Effects of rural–urban development transformation on energy consumption and CO₂ emissions: A regional analysis in China

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ABSTRACT

Since the 1980s, China has been undergoing a period of rural–urban transformation. The rapid rural–urban development transformation (RUDT) in China has caused an excessive consumption of resources and environmental deterioration. Based on balanced provincial panel data in China gathered from 1990 to 2012, this study used an improved STIRPAT model to investigate the effects of RUDT on energy consumption and CO₂ emissions on the regional and national levels. The empirical results showed that the impact of RUDT on energy consumption and CO₂ emissions in China varied greatly across regions. The demographic transformation (measured by urbanization level) increased energy consumption and CO₂ emissions in China and its eastern and central regions. The impact of employment structural transformation on energy consumption and carbon emissions across China generally was positive and significant but differed considerably across regions. The industrial structural transformation was positively correlated with and had a significant impact on energy consumption and emissions in the eastern and central regions, and that effect declined continuously from the eastern region to the central and western regions. Furthermore, the positive effect of land use transition on energy consumption and CO₂ emissions in the western region was greater than that in the eastern and central regions. These findings can provide policymakers with a sound scientific basis for energy saving and emission reduction decisions.

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Contents

1. Introduction	864
2. Data and methods	865
2.1. Data description	865
2.2. Measurement of RUDT	865
2.3. STIRPAT model	866
2.4. Model estimation	867
3. Results	867
3.1. RUDT, energy consumption and CO ₂ emissions in China	867
3.1.1. Demographic transformation	867
3.1.2. Industrial and employment structural transformation	869
3.1.3. Land use transition	870
3.1.4. Energy consumption and CO ₂ emissions	870
3.2. The impact of RUDT on energy consumption	871
3.3. The impact of RUDT on CO ₂ emissions	871
4. Discussion	871
5. Conclusions and policy implications	872
Acknowledgements	873

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Appendix A.	873
References	874

1. Introduction

Rural–urban transformation has been an important socio-economic phenomenon worldwide since the 18th century [1]. Rural–urban development transformation (RUDT) is a comprehensive human process of element transfer, strategy change and mechanism transformation between rural and urban regions, which involves rural–urban migration and changes in demographic, industrial and employment structures as well as land-use patterns [2,3]. These changes signify a transformation from previously isolated urban and rural socio-economic structures toward a more coordinated urban–rural relationship [4]. RUDT can be roughly divided into two stages. The first stage mainly includes the agglomeration of populations into cities, the shift from agricultural activities towards non-agricultural ones, the transformation of the industrial structure from the primary industry to secondary and tertiary industries, and the conversion of agricultural land to non-agricultural purposes. The second stage is the process through which urban civilization diffuses to rural areas, which involves changes in the culture and lifestyles of the rural residents [1]. RUDT can be divided into morphological (including demographic and employment) transformation and functional (industrial) transformation [5]. Rural–urban integration or a *desakota* region is the final desired result of RUDT (Fig. 1) [1,6]. *Desakota* is a region where there are no clear boundaries between rural and urban areas, which represents an intensive mixture of agricultural and non-agricultural activities that often stretch along corridors between large cities' cores [6].

The spatial-temporal patterns, regional characteristics, and dynamic mechanisms of RUDT and their impact on poverty reduction have been extensively and intensively studied in recent years [7–10]. Henderson and Wang [7] proposed a model for measuring the rural–urban spatial transformation in different countries and focused on the driving forces, processes and potential impacts of such a transformation. Two consecutive World Development Reports focused on RUDT and noted that its process was geographically uneven [11,12]. A country's RUDT was determined by a complex interaction of its history, policies and institutions [13]. McGee [8] explored the special features of RUDT in East Asia over the last three decades. Christiaensen and Todo [9] noted that converting an agricultural economy to a rural non-farm economy in secondary towns accelerated poverty reduction more than did agglomeration in mega cities [9], but Imai et al. [10] argued that rural development was more important than urbanization in poverty reduction. Most of the existing studies on RUDT primarily focus on developing or less-developed countries [6,8,13].

China entered a period of rapid RUDT when economic reforms and the open-door policy were initiated in 1978, which brought a series of challenges for sustainable development and environmental protection on various geographical scales. Of particular concern were the growing economic disparities between regions regarding prospects for farming communities [8,14–16]. RUDT in China was characterized by radical changes in the industrial, employment and consumption structures and the corresponding changes in demographic structures and land use models between rural and urban regions [8,15]. These changes were radical not only because of China's ongoing restructuring of its previously planned economy but also because of its population size, regional diversity and the special dual-track structure of rural and urban regions [8]. Laquian [17] noted that China's RUDT

origins were in rural development and that this transition had positive economic and social effects but also brought about negative environmental effects. Tang and Chung [18] analyzed RUDT in China from the perspective of illegal land use and construction. RUDT in China has increased the gap between rural and urban areas and exacerbated the urban–rural dual structure [15]. The income ratio between urban and rural households increased from 2.36:1 in 1990 to 3.10:1 in 2012 (Fig. 2) [19]. Because of rural population migration and land recession, hollowed villages in rural China have become increasingly aggravated, which has caused severe environmental problems [20]. An important national strategy of 'building a new countryside' was announced by the Chinese central government in 2006 to coordinate urban and rural development [21]. Liu et al. [16] found that the urban–rural equalized development level of China decreased from the eastern region to the central and western regions. Some major national policies (i.e., the household responsibility system and household registration system), industrialization, public infrastructure and geographic conditions have been considered the driving forces of RUDT in China [8,15,17,20,22].

The transformations in demographic, employment and industrial structures between rural and urban regions, and changes in land use patterns are the main aspects of RUDT [1,7,8,15]. The rapid RUDT in China has caused an excessive consumption of resources and environmental deterioration [4,8,15,17]. Considerable attention has been paid to the effects of urbanization on energy consumption and CO₂ emissions on different spatial scales in China [23–25]. For instance, Wei et al. [26] used a consumer lifestyle approach to quantify the direct and indirect impact that the lifestyles of urban and rural residents had on China's energy consumption and CO₂ emissions. Urbanization slowed per capita residential energy consumption growth in China, but it contributed to an increase of residential indirect CO₂ emissions [27]. Using the STIRPAT model, Zhang and Lin [25] found that urbanization increased energy consumption and CO₂ emissions in China. Similar conclusions have been drawn for Beijing [28] and for the Guangdong province of China [29]. Additionally, Zhou et al. [30] analyzed the relationship between the industrial structural transformation and CO₂ emissions using provincial panel data and suggested that upgrading and optimizing China's industrial structure was an effective way to reduce CO₂ emissions in China. This research provides conclusive evidence that urbanization has contributed to the increase in energy consumption and CO₂ emissions in China.

These studies provide a scientific basis for effective energy saving and emission reduction strategies for different countries and regions. However, most of the existing studies focus only on the effects of urbanization on energy consumption and CO₂ emissions and have not fully considered other important factors of RUDT, e.g., the transformations in employment and industrial structures or the land use patterns. Furthermore, regional discrepancies in geographical and biophysical conditions exist in China, and the environmental issues due to the rapid RUDT vary across regions. A better understanding of the relationships among RUDT, energy consumption and CO₂ emissions with consideration of regional differences is still necessary and urgent. Thus, the main aim of this study was to examine the impacts of RUDT on energy consumption and CO₂ emissions in China. Based on a balanced panel dataset of 30 provinces in China from 1990 to 2012, we used an improved STIRPAT model to investigate the effects of RUDT on energy use and CO₂ emissions with a full consideration of regional differences.

This study contributes to the field in the following three ways: first, this study systematically examines the status quo of RUDT in

China from the perspectives of population, industry, employment and land. A large amount of literature focuses on China's RUDT from only one viewpoint, i.e., only rural–urban migration or industrial or employment structure changes, which may limit the understanding of Chinese rural–urban transformation. Second, we use an improved STIRPAT model to assess the impact of RUDT on energy consumption and CO₂ emissions in China and account for regional differences. China's RUDT has profoundly changed the flow of elements and spatial connection in rural and urban areas. Uncoordinated rural–urban transformation may exacerbate the excessive consumption of resources and exert pressure on the environment. Finally, we investigate the effect of land-use change (which is an often overlooked factor in the human–environment impact assessment literatures) on carbon emissions. Based on these empirical investigations, a possible low-carbon development path is explored, and some relevant policy suggestions for policymakers are provided.

The remainder of this paper is structured as follows. Section 2 presents the data and methods for measuring the RUDT and its impact on energy consumption and CO₂ emissions in this paper. Section 3 provides the empirical results. Section 4 discusses the results, while the conclusions and policy implications are presented in Section 5.

2. Data and methods

2.1. Data description

This paper used a balanced panel dataset of 30 provinces in China over the period 1990–2012 (Hong Kong, Macao, Taiwan and Tibet

are not included for lack of data). The data of the provincial population size, GDP, urban population, the added values of secondary and tertiary industry, the percentages of population employed in secondary and tertiary industry, and the per capita disposable income of urban residents and the per capita net income of rural dwellers were obtained from the China Statistical Yearbook and the China Compendium of Statistics. Cultivated land occupied by construction was collected from the China Land and Resources Almanac. The data on energy consumption were obtained from the China Energy Statistical Yearbook. The energy-related CO₂ emissions were calculated according to the formula of CO₂ emissions in the Intergovernmental Panel on Climate Change (IPCC) (2006) (Provided by website: <http://www.ipcc-nggip.iges.or.jp/>). To eliminate the influence of price index, the GDP was calculated at the constant price (1990 prices) and the added values in secondary and tertiary industry were calculated accordingly. Table 1 provides a detailed description of all variables used in this study.

2.2. Measurement of RUDT

In this study, measuring RUDT primarily involved the transformation of demographic, employment and industrial structures in rural and urban areas and the land use pattern transitions [1,4,5,6,31,32] (Fig. 3). The change in the proportion of the urban population relative to the total population (urbanization) was used to reflect the demographic transition (DT) between rural and urban regions [1,7]. Percentages of the population employed in secondary and tertiary industries were chosen to measure the employment structural transformation (EST) [1,32], and percentages of the added value of secondary and tertiary industries in GDP were used to measure the industrial structural transformation (IST) [8,32].

Land use transition (LUT) reflects the changes in land use morphology (including dominant and recessive morphology) of a certain region over a certain time period driven by socio-economic change and innovation [33]. Dominant morphology refers to the quantity, structure and spatial pattern of land, and recessive morphology includes land use features, e.g., quality, property rights, price, and management mode [33]. In the present study, because of data limitations, we focused on only one aspect of the changes in dominant morphology, i.e., cultivated land occupied by construction [31,32,34,35]. Urbanization, industrialization and modernization are important ways to achieve rural–urban integration [4]. Rapid urban population and economic growth and the construction and maintenance of urban infrastructure in the process of RUDT will likely cause more resource consumption and emit more CO₂ [24,36].

Fig. 1. Diagram of rural–urban transformation. Source: modified from Hu [1].

Fig. 2. Annual per capita disposable income of urban and rural households in China from 1990 to 2012. Note: The income ratio was calculated by dividing the per capita disposable income of urban residents by the per capita net income of rural dwellers. Source: NBS [19].

Table 1
Description of the variables used in the study for the period 1990–2012.
Sources: China Statistical Yearbook, China Compendium of Statistics, China Land & Resources Almanac, China Rural Statistical Yearbook and China Energy Statistical Yearbook during 1991–2013.

Type	Variable	Definition	Unit
Environment impact	Carbon dioxide emissions (CO ₂)	Emission from fuel combustion	10 ⁴ tons
	Energy intensity (EI)	Energy consumption divided by GDP	Tec/10 ⁴ yuan
Demographic transformation (DT)	Energy consumption (EC)	Sum of energy use	10 ⁴ tec
Employment structural transformation (EST)	Urbanization (URBA)	Percentage of the urban population in the total population	Percent
	Share of secondary industry employment (EP2)	Percentage of population employed in secondary industry	Percent
	Share of tertiary industry employment (EP3)	Percentage of population employed in tertiary industry	Percent
Industrial structural transformation (IST)	Share of secondary industry in GDP (INDU)	Percentage of the added value of secondary industry to GDP	Percent
	Share of tertiary industry in GDP (TERT)	Percentage of the added value of tertiary industry to GDP	Percent
	Farmland conversion (LAND)	Cultivated land occupied by construction	Hectare
Land use transformation (LUT)	Rural–urban income gap (URI)	Ratio of the per capita disposable income of urban residents to the per capita net income of rural households	Ratio

Fig. 3. RUDT and its impacts on energy consumption and CO₂ emissions.
Source: Author's draw.

2.3. STIRPAT model

The effect of demographic (P), economic (A) and technologic (T) factors on the environment is mainly postulated in the IPAT model ($I=PAT$), which is firstly proposed by Ehrlich and Holdren [37]. The IPAT model is limited because it analyzes a problem by changing a factor while keeping others constant, resulting in proportionate impacts on the dependent variable [38,39]. To overcome these weaknesses, Dietz and Rosa [38] reformulated the IPAT model into a stochastic model (STIRPAT), which can statistically assess non-monotonic or non-proportional impacts of driving forces on the environment. York et al. [40] refined the STIRPAT model and expanded it by incorporating additional factors, such as quadratic terms or different components of P , A or T . Presently, the STIRPAT model has been successfully utilized to analyze the effects of driving forces on a variety of environmental impacts [28,29,36,39–42], it can be given as following equation:

$$I_{it} = \alpha P_{it}^b A_{it}^c T_{it}^d \varepsilon_{it} \quad (1)$$

After taking logarithms, the model takes the following form:

$$\ln(I_{it}) = a + b \ln(P_{it}) + c \ln(A_{it}) + d \ln(T_{it}) + \varepsilon_i \quad (2)$$

where suffixes i and t refer to provinces and years, respectively; P is population size; A is real GDP per capita; T represents technology; and the dependent variable I stands for pollutant emissions;

ε_i is the error term, a is the constant term; b , c and d are, respectively, the coefficients of P , A and T .

The STIRPAT model allows factors to be added to assess their impact on the environment. In the STIRPAT model, factors P and A are decomposable, as is T [40]. To further examine the impact of RUDT on energy consumption and CO₂ emissions, we extended the STIRPAT model by incorporating the DT, IST, EST, LUT, and energy intensity factors into the model. The improved STIRPAT model was changed as follows:

$$\ln(EC_{it}) = a_0 + a_1 \ln(EP2_{it}) + a_2 \ln(EP3_{it}) + a_3 \ln(URBA_{it}) + a_4 \ln(URI_{it}) + a_5 \ln(INDU_{it}) + a_6 \ln(TERT_{it}) + a_7 \ln(LAND_{it}) + \varepsilon_{1it} \quad (3)$$

$$\ln(I_{it}) = b_0 + b_1 \ln(EP2_{it}) + b_2 \ln(EP3_{it}) + b_3 \ln(URBA_{it}) + b_4 \ln(URI_{it}) + b_5 \ln(INDU_{it}) + b_6 \ln(TERT_{it}) + b_7 \ln(LAND_{it}) + b_8 \ln(EI_{it}) + \varepsilon_{2it} \quad (4)$$

where EP2 and EP3 represent EST (expressed as the percentages of population employed in secondary and tertiary industries, respectively); URBA represents DT (expressed as the percentage of the population living in urban areas); INDU and TERT represent IST (expressed as shares of the added value of secondary and tertiary industry to the GDP, respectively); URI is the rural–urban income gap; LAND represents LUT (expressed as the cultivated land area occupied by construction); EI is energy intensity (expressed as the energy use per unit of GDP); EC denotes energy consumption; and I represents the environmental impact (proxied by energy-related CO₂ emissions). The energy intensity variable is included in only the emission models because it contains part of the dependent variable.

Table 2

Estimation result for energy use models (the whole sample and the eastern region).

Variable	The whole sample			Eastern region		
	FE(1)	FGLS(2)	DK(3)	FE(4)	FGLS(5)	DK(6)
Ln(EP2)	−0.048	0.385***	0.423***	0.117	−0.851***	−0.925***
Ln(EP3)	0.480***	0.347***	0.358*	1.096***	−0.353***	−0.435
Ln(URBA)	0.738***	0.326***	0.324***	0.673***	0.441***	0.441***
Ln(URI)	0.527***	0.672***	0.687***	0.391***	0.999***	1.113***
Ln(INDU)	0.987*	0.109***	0.096	0.669***	2.680***	2.740***
Ln(TERT)	0.618	−0.329***	−0.374	0.618**	1.563***	1.962**
Ln(LAND)	0.039**	0.540***	0.574***	−0.054**	0.296***	0.369***
Constant	−2.174**	0.643***	0.430	−2.613**	−7.774***	−9.615***
R ²	0.821	–	0.682	0.893	–	0.785
Autocorrelation test	F(1, 29)=138.08***			F(1, 10)=19.98***		
Cross-sectional dependence test	44.15***			16.20***		
Heteroskedasticity test	$\chi^2(30)=550.09$ ***			$\chi^2(11)=145.29$ ***		
Observations	690	690	690	253	253	253

Variable	Central region			Western region		
	FE(7)	FGLS(8)	DK(9)	FE(10)	FGLS(11)	DK(12)
Ln(EP2)	−0.394***	−0.013	−0.054	0.051	−0.231***	−0.366**
Ln(EP3)	0.405***	−0.617***	−0.820**	0.340***	0.738***	0.949***
Ln(URBA)	1.161***	0.571***	0.676***	0.213**	−0.063	−0.141
Ln(URI)	0.283***	0.687***	0.751***	0.294***	0.102	0.020
Ln(INDU)	0.320	1.575***	1.720***	2.113***	1.424***	1.454**
Ln(TERT)	−0.241	1.221***	1.478***	0.906***	−0.548***	−0.819
Ln(LAND)	0.046*	0.134***	0.226***	0.209***	0.465***	0.576***
Constant	3.558***	−3.105***	−4.935***	−6.552***	−0.337	−0.237
R ²	0.866	–	0.771	0.866	–	0.786
Autocorrelation test	F(1, 7)=55.64***			F(1, 10)=146.72***		
Cross-sectional dependence test	13.22***			8.09***		
Heteroskedasticity test	$\chi^2(8)=40.92$ ***			$\chi^2(11)=66.68$ ***		
Observations	184	184	184	253	253	253

Notes: FE (Fixed effects); FGLS (Feasible generalized least squares); DK (Regression with Driscoll–Kraay standard errors).

*** Denotes rejection of the null hypothesis of nonstationary at the 1% significance level.

** Denotes rejection of the null hypothesis of nonstationary at the 5% significance level.

* Denotes rejection of the null hypothesis of nonstationary at the 10% significance level.

2.4. Model estimation

Two steps were performed to evaluate the impact of RUDT on energy consumption and emissions for the entirety of China and for the three regions [24,36]. First, the LLC, IPS, Fisher-ADF and Fisher-PP statistics were used to test for the presence of the panel unit root [43–46]. The panel unit root test results show that many variables are non-stationary in their levels, but most of them become stationary at the 5% significance level after taking first differences (see Table A1 in Appendix A). Second, we estimated the whole sample without consideration of regional differences. Furthermore, to investigate whether the impact of RUDT on the environment varies across regions in China, the whole sample was divided into three regions, i.e., the eastern region (including Liaoning, Beijing, Tianjin, Hebei, Shandong, Jiangsu, Shanghai, Zhejiang, Guangdong, Fujian and Hainan), the central region (including Heilongjiang, Jilin, Shanxi, Henan, Anhui, Jiangxi, Hubei and Hunan) and the western region (including Xinjiang, Gansu, Qinghai, Inner Mongolia, Ningxia, Shaanxi, Sichuan, Chongqing, Guizhou, Yunnan and Guangxi). The classification by region is common in China, considering China's economic development level and geographic position [25,47,48]. The impact of the RUDT on energy use and CO₂ emissions for the whole sample and for the three regions were estimated using three methods: fixed effects (FE), the feasible generalized least squares (FGLS) and the linear regression with Driscoll–Kraay standard errors (DK), generating twenty-four models. Specifically, the FE estimation was applied to alleviate heterogeneity bias. The autocorrelation in the fixed effect

models was verified by the Wooldridge test and the autocorrelation in the fixed effect models was found [49]. Moreover, we confirmed the presence of groupwise heteroskedasticity in all modes using the modified Wald statistic [50]. We also detected the existence of cross-sectional dependence by Pesaran test in the fixed effect models [51]. The FGLS estimation was employed to address those issues. However, the FGLS method is infeasible if the panel's time dimension T is smaller than its cross-sectional dimension N , and it tends to produce unacceptably small standard error estimates [52]. To solve the issues, the Driscoll–Kraay estimation was applied. Besides being heteroscedasticity consistent, the Driscoll–Kraay standard error estimates are robust to general forms of cross-sectional and temporal dependence [53]. The results are listed in Tables 2 and 3. Additionally, the multicollinearity among the explanatory variables in the FD models was tested by the variance inflation factors (VIF). The VIF values are all less than 10, indicating no multicollinearity [25,54] (see Table A2 in Appendix A).

3. Results

3.1. RUDT, energy consumption and CO₂ emissions in China

3.1.1. Demographic transformation

RUDT involved the agglomeration of populations into cities, with increasing numbers of cities and increasing populations of individual cities [7]. As the world's most populous country, China

Table 3
Estimation result for CO₂ emission models (the whole sample and the eastern region).

Variable	The whole sample			Eastern region		
	FE(13)	FGLS(14)	DK(15)	FE(16)	FGLS(17)	DK(18)
Ln(EP2)	−0.072	0.430***	0.435***	−0.212	−1.134***	−1.359***
Ln(EP3)	0.182*	0.483***	0.540**	0.997***	−0.425	−0.463
Ln(URBA)	0.751***	0.394***	0.423***	0.531***	0.575***	0.541***
Ln(URI)	0.420***	0.711***	0.760***	0.323**	1.169***	1.162***
Ln(INDU)	1.392***	0.089***	0.053	2.073***	3.210***	3.384***
Ln(TERT)	0.732***	−0.665***	−0.685	1.625***	0.277***	2.202***
Ln(LAND)	0.011	0.603***	0.647***	−0.079***	1.625***	0.396***
Ln(EI)	−0.070*	0.206***	0.265***	0.118	0.203***	0.258**
Constant	−3.084***	−0.043	−0.584	−9.761***	−0.037	−12.527***
R ²	0.779	–	0.630	0.849	–	0.791
Autocorrelation test	F(1, 29)=241.99***			F(1, 10)=76.29***		
Cross-sectional dependence test	34.73***			13.74***		
Heteroskedasticity test	$\chi^2(30)=1476.09$ ***			$\chi^2(11)=347.59$ ***		
Observations	690	690	690	253	253	253

Variable	Central region			Western region		
	FE(19)	FGLS(20)	DK(21)	FE(22)	FGLS(23)	DK(24)
Ln(EP2)	−0.143	0.173**	0.068	−0.066	−0.237***	−0.446
Ln(EP3)	0.203	−0.288**	−0.514	0.154	0.635***	1.059***
Ln(URBA)	1.006***	0.213***	0.287*	0.296***	−0.124**	−0.107
Ln(URI)	0.213*	0.617***	0.580***	0.362***	0.096	0.073
Ln(INDU)	0.030	2.193***	2.537***	1.945***	1.615***	1.786**
Ln(TERT)	−0.372	1.438***	1.798***	0.652***	−0.483**	−0.827**
Ln(LAND)	0.037	0.126***	0.158***	0.211***	0.433***	0.615***
Ln(EI)	−0.158**	0.122***	0.069**	−0.089	−0.017	0.202**
Constant	5.379***	−6.837***	−8.740***	−4.870***	−0.835	−2.451
R ²	0.82	–	0.768	0.817	–	0.701
Autocorrelation test	F(1, 7)=358.72***			F(1, 10)=146.34***		
Cross-sectional dependence test	10.24***			9.21***		
Heteroskedasticity test	$\chi^2(8)=246.3$ ***			$\chi^2(11)=200.65$ ***		
Observations	184	184	184	253	253	253

Notes: FE (Fixed effects); FGLS (Feasible generalized least squares); DK (Regression with Driscoll–Kraay standard errors).

*** Denotes rejection of the null hypothesis of nonstationary at the 1% significance level.

** Denotes rejection of the null hypothesis of nonstationary at the 5% significance level.

* Denotes rejection of the null hypothesis of nonstationary at the 10% significance level.

Fig. 4. Urban and rural population and urbanization rate in China between 1990 and 2012.

Source: NBS [19].

has experienced unprecedented urbanization in recent decades, with the urban population increasing from 302 million in 1990 to 711 million in 2012 (Fig. 4). The urbanization rate in China has increased from 26.41 percent in 1990 to 52.57 percent in 2012. During the same period, China's rural population decreased from 841 million in 1990 to 642 million in 2012, with an average annual

decrease of 1.2%. The urban population surpassed the rural population for the first time in the country's history in 2011.

Urban population growth has mainly been attributed to mass rural–urban migration in China [22]. China has witnessed the world's greatest rural–urban migration over the last three decades. It is estimated that more than 200 million rural residents have migrated

Fig. 5. Changes in industrial structure for China between 1990 and 2012.

Source: NBS [19].

Fig. 6. Changes in employment structure by industry for China between 1990 and 2012.

Source: NBS [19].

Fig. 7. Cultivated land occupied by construction in China (a) and its three regions (b) between 1990 and 2012.

Sources: MLR, 1991–2013 [60].

to cities and towns within China over the last three decades [55]. Interprovincial migrants were encouraged by the rural–urban income gap and discouraged by their geographic distance to destinations [22]. The total interprovincial migration volume in China has increased significantly from 10.7 million in 1990–1995 to 55.2 million in 2005–2010 [56]. Most eastern provinces were the most prominent destinations of interprovincial migration and had relatively high aggregate net migration volume over the past two decades [56]. Internal migration in China is special in that it is heavily controlled and regulated by the household registration system (hukou). The rate of

hukou migration as a percentage of China's total population has declined from 1.7% in 1982 to 1.3% in 2010.

3.1.2. Industrial and employment structural transformation

The transition from predominantly rural to increasingly urban economies is part of RUDT. Great changes have occurred in the industrial structure of China over the past several decades, which showed that the value added to the GDP by tertiary industries has been on the rise but that primary industry has been decreasing (Fig. 5). Specifically, from 1990 to 2012 the primary industry share

Fig. 8. Energy consumption and CO₂ emissions for China (a) and its three regions (b) between 1990 and 2012.

Sources: The energy consumption is obtained from China Energy Statistical Yearbook during 1991–2013, and the CO₂ emissions are based on author's calculations.

decreased from 27.1% to 10.1%, whereas the tertiary industry share increased from 31.5% to 44.6%. The ratio of added value in the primary, secondary and tertiary industries in 1990 was 27:43:31, whereas that ratio was adjusted to 10.1:45.3:44.6 by 2012.

RUDT is also accompanied by an occupational shift from agricultural activities toward more remunerative non-agricultural activities [10]. The economic structure and industrial distribution reforms have resulted in great changes in employment structures in China, which have meant an increasing number of people employed in secondary and tertiary industries. In 2012, the ratio of employees in primary, secondary and tertiary industries stood at 33.6:30.3:36.1, compared with 60.1:21.4:18.5 in 1990 (Fig. 6).

3.1.3. Land use transition

Land use is a mirror of the society; various socio-economic and environmental issues brought about by RUDT can be reflected in land use [33]. Since 1998, the Chinese central government has begun to implement extremely restrictive and highly centralized policies and regulations regarding the conversion of cultivated land to non-agricultural construction land [57,58]. Nevertheless, illegal land use and construction was still prevalent in rural China, where a large amount of cultivated land has been converted to non-agricultural use [18]. Between 1996 and 2008, the country's cultivated land area converted by construction increased from 83.79 thousand hectares to 259.35 thousand hectares, with an increase of 7.64 thousand hectares per year (Fig. 7). The average annual cropland area occupied by construction in China has increased drastically from approximately 1.3 million hectares in 1990–2000 to more than 2 million hectares in 2000–2010, thus further highlighting the conflict between urbanization and cropland conservation [59]. The cumulative cultivated land losses due to construction occupation in eastern China were approximately 2000 thousand hectares between 1990 and 2012, which was significantly higher than the losses in central China (1116 thousand hectares) and western China (1041 thousand hectares) [60]. Rural–urban migration, urbanization and economic development are

mainly responsible for the rapid conversion to non-agricultural land in China over the past decades [59].

3.1.4. Energy consumption and CO₂ emissions

The rapidly increasing energy demand made China the world's largest energy consumer in 2010 and CO₂ emitter in 2007 [61]. The total primary energy consumption in China increased from 969 million tons of coal equivalent (MtCE) in 1990 to 4432 MtCE in 2012, with an average annual growth rate of 7.15% (Fig. 8a). In 2012, China's energy consumption accounted for 22% of global primary energy consumption. By 2030, it is expected that the primary energy consumption in China will be double the actual consumption of 2010. Due to abundant domestic stock of coal, China is heavily dependent on coal as its primary source of energy [62]. Coal consumption is largely responsible for the high levels of air pollution in China [63]. China's CO₂ emissions have significantly increased from 682.7 million tons (Mtons) in 1990 to 2836 Mtons in 2012 (Fig. 8a). There has been a relatively rapid growth rate of CO₂ emissions in China over the last two decades [64]. It is predicted that by 2030, China's primary energy demand and CO₂ emissions will reach 22.8% and 31% of the world's total [65]. Confronting to better conform to international restrictions concerning the reduction of greenhouse gas emissions, the Chinese government in the "Twelfth Five-Year Plan" set a goal to reduce its unit GDP energy consumption and CO₂ emissions by 16% and 17% by 2015 compared with 2010, respectively [66].

Between 1990 and 2012, energy consumption in the eastern, central and western regions of China also showed an increasing trend (Fig. 8b). The average annual growth rates of energy use in the eastern, central and western regions were 7.49%, 6.26% and 7.58%, respectively. This finding indicates that the growth rate of energy consumption in western China was larger than that in the eastern and central regions over the past two decades. Correspondingly, energy-related CO₂ emissions in the eastern region remained at a relatively high level from 1990 to 2012. Interestingly, the CO₂ emissions in the western region in 2012 surpassed those in the central region, which

may be related to a higher growth rate in energy consumption of western China in recent years.

3.2. The impact of RUDT on energy consumption

Table 2 provides the estimates of the effects of RUDT on energy consumption for both the whole sample and the three regions. As the DK models (model 3, 6, 9 and 12) are the preferred models, we only focus on these models. For the whole sample, the demographic transition (measured by urbanization level) had a positive impact on energy consumption in China. The elasticity of urbanization on energy use in China is 0.324, which indicates that a 1% increase in urbanization level increased the energy consumption by 0.324%. The elasticities of the shares of population employed in secondary and tertiary industry to energy use are 0.423 and 0.358, respectively, which suggests that the EST increased energy consumption in China. Interestingly, the impact of IST on energy consumption in China was not significant over the past two decades. The LUT had a significant and positive impact on energy consumption in China, which shows that an increase of 1% of the LUT promotes energy use by 0.574%. Furthermore, the increasing rural–urban income gap also had a positive impact on energy consumption in China. A 1% increase in the rural–urban income gap increased energy consumption by 0.687%.

On the regional scale, as shown in models 6, 9 and 12, the impact of RUDT on energy consumption varied across regions. The elasticities of urbanization to energy consumption in the eastern and central regions were 0.441 and 0.676, respectively, whereas the western region exhibited a negative but statistically insignificant at the 10% level. The EST (percentage of population employed in secondary industry) had a significant and positive impact on energy consumption in eastern and western China, but the impact on the central region was not obvious. The correlation between the percentage of population employed in tertiary industry and energy consumption in the central region was negative, but it was positive in the western region and insignificant in the eastern region. The IST (measured by shares of added value of contributed by secondary and tertiary industries to the GDP) increased energy consumption in the eastern, central and western regions except for the share of tertiary industry output in western China. The elasticities of secondary and tertiary industry shares to energy consumption were 2.740 and 1.962 in the eastern region, 1.720 and 1.478 in the central region, and 1.454 and -0.819 in the western region, respectively. This implies that the impact of the IST on energy use in the eastern region was larger than that in the central and western regions. The estimated coefficients of rural–urban income disparity on energy consumption in eastern and central China were 1.113 and 0.751, respectively, whereas the coefficient in the western region was positive but statistically insignificant. This difference could be explained by the facts that the rural–urban income gap in eastern China is relatively small and that this region needs more energy resources to support and maintain its public infrastructure than the central and western regions. Additionally, the elasticities of the LUT on energy consumption in the eastern, central and western regions were 0.369, 0.209 and 0.576, respectively, which indicated that the LUT had a moderate impact on regional energy consumption in China.

3.3. The impact of RUDT on CO₂ emissions

Table 3 presents the estimates of the effects of RUDT on CO₂ emissions for both the whole sample and the three regions. Based on model 15, the elasticities of the DT, EST and LUT on CO₂ emissions were positive and statistically significant at the 5% level or lower. This result demonstrated that except for the IST, RUDT contributed to the increase in CO₂ emissions in China. The

elasticity of energy intensity to CO₂ emissions was also positive and significant in China.

The impacts of RUDT on CO₂ emissions also differed across regions. The elasticities of urbanization level on CO₂ emissions in the eastern and central areas were positive and significant at the 10% level or lower but were insignificant in the western region. A 1% increase in urbanization increased CO₂ emissions in the eastern and central regions by 0.541% and 0.287%, respectively. Additionally, the effects of the EST on CO₂ emissions varied across regions. The proportion of secondary industry employment had a negative effect on CO₂ emissions in the eastern region, whereas the impacts in the central and western regions were not significant. The elasticity of the proportion of tertiary industry employment to CO₂ emissions in the western region was 1.059 but was insignificant in both the eastern and central regions. The elasticity of the proportion of secondary industry output in GDP on CO₂ emissions in the eastern region was 3.384, which was significantly greater than that in the central (2.537) and western regions (1.786). The coefficients of the proportion of tertiary industry output on CO₂ emissions were positive and statistically significant in the eastern and central regions but were negative and statistically significant in the western region at the 5% level. These results demonstrated that the IST had a strong and positive influence on CO₂ emissions on the regional scale, except for in western China. Further, the coefficients of the LUT were significantly positively correlated with CO₂ emissions at the 1% level in the three regions. A 1% increase in the LUT increased CO₂ emissions by 0.396%, 0.158% and 0.615% in the eastern, central and western regions, respectively, which showed that the effect of the LUT on CO₂ emissions in the western region was larger than that in the eastern and central regions. The effect of the rural–urban income gap on CO₂ emissions in the eastern region was larger than that in the central, but it was not significant in the western region. The elasticity of energy intensity on CO₂ emissions was statistically significant at the 5% level, which showed that a 1% increase in energy intensity increased CO₂ emissions by 0.258%, 0.069% and 0.202% in the eastern, central and western regions, respectively.

4. Discussion

China's RUDT has profoundly changed the flow of elements and the spatial connection in rural and urban areas. On the one hand, rapid rural–urban population migration and rampant land-use conversion for non-agricultural purposes has brought the many urban curses of crowding, air and water pollution but has also exacerbated rural environmental degradation and land hollowing [31,67,68]. On the other hand, RUDT is the foundation and driving force of urban–rural integration and equalized development, which can contribute to changes in resource allocation and economic growth modes in rural and urban areas. Thus, revealing RUDT's effect on energy consumption and carbon emissions could provide a beneficial reference tool for the national strategy for urbanization and environmental planning. Understanding the driving forces behind China's growing CO₂ emissions could also provide insight into how other emerging economies may develop a low emissions future [69]. In the present study, we found that the effects of urbanization on energy consumption and CO₂ emissions across China generally and in its eastern and central regions were positive and statistically significant, whereas those in the western region were negative but insignificant. This finding is consistent with previous studies that have indicated that urbanization increases energy use and CO₂ emissions in China [25,27,70]. Cole and Neumayer [71] also found that a 10% increase in the urbanization rate increased CO₂ emissions by 7% in 86 countries around the world. Similar evidence was obtained from the Middle

East and North African (MENA) countries and showed that slowing urbanization can help reduce the energy consumption and pollutant emissions in MENA countries [72,73]. Because of the lack of basic public services in many western region cities, the negative relationship between urbanization and energy use was likely the result of modernization rather than the scale of economies or public infrastructure [24]. Further urbanization in the eastern region increased rather than decreased energy consumption, which supported the urban environmental transition theory that states that issues related to energy use are more evident in economically developed areas [36]. However, our findings were not supported by Martínez-Zarzoso and Maruotti [74], whose results showed that the elasticity of CO₂ emissions to urbanization was positive for countries with low urbanization and negative for countries with high urbanization. Wang et al. [75] discovered an inverse U-shaped curve relationship between urbanization and carbon emissions in OECD countries. Sadorsky [76] also found that the urbanization-emissions elasticity in emerging economies was positive but statistically insignificant. Urbanization is a complex process that involves a population shift from rural to urban areas and a change of rural lifestyles to urban ones. More urban infrastructure will inevitably be required to support the continuously growing urban population, which will potentially lead to additional energy demand and emit more CO₂ [25,29,77]. Feng et al. [78] also demonstrated that urbanization and associated income and lifestyle changes were important driving forces for the growth of CO₂ emissions in most regions in China. Chinese urbanization has been characterized by excessive farmland conversion for non-agricultural use [32]. This great land conversion has induced serious land-use problems such as arable land loss, the increase of landless peasants, the abandonment of arable land and rural hollowing [31].

Further investigation has shown that the EST has a positive impact on energy consumption and CO₂ emissions across China, but that effect differed greatly across regions. In eastern China, the proportion of population employed in secondary industry decreased its energy use and CO₂ emissions; and the negative effect of the proportion of population employed in tertiary industry was statistically significant. In western China, the proportion of population employed in tertiary industry increased its energy consumption and CO₂ emissions. In central China, the effect of EST on energy use and CO₂ emissions was statistically insignificant. The effect of IST on energy consumption and CO₂ emissions across China was not significant, but the effect in the three regions was positive and statistically significant, with a continuous decline observed from the eastern region to the central and western regions. This could be due to denser populations, advanced industrialization and rapid urbanization in the eastern region, which requires additional energy and emits more CO₂ [79]. This result did not confirm the view that industrial structural adjustment effectively reduced the CO₂ emissions in China [30]. Furthermore, energy intensity increased CO₂ emissions in the eastern, central and western regions. This result is supported by Zhang and Lin [25]. The effect of energy intensity on CO₂ emissions in the eastern region was greater than that in the western and central regions. Therefore, optimizing the industrial structure and improving energy efficiency may be an effective method of emission abatement for eastern China. Developing and utilizing renewable energy resources may also be one of the most efficient and effective solutions to environmental problems [80]. Additionally, urban–rural income inequality (URI) had a positive impact on energy consumption and CO₂ emissions, and the impact in the eastern region was greater than that in the central and western regions. This result is also supported by Zhang and Zhao [48], who found that the effect of income disparity on CO₂ emissions in the eastern region was greater than that in the western region.

The rural–urban transformation in China has highly accelerated the process of land conversion, especially farmland conversion for non-agricultural purposes [32,34]. The impact of land-use transformation on energy consumption and CO₂ emissions has also differed across regions. Land use transformation had a strong and positive impact on energy consumption and CO₂ emissions in China and in the three regions, and the impact declined continuously from the western region to the eastern and central regions. In the western region, with the progress of the West Development Project, commercial, transportation activities and the size of the urban infrastructure have developed further. Furthermore, industrial technology is less developed, and energy efficiency is lower in the western region than in the eastern region. Therefore, the further conversion of land to non-agricultural purposes in the western region will likely require more energy resources and emit more CO₂. Land resources are very scarce in eastern China, and its land utilization degree is higher than that found in the middle and western regions [81]. The increasing urban population, the scarcity of urban land, the competitive pressures of markets and the technological innovation in the eastern region encourage the substitution of traditional energy by renewable energy resources, which contribute to reduced fossil energy consumption [25]. However, land use change has become an important source of carbon emissions, second only to fossil fuel combustion [82]. Over the past two decades, illegal land use and construction have been prevalent in rural China, where a large amount of cultivated land has been converted to non-agricultural use [18,58]. The change from agricultural land to construction land increases carbon emissions [83]. During the period 1850–1998, the contribution of land-use change to anthropogenic carbon emissions produced approximately 33% of total emissions over the last 150 years [84], and 12.5% of total emissions over 1990 to 2010 [85]. Deforestation and forest degradation in the process of rapid urbanization are currently estimated to contribute 6–17% of total anthropogenic CO₂ emissions [86]. By 2030, urban expansion is forecasted to have a significant impact on global carbon pools, especially in the pan-tropics [87]. Ali and Nitivattananon [88] also found that there is a positive relationship among energy use, CO₂ emissions and land use change in a metropolitan city of Pakistan. In China, the conversion of land to non-agricultural use has contributed to increasing carbon emissions since the early 1960s. Dong [89] found that CO₂ emissions from land-use change in China between 1950 and 2005 were approximately 10.6 billion tons, which accounted for 12% of global carbon emissions from land-use change over the same period. Therefore, it is necessary to control the excessive expansion of construction land and optimize land use structure for reducing carbon emissions in China. Currently, the relevant studies need to focus on how RUDT affects carbon emissions and on environmental restriction of the processes and patterns of RUDT. Knowledge about the environmental impacts of RUDT and its feedback mechanism is fundamentally necessary for developing scientific ideas about healthy urbanization.

5. Conclusions and policy implications

Based on a balanced panel data covered 30 provinces of China for the period 1990–2012, this study used an improved STIRPAT model to investigate empirically the impact of RUDT on energy consumption and CO₂ emissions, considering regional differences. The sample was divided into three regions (eastern, central and western). China's RUDT was measured by the transformation in demographic, employment and industrial structures and land use patterns. The results suggested that the rural–urban transformation in China has resulted in the decline in the proportion of the employed population in agriculture; the depopulation of rural areas, and a restructuring of agriculture with growing emphasis on capital intensity, off-farm employment, and the conversion of farmland to non-agricultural uses.

Further investigation demonstrated that the effects of the RUDT on energy consumption and CO₂ emissions varied greatly across regions. Demographic transformation between rural and urban areas increased energy consumption and CO₂ emissions across China generally and in the eastern and central regions, whereas the relationships between demographic transformation, energy consumption and CO₂ emissions in the western region were not significant. The impact of employment structural transformation on energy consumption and CO₂ emissions across China generally was positive and statistically significant but differed considerably across regions. The proportion of the population employed in secondary industries had a negative and significant impact on energy consumption and CO₂ emissions in the eastern and western regions, whereas the impact in the central region was insignificant. The industrial structural transformation contributed to the increase of energy use and CO₂ emissions in the eastern and central regions, and its effect on energy use and CO₂ emissions declined continuously from the eastern region to the central and western regions. The land use transition increased energy consumption and CO₂ emissions across China generally and in the three regions. The impact of land use transition on energy consumption and CO₂ emissions in the western region was greater than that in the eastern and central regions. Furthermore, energy intensity had a moderate impact on CO₂ emissions across China generally and in the three regions.

Our results will be of special interest to policy makers and urban planners in China. Because further RUDT will require more energy consumption and emit additional CO₂, it will be essential for the government to control the pace of urbanization and the expansion of construction land, to develop sustainable infrastructure systems and to improve energy efficiency. Furthermore, considering the regional differences in RUDT impact on energy and CO₂ emissions, mitigation

strategies should focus on controlling the scale of urbanization development, optimizing the industrial structures and improving the energy efficiency in eastern and central China, where the main industries are primarily technology-intensive, labor-intensive and light industry types. Western China should pay more attention to the improvement of employment structure and the protection of cultivated land. Because of the regional disparities in anthropogenic impact on the environment, formulating specific region-oriented energy saving and emission reduction strategies may provide a more practical and effective approach to achieving sustainable development in China. However, this study is still preliminary, and the impact of RUDT on the environment based on high-resolution panel data is worthy of further study. Moreover, the impact of land conversion to non-agricultural uses on the environment is also worthy of close research attention.

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Appendix A

See Tables A1 and A2

Table A.1

Panel unit root tests.

Variable	Levels				First differences			
	LLC	IPS	ADF	PP	LLC	IPS	ADF	PP
Ln(EC)	−0.82	−0.13	58.75	116.50***	−10.69***	−9.04***	182.47***	290.77***
Ln(CO ₂)	−0.36	−0.13	63.95	44.88	−9.17***	−8.66***	176.63***	235.00***
Ln(EI)	−3.47***	−5.47***	130.56***	88.64***	−12.71***	−11.28***	202.66***	274.02***
Ln(EP2)	−0.30	0.05	65.48	23.52	−7.68***	−9.19***	190.82***	306.73***
Ln(EP3)	−3.12***	−0.85***	99.04***	62.41***	−13.07***	−14.65***	305.67***	426.65***
Ln(URBA)	−0.77	−0.16	54.55	45.43	−16.86***	−12.89***	252.29***	323.56***
Ln(URI)	−2.15***	−4.60***	105.41***	106.32***	−12.92***	−8.95***	187.78***	300.52***
Ln(INDU)	−2.62***	−3.27***	101.68***	53.68	−15.29***	−13.96***	285.85***	410.55***
Ln(TERT)	−6.07***	−6.32***	158.87***	290.73***	−12.35***	−19.64***	393.05***	1552.77***
Ln(LAND)	−6.22***	−6.88***	156.83***	172.48***	−16.04***	−18.42***	373.22***	1360.26***

Notes: Exogenous variables: Individual effects and individual linear trends. Automatic selection of lags based on AIC: 0 to 4. Newey-West automatic bandwidth selection and Bartlett Kernel.

*** Denotes rejection of the null hypothesis of nonstationary at the 1% significance level.

Table A.2

VIF tests for multicollinearity.

Variable	Model 3	Model 6	Model 9	Model 12	Model 15	Model 18	Model 21	Model 24
Ln(EP2)	3.02	8.32	1.32	1.79	3.03	8.55	1.38	1.85
Ln(EP3)	4.51	8.98	5.55	2.34	4.83	9.53	6.51	2.63
Ln(URBA)	3.87	4.99	5.43	2.29	3.88	5.02	5.44	2.41
Ln(URI)	1.91	1.5	1.53	1.68	1.93	1.84	1.62	1.79
Ln(INDU)	2.81	9.86	2.58	2.41	2.81	9.97	2.95	2.42
Ln(TERT)	3.57	8.4	2.61	2.5	3.62	8.73	2.65	2.52
Ln(LAND)	1.25	2.12	1.47	1.1	1.59	2.31	1.8	1.64
Ln(EI)	–	–	–	–	1.9	2.24	2.29	2.87
Mean VIF	2.99	5.975	2.93	2.02	2.95	6.02	3.08	2.27

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