Yu X, Wu Z, Zheng H, Li M, Tan T (2020) How urban agglomeration improve the emission efficiency? A spatial econometric analysis of the Yangtze River delta urban agglomeration in China. J Environ Manag 260:110061. https://doi.org/10.1016/j.jenvman.2019.110061
Yuan R, Rodrigues JFD, Behrens P (2019) Driving forces of household carbon emissions in China: a spatial decomposition analysis. J Clean Prod 233:932–945. https://doi.org/10.1016/j.jclepro.2019.06.110
Yuan X, Sheng X, Chen L, Tang Y, Li Y, Jia Y, Qu D, Wang Q, Ma Q, Zuo J (2022) Carbon footprint and embodied carbon transfer at the provincial level of the Yellow River basin. Sci Total Environ 803:149993. https://doi.org/10.1016/j.scitotenv.2021.149993
Zeng L, Li RYM, Huang X (2021) Sustainable mountain-based health and wellness tourist destinations: the interrelationships between tourists' satisfaction, behavioral intentions, and competitiveness. Sustainability 13(23):13314. https://doi.org/10.3390/su132313314
Zhang W, Liu X, Wang D, Zhou J (2022) Digital economy and carbon emission performance: evidence at China's city level. Energy Policy 165:112927. https://doi.org/10.1016/j.enpol.2022.112927
Zhang Z, Guan D, Wang R, Meng J, Zheng H, Zhu K, Du H (2020) Embodied carbon emissions in the supply chains of multinational enterprises. Nat Clim Change. https://doi.org/10.1038/s41558-020-0895-9
Zheng H, Többen J, Dietzenbacher E et al. (2021) Entropy-based Chinese city-level MRIO table framework. Econ Syst Res 27:1–26. https://doi.org/10.1080/09535314.2021.1932764
Zhou S, Teng F (2013) Estimation of urban residential electricity demand in China using household survey data. Energy Policy 61:394–402. https://doi.org/10.1016/j.enpol.2013.06.092
Zhu Q, Sang X, Li Z (2023) Economic growth and household energy footprint inequality in China. PLoS ONE 18(3):e0282300. https://doi.org/10.1371/journal.pone.0282300

Acknowledgements
This study is supported by the Major Project of the National Social Science Fund (Grant No. 22ZDA108) and the Fundamental Research Funds for the Central Universities (No. JBK2304122). The authors wish to thank the relevant department for its funding.

Author contributions
BL: Data curation, Software, Formal analysis, and Writing—original draft; HY: Data curation, Software, Formal analysis, and Writing—original draft; HZ: Data curation, Resources, Formal analysis, and review; XY: Formal analysis, and review. All authors read and approved the final transcript and agreed to be accountable for all aspects of the work.

Competing interests
The authors declare no competing interests.

Ethical approval
This article does not contain any studies with human participants performed by any of the authors.

Informed consent
This article does not contain any studies with human participants performed by any of the authors.

Additional information
Supplementary information The online version contains supplementary material available at https://doi.org/10.1057/s41599-023-02100-3.

Correspondence and requests for materials should be addressed to Bingjiang Luan or Hanshuo Yang.