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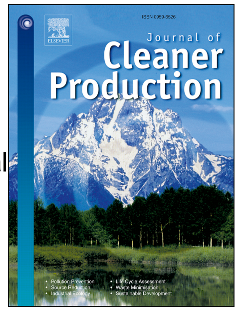

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Impacts of urbanization on water use and energy-related CO_2 emissions of residential consumption in China: A spatio-temporal analysis during 2003-2012

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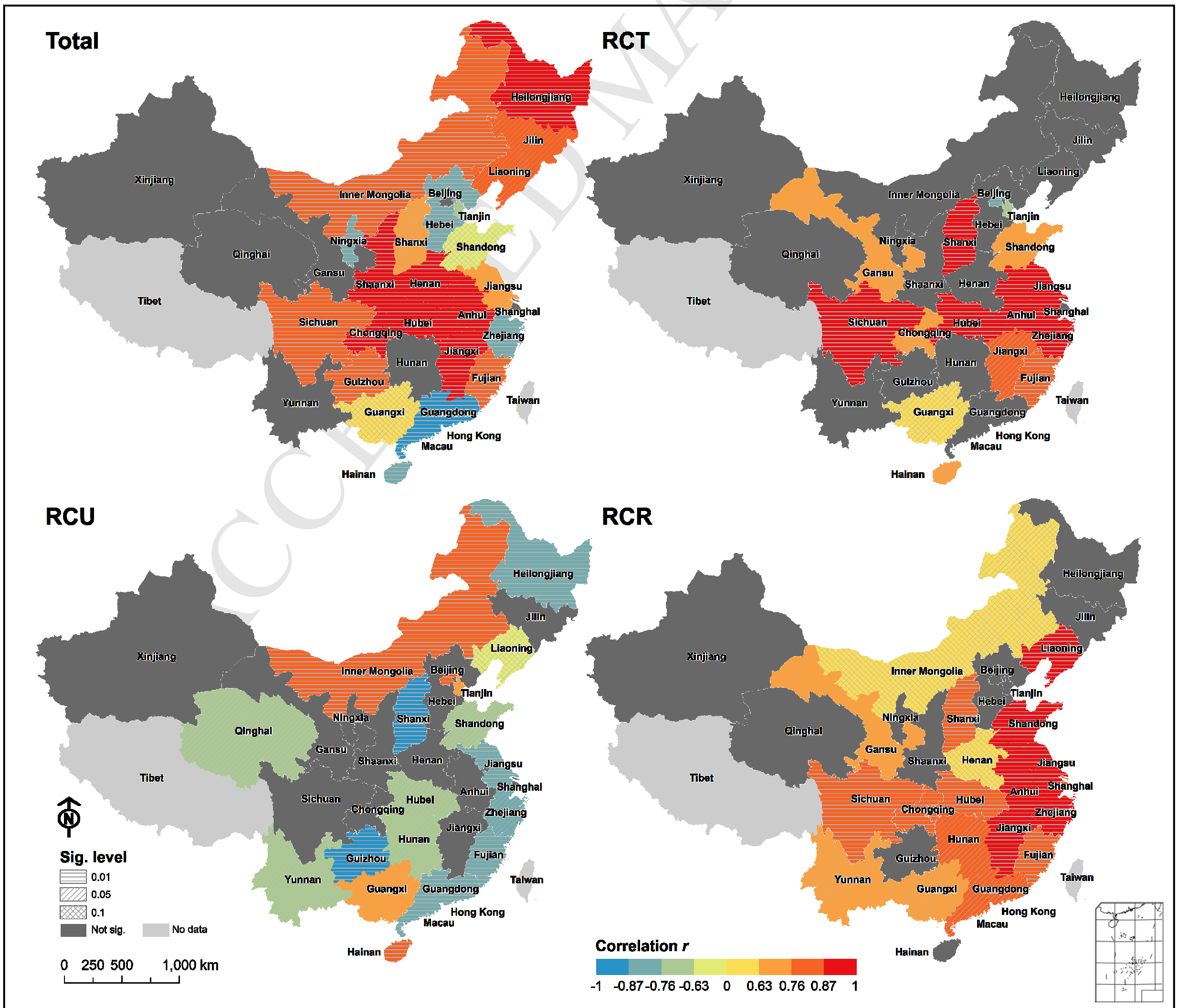
Graphical abstract



High correlation between per capita water use and energy-related CO2 emissions of residential consumption in China's urban and rural areas

Impacts of urbanization on water use and energy-related CO_2 emissions of residential consumption in China: A spatio-temporal analysis during 2003-2012

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Abstract

China has been undergoing unprecedented urbanization since the 1978 economic reform, with the present growth rate of 20 million people per year. This rapid and perennial progress has been raising concerns about environmental sustainability, due to a severe nationwide deterioration of China's environment and ecosystems in the context of ceaselessly increasing demand for water and energy. It is therefore of prime necessity and importance to comprehend China's water and energy security under the effect of dramatic demographic changes. Analyses of this issue still remain few and far between, and a comprehensive picture is not available that would help understand China's recent development in urbanization, its spatial features and links to water and energy security, particularly regarding residential consumption, and related national policy-making. Consequently, we address these knowledge gaps by performing an integrated and quantitative spatio-temporal analysis of the impacts of China's urbanization on water use and energy-related CO_2 emissions of residential consumption. We propose adding residential per capita water use and per capita energy-related CO_2 emissions as national indicators for policy-making targets of China's water and energy security. Over the study period of 2003-2012, per capita rural residential water use was on the increase, while

urban use showed the opposite trend. Rural consumption has been remarkably higher than the urban, and this gap appears to be growing. In contrast, the per capita energy-related CO_2 emissions of residential consumption augmented significantly in both urban and rural areas nationwide. Besides, both the total and rural per capita residential water use and energy-related CO_2 emissions showed a significant positive correlation. However, in urban areas this correlation was negative.

Keywords

Urbanization; Residential water use; Residential energy consumption; CO_2 emissions; Policy-making; China

Nomenclature

CC_i	CO_2 emission factor of fuel type *i*
C_m^R	national total CO_2 emissions of residential consumption in year *m*
C_{mkji}^R	CO_2 emissions of residential consumption from the combustion of fuel type *i* in sector *j* of province *k* in year *m*
ERCE	energy-related CO_2 emissions
ERCERC	energy-related CO_2 emissions of residential consumption
FF_{mi}	energy factor of fuel type *i* in year *m*
F_{mkji}^R	standard quantity of the final residential consumption of fuel type *i* in sector *j* of province *k* in year *m*
$F_{mkji}^{R\,'}$	physical quantity of the final residential consumption of fuel type *i* in sector *j* of province *k* in year *m*
GDP	gross domestic product
G_m	gross rate of coal consumption for electricity generation in year *m*
H&E	heat and electricity
i	fuel type
j	area of residential consumption
k	province of China
L_{mkji}	loss of fuel type *i* in sector j of province *k* in year *m*

O_i	fraction of carbon oxidized in use of fuel type i
p	significance level
Q	Sen's slope, describing magnitude of a trend
r	Pearson’s correlation coefficient
T	theoretical rate of coal consumption for electricity generation
TCE	tonne of coal equivalent, i.e. unit of energy generated from metric ton of coal
WU	water use
WURC	water use of residential consumption

1. Introduction

Our planet is in the midst of a rapid urbanization process; each year, there are on average 76 million new urban dwellers, in comparison with the annual total population growth of 78 million **(United Nations, 2015)**. Of these new urban dwellers, 20 million reside in one single nation, China **(National Bureau of Statistics of China, 2016; Cai et al., 2017a)**. China’s urbanization is particularly fast, as its total population has been growing annually only by approximately 6.5 million over the last decade, and thus the rural population has been shrinking rapidly **(National Bureau of Statistics of China, 2016; Cai et al., 2017a)**. A key driver of this process is the 1978 economic reform, which set the policy outlines for China’s socioeconomic development **(Cai et al., 2016; Christensen et al., 2016; Wang et al., 2016; Fan et al., 2017)**. It is currently projected that the degree of China’s urbanization (percentage of urban population) will surpass 75% by 2050, which would be substantially greater than that in 2015 (56.1%) and about 4.2 times that in 1978 (17.9%) **(United Nations, 2015; National Bureau of Statistics of China, 2016)**.

This rapid and perennial progress of urbanization has led to, besides vast demographic, societal, and economic changes, also to soaring concerns about environmental sustainability, due to a severe nationwide deterioration of China's environment and ecosystems caused by ceaseless increase in demand for water and energy **(Liu and Yang, 2012; Varis et al., 2014; Ang et al., 2015; Huang et al., 2016; Bretschger and Zhang, 2017)**. Facing this challenge, China's need to strive towards sustainable urbanization persists **(Cai et al., 2016)**. China's 10^{th} Five-Year Plan on national economy and social development can be portrayed as the milestone call for action on these issues. Ever since it was set in force in 2001, emphasis has been placed on sustainability as an overarching principle for China's urbanization related policy-making, in particular to best contribute to long-term sustainable water and energy security **(Wu et al., 2014; Liu and Qin, 2016; Zheng et al., 2016; Cai et al., 2017b)**. Therefore, it is of prime necessity and importance to examine the impacts of China's urbanization on its water and energy security.

Water and energy are not only tightly interlinked, but also highly interdependent. The emerging concept of water-energy nexus has thus been recognized during the past decade as a means of embracing and exploiting this interlinkage and interdependency between water and energy, along with their externalities **(Cai et al., 2016; Zheng et al., 2016)**. It articulates that it is crucial to consider water and energy security jointly, especially from the point of view of China's current dramatic demographic transition. However, there is to our knowledge, a substantial lack of understanding of the joint impacts of urbanization in China on both water and energy security. The existing studies on water security (e.g., Hubacek et al. **(2009)**, Yan et al. **(2015)**, and Li et al. **(2017)**) or energy security (e.g., Wu et al. **(2016)**, Fan et al. **(2017)**, and He et al. **(2017)**) within the theme of the urbanization were conducted only at regional or national scales, but not provinces, which has failed to paint a complete picture of China's spatial heterogeneity. Hence, it is essential and critical to assess the impacts of China's urbanization on its water and energy security in an integrated manner in the context of macro-level socioeconomic development, with a policy-relevant spatio-temporal resolution.

In our previous study **(Cai et al., 2016)**, we elaborated the diversity and ongoing evolution of the definition and themes of water and energy security, along with their indicators. With regard to water security, Hubacek et al. **(2009)** investigated current trajectories and scenarios for water footprints. Yan et al. **(2015)** assessed water use in agriculture. Li et al. **(2017)** focused on urban rainwater management. In terms of energy security, energy-related CO_2 emissions (ERCE) has been considered to be a common and straightforward indicator **(Wu et al., 2016; Fan et al., 2017; He et al, 2017)** and its relationship to urbanization was further explored **(Cao et al., 2016; Wang et al., 2016; Xu et al, 2016)**. However, when per capita ERCE was analyzed in these studies, it included ERCE of residential consumption (ERCERC) as well as ERCE of primary, secondary, and tertiary industry in urban areas. Despite the fact that the urbanization progress can help optimize China's industrial transition to enhance its economic competitiveness **(Wang, 2014; Liu and Qin, 2016; Bretschger and Zhang, 2017)**, it is more important to specifically identify the effects of demographic redistribution that is the essence of urbanization. Water use intensity (water use (water withdrawal) per unit of gross domestic product (GDP)) and energy-related carbon intensity (ERCE per unit of GDP), are both included in national indicators for policy-making targets of China's water and energy security in the context of its economic structural changes. We found earlier a significant positive correlation between them **(Cai et al., 2016)**, and thus we propose here that per capita water use of residential consumption

(WURC) and per capita ERCERC could be considered as two additional national indicators for policy-making targets of China's water and energy security influenced by its urbanization. Accordingly, it is of great interest to investigate the relationship between these two indicators.

Moreover, China's national policies have been playing a fundamental role in promoting water and energy security for residential consumption in the context of its urbanization. During our specific ten-year study period, i.e. China's water pricing reforms were set in force in 2002 to reduce WURC in urban areas **(Zhong and Mol, 2010)**, while until 2012, a pilot run of national residential tiered electricity pricing reforms was launched **(Zhang and Qin, 2015)**, it is critical to compare the differences between per capita WURC and per capita ERCERC, resulting from China's national policies, to address how to develop these two potential national indicators for policy-making targets together.

Our principal aim of this study is consequently to comprehend (1) how China's recent urbanization development has impacted residential water use and energy consumption, with policy-relevant spatial resolutions; (2) how China's national polices influence water and energy security for residential consumption; and (3) how China's national policy-making for water and energy security could benefit from our proposed indicators (per capita WURC and per capita ERCERC). To fill these knowledge gaps, we conducted a quantitative spatio-temporal analysis of per capita WURC and per capita ERCERC under the effect of China's urbanization during 2003-2012. The specific objectives are to (1) quantify the degree of China's urbanization at national and provincial scales; (2) assess possible trends of national and provincial per capita WURC and per capita ERCERC changes in urban and rural areas; (3) investigate the relationship between per capita WURC and per capita ERCERC in urban and rural areas at national and provincial scales; and (4) reflecting on the findings in light of China’s current national policies.

2. Material and methods

2.1. Classification of urban and rural areas

By definition, the term *urbanization* refers to the development and expansion of cities, where cities are broadly considered as areas with high concentrations of people and human-made structures **(Wu et al., 2014; Cai et al., 2017a)**. These areas thereby need to be defined to identify China’s cities and their boundaries.

China’s cities are in administrative terms typically relatively large metropolitan regions, which include both urban and rural areas **(Huang et al., 2016)**. Therefore, we collected the data from the China’s statistical yearbooks **(National Bureau of Statistics of China, 2004c; 2005c; 2006c; 2007c; 2008c; 2009c; 2010c; 2011c; 2012c; 2013c)** which are based on the census-reported urban population of a subset of districts within each prefectural-level city, satisfying a variety of criteria, namely being part of contiguous built-up areas, being the location of the local government, being a “Street” (jiēdào 街道) or having a “Resident Committee” (jūwěihuì 居委会) **(United Nations, 2015)**. Correspondingly, the data of rural areas contain not only the data of rural areas in prefectural-level cities, but also the data of county-level cities and counties, which are not considered urban **(National Bureau of Statistics of China, 2004c; 2005c; 2006c; 2007c; 2008c; 2009c; 2010c; 2011c; 2012c; 2013c)**.

2.2. Estimation of water use of residential consumption

China's domestic water use consists of water use of residential consumption (WURC), and water use in tertiary industries. Residential consumption includes the water from both household faucets and shared taps that are used for drinking, cooking, bathing, washing clothes, and similar purposes, such as watering flowers or washing cars **(Zhang and Brown, 2005)**. Water use in tertiary industry refers to all other economic activities not included in the primary industry (agriculture, forestry, animal husbandry, and fishery) or secondary industry (industry and construction), including various public and private services and information technology **(National Bureau of Statistics of China, 2004c; 2005c; 2006c; 2007c; 2008c; 2009c; 2010c; 2011c; 2012c; 2013c)**. The bulletin of China's first national census for water indicates that WURC is estimated at 65% of the total domestic water use **(Ministry of Water Resources of China and National Bureau of Statistics of China, 2013)**. The amount of WURC in urban areas is available in the China city statistical yearbooks **(National Bureau of Statistics of China, 2004a; 2005a; 2006a; 2007a; 2008a; 2009a; 2010a; 2011a; 2012a; 2013a)**. Thus, the amount of WURC in rural areas can be estimated as the difference between the amount of total WURC and WURC in urban areas.

2.3. Estimation of energy-related CO_2 emissions of residential consumption

According to our previous study **(Cai et al., 2016)**, we made use of all 21 actual fuel types consumed in China and their CO_2 emission factors at both provincial and national scales, in order to improve accuracy, contrary to existing studies estimating China's CO_2 emissions from fuel combustion **(Yuan et al., 2014; Zhao and Liu, 2014; Chen and Yang, 2015; Luukkanen et al., 2015; Ouyang and Lin, 2015)**. This estimation was performed using Eq.

(1):

$$
\begin{aligned}
C_m^R &= \sum_{k=1}^{30}\sum_{j=1}^{2}\sum_{i=1}^{21} C_{mkji}^{R} \\
&= \sum_{k=1}^{30}\sum_{j=1}^{2}\sum_{i=1}^{21} F_{mkji}^{R} \times CC_i \times O_i \\
&= \sum_{k=1}^{30}\sum_{j=1}^{2}\sum_{i=1}^{21} F_{mkji}^{R\,'} \times FF_{mi} \times CC_i \times O_i
\end{aligned} \tag{1}
$$

where C_m^R is the national total CO_2 emissions of residential consumption in year *m* (*m* = 2003, 2004, …, 2012) (in metric tonnes); *k* is the province of China (*k* = 1, 2, …, 30); *j* is the area of residential consumption, in which the numbers of 1 and 2 denote urban and rural residential consumption, respectively; *i* is the fuel type consumed by each sector, in which the numbers of 1, 2, …, 21 denote raw coal, cleaned coal, other washed coal, briquettes, coke, coke oven gas, blast furnace gas, other gas, other coking products, crude oil, gasoline, kerosene, diesel oil, fuel oil, liquefied petroleum gas, refinery gas, other petroleum products, natural gas, liquefied natural gas, heat, and electricity; C_{mkji}^R is the CO_2 emissions of residential consumption from the combustion of fuel type *i* in sector *j* of province *k* in year *m* (t); CC_i is the CO_2 emission factor of fuel type *i* (t/TCE (tonne of coal equivalent)); O_i is the fraction of carbon oxidized of fuel type *i*; and F_{mkji}^R is the standard quantity of the final residential consumption of fuel type *i* in sector *j* of province *k* of year *m* (TCE); $F_{mkji}^{R\,'}$ is the quantity in original units of the final residential consumption of fuel type *i* in sector *j* of province *k* of year *m* (t or 10^4 m^3 or 10^6 kJ or 10^4 kWh); and FF_{mi} is the energy factor of fuel type *i* of year *m* (TCE/t or TCE/10^4 m^3 or TCE/10^6 kJ or TCE/10^4 kWh).

Losses occur in the production of heat and electricity specifically. These losses should be taken into account, due to the fact that CO_2 has been emitted during the transformation from fossil fuels. So Eq. (1) can be modified to differentiate between the fuel types as

$$C_m^R = \sum_{k=1}^{30}\sum_{j=1}^{2}\sum_{i=1}^{19} F_{mkji}^{R\,'} \times FF_{mi} \times CC_i \times O_i + \sum_{k=1}^{30}\sum_{j=1}^{2}\sum_{i=20}^{21} (F_{mkji}^{R\,'} + L_{mkji}) \times FF_{mi} \times CC_i \times O_i \quad (2)$$

where L_{mkji} is the loss of fuel type i in sector j of province k of year m (10^6 kJ or 10^4 kWh).

Additionally, given the fact that China's electricity structure is still dominated by coal, the share of which was around 75-80% during 2003-2012 **(Jiang, 2015; Ouyang and Lin, 2015)**, it is useful to convert the physical quantity of electricity generation into TCE, i.e. a coal equivalent. Thus, Eq. (2) can be developed as

$$C_m^R = \sum_{k=1}^{30}\sum_{j=1}^{2}\sum_{i=1}^{19} F_{mkji}^{R\,'} \times FF_{mi} \times CC_i \times O_i + \sum_{k=1}^{30}\sum_{j=1}^{2}\sum_{i=20} (F_{mkji}^{R\,'} + L_{mkji}) \times FF_{mi} \times CC_i \times O_i + \sum_{k=1}^{30}\sum_{j=1}^{2}\sum_{i=21} (F_{mkji}^{R\,'} + L_{mkji}) \times \frac{G_m}{T} \times FF_{mi} \times CC_i \times O_i \quad (3)$$

where G_m is the gross rate of coal consumption for electricity generation of year m (g/kWh); T is the theoretical rate of coal consumption for electricity generation in ideal conditions, whose value is 122.9 g/kWh **(Office of National Coordination Committee on Climate Change of**

China and Energy Research Institute of National Development and Reform Commission of China, 2007).

2.4. Spatial and temporal analysis

For simplicity, the term *province* was used to represent all 34 provincial jurisdictions, namely 23 provinces, 5 autonomous regions, 4 municipalities, and 2 Special Administrative Regions. Due to lack of data availability, the jurisdictions Tibet, Hong Kong, Macau, and Taiwan were excluded from the analysis. Accordingly, data were collected on 30 provinces, which were classified into 2 categories as follows **(Cai et al., 2016)**:

1) Coastal provinces: 11 provinces in Northeast China (Liaoning) and East China (Beijing, Tianjin, Hebei, Shandong, Jiangsu, Shanghai, Zhejiang, Fujian, Guangdong, Hainan);
2) Inland provinces: 19 provinces in Northeast China (Heilongjiang, Jilin), Central China (Shanxi, Henan, Hubei, Hunan, Anhui, Jiangxi), and West China which is covered by the China Western Development Policy (Xinjiang, Inner Mongolia, Qinghai, Gansu, Ningxia, Shaanxi, Sichuan, Chongqing, Yunnan, Guizhou, Guangxi).

To assess the statistical significance of possible trends in each indicator during this 10-year period, a non-parametric statistical method, namely the Mann-Kendall test, was used **(Mann, 1945; Kendall, 1975; Gocic and Trajkovic, 2013)**. Unlike ordinary least squares regression, the Mann-Kendall test is less affected by missing values and uneven data distribution, and is relatively robust to extreme values and serial dependence **(Udelhoven,**

2011; Yin et al., 2012). To identify the magnitude of each trend, Sen's slope (Q) was calculated **(Sen, 1968; Hirsch et al., 1982; Gocic and Trajkovic, 2013)**. As a non-parametric linear regression analysis, it is not sensitive to gross data errors or outliers **(Gilbert, 1987; Bouza-Deano et al., 2008; Yin et al., 2012)**.

2.5. Data

To support the above estimation processes, the annual provincial data of (i) total population, (ii) urban and rural population, (iii) total water withdrawal, and (iv) total domestic water use during the study period were collected from the China statistical yearbooks **(National Bureau of Statistics of China, 2004c; 2005c; 2006c; 2007c; 2008c; 2009c; 2010c; 2011c; 2012c; 2013c)**, while the data of (v) WURC in urban areas from the China city statistical yearbooks **(National Bureau of Statistics of China, 2004a; 2005a; 2006a; 2007a; 2008a; 2009a; 2010a; 2011a; 2012a; 2013a)**.

The data of (vi) $F_{mkji}^{R'}$, (vii) FF_{mi}, (viii) L_{mkji}, and (ix) G_m during the study period were collected from the China energy statistical yearbooks **(National Bureau of Statistics of China, 2004b; 2005b; 2006b; 2007b; 2008b; 2009b; 2010b; 2011b; 2012b; 2013b)**, whereas the data of (x) CC_i and (xi) O_i from the China national greenhouse gas inventory **(Office of National Coordination Committee on Climate Change of China and Energy Research Institute of National Development and Reform Commission of China, 2007)**. Besides, the data of (xii) total ERCE were from our previous study **(Cai et al., 2016)**.

3. Results

3.1. Quantification of degree of national and provincial urbanization

China’s population manifested a significant increasing trend during 2003-2012 **(Table S.1)**. This was also the case in the majority of provinces, with 6 inland provinces (Henan, Hunan, Anhui, Sichuan, Guizhou, and Guangxi) as exceptions **(Fig. 1 and Table S.1)**. Owing to the fact that the coastal provinces had much faster socioeconomic development than the inland ones throughout the study period **(Cai et al., 2016)**, the general tendency was the flow of the population from developing inland provinces into developed coastal provinces.

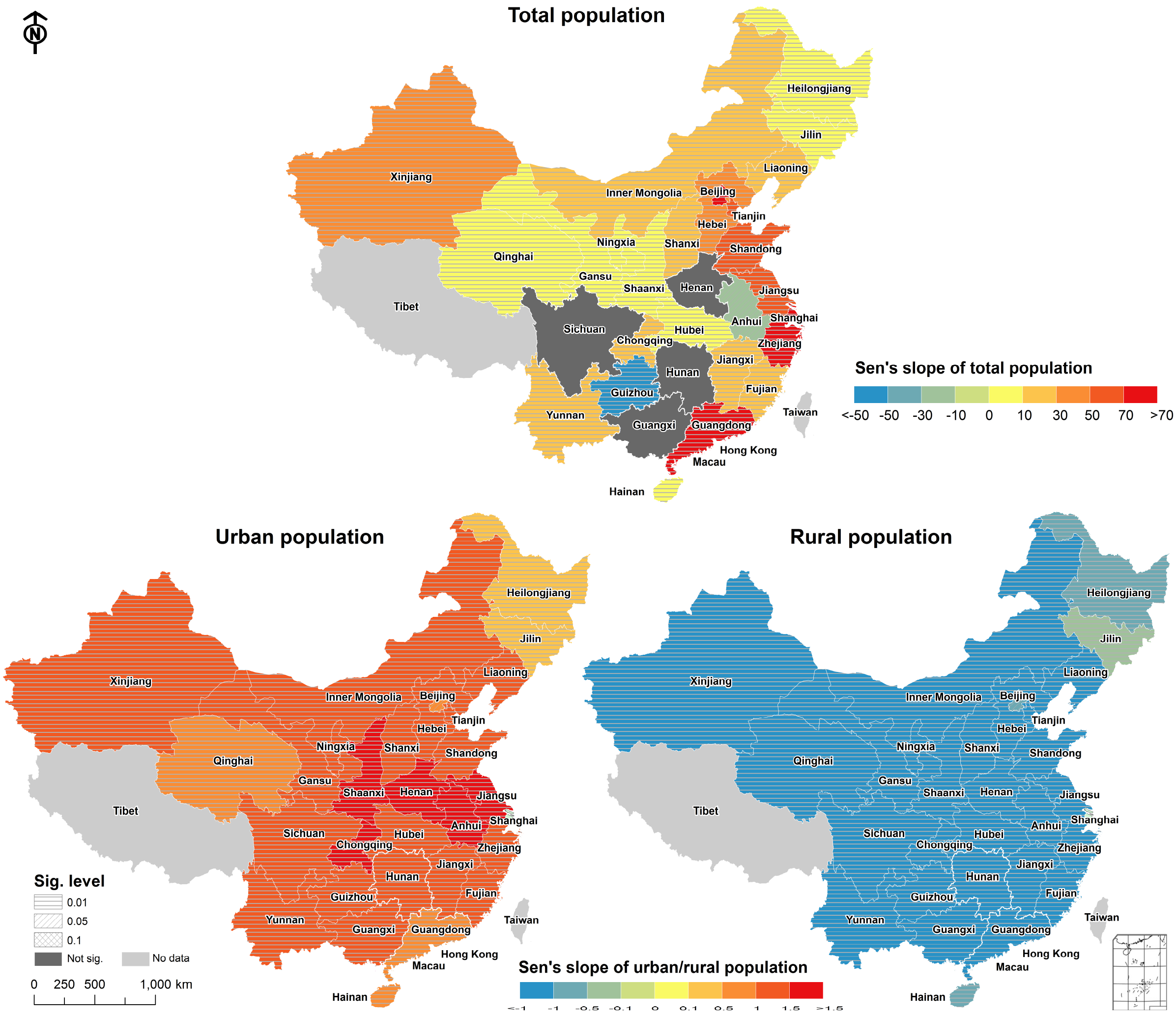

Fig. 1. China’s provincial population during 2003-2012: Results of Mann-Kendall test and Sen's slope. (1) Data of total population (10^4 persons) are available in Table S.1; (2)

Urban and rural populations denote population shares in urban and rural areas (%). Their data are available in Table S.2-S.3 respectively; (3) The scale difference of Sen's slope between total population and population shares is due to the dimensional difference of their data.

China's urban population showed a significant increasing trend, whereas the rural population had a significant decreasing trend **(Tables S.2-S.3)**. The degree of China's nationwide urbanization rose from 40.5% in 2003 to 53.2% in 2012. At the provincial scale, the same significant changes were found in urban and rural areas of all provinces, with Shanghai (coastal province) being on average the most urbanized province across the country during this ten-year period **(Fig. 1 and Tables S.2-S.3)**. The degrees of coastal and inland provinces' urbanization climbed from averages of 50.5% and 35.9% in 2003 to 66.1% and 47.3% in 2012 respectively. Being in different phases of socioeconomic development, this wide disparity of urbanization progress between coastal and inland provinces thus demonstrated that China experienced a heterogeneous urbanization rate nationwide, which would lead to quite diverse scenarios of its impact on per capita WURC and per capita ERCERC among these provinces.

3.2. Water: growing per capita consumption in rural areas

For China as a whole, the values of per capita total WURC indicated a significant increasing trend during 2003-2012, from 32.0 m^3/person in 2003 to 35.2 m^3/person in 2012 **(Table S.9)**. This corresponds to 87.6 and 96.4 l/person/day, respectively. A significant increasing trend was also detected in rural areas, where the per capita WURC went up from

29.8 to 42.6 m^3/person (81.6 to 116.6 l/person/day) **(Table S.11)**. In contrast, there was a significant decreasing trend in urban areas, where the per capita WURC reduced from 35.4 to 28.6 m^3/person (97.0 to 78.4 l/person/day) **(Table S.10)**. It is important to note that although China's degree of urbanization grew substantially over the study period, the percentages of urban and rural WURC of the total residential consumption stayed almost unchanged **(Tables S.6 and S.7)**. As the urban and rural WURC shares did not change much and the urban shares were smaller all the time, the rural areas became the main contributor to the growing per capita total WURC at the national scale.

With regard to the provincial values of per capita total WURC, significant increasing trends were found in 45% (5 out of 11) of coastal provinces and 32% (6 out of 19) of inland provinces **(Fig. 2 and Table S.9)**, which was in line with the same significant changes of the provincial total WURC **(Supplementary results)**. On average, the per capita total WURC in coastal provinces lifted from 33.1 to 36.8 m^3/person (90.7 to 100.8 l/person/day), and in inland provinces from 29.6 to 31.6 m^3/person (81.1 to 86.6 l/person/day). So the coastal provinces in general had greater per capita total WURC than the inland ones, yet the changes were not significant in all provinces. Beijing (coastal province) was the only province that held a significant decreasing trend and its per capita total WURC value sank from 60.3 to 50.3 m^3/person (165.2 to 137.8 l/person/day) **(Fig. 2 and Table S.9)**, although its total WURC value significantly increased due to population growth **(Table S.4)**.

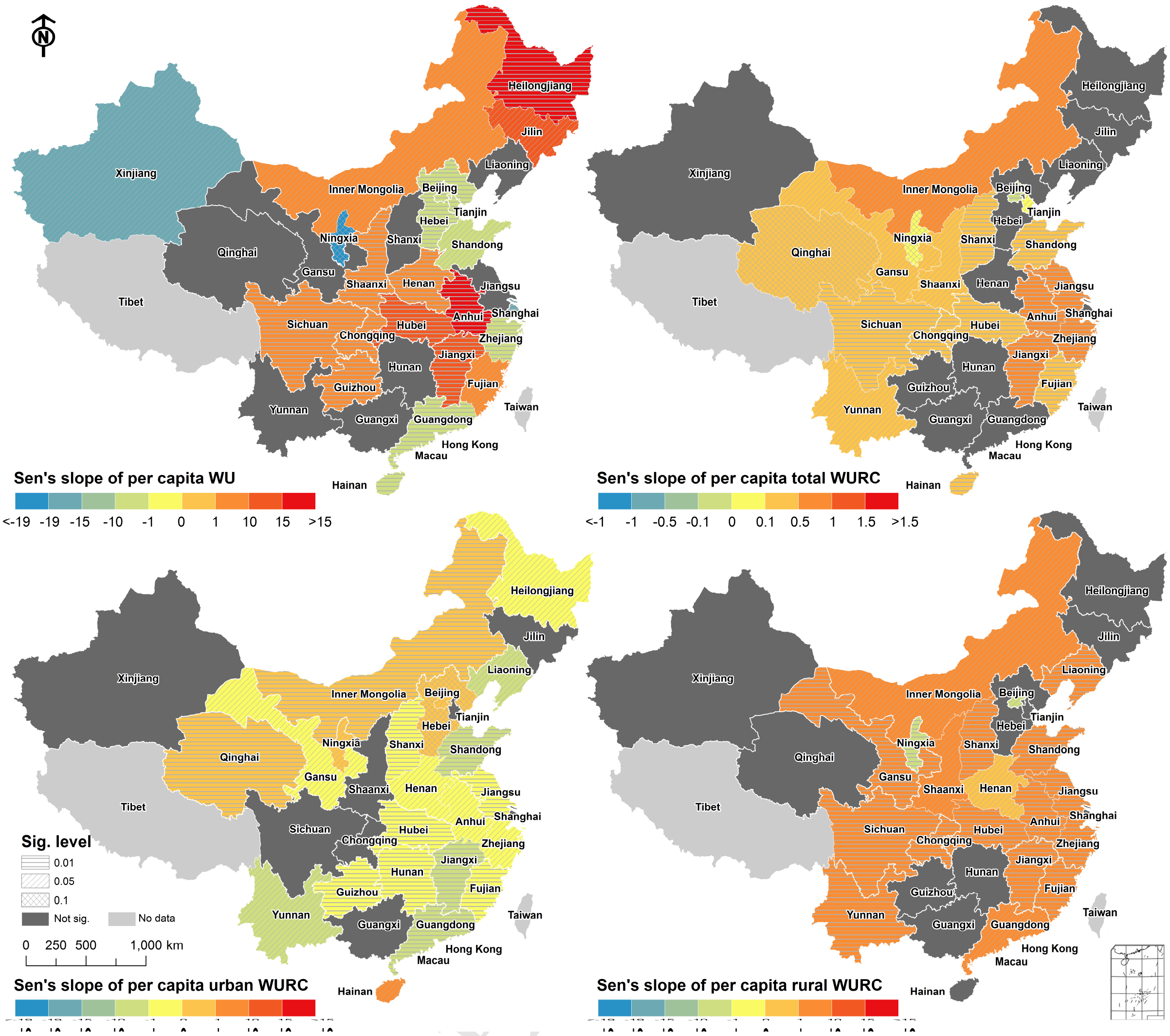

Fig. 2. China's provincial per capita water use of residential consumption (WURC, m^3/person) during 2003-2012: Results of Mann-Kendall test and Sen's slope. Data of per capita total water use (WU) and per capita total WURC are available in Table S.8-S.9. Data for urban and rural areas are available in Table S.10-S.11.

In terms of urban vs rural per capita WURC by province, the urban values indicated significant decreasing trends in 36% (4 out of 11) of coastal provinces and 26% (5 out of 19) of inland provinces, while there were significant increasing trends in Inner Mongolia and Qinghai (inland provinces) **(Fig. 2 and Table S.10)**. This was, however, not fully consistent with the significant changes of the urban WURC detected in the same provinces **(Supplementary results)**. On average, the per capita urban WURC in coastal provinces dropped from 39.5 to 30.7 m^3/person (108.2 to 84.1 l/person/day), whereas that in inland provinces from 25.5 to 23.4 m^3/person (69.9 to 64.1 l/person/day). On the contrary, the rural values showed significant increasing trends in 45% (5 out of 11) of coastal provinces and 42% (8 out of 19) of inland provinces, while there was a significant deceasing trend in Ningxia (inland province) **(Fig. 2 and Table S.11)**. It was also mostly inconsistent with the significant changes of the rural WURC found in the same provinces **(Supplementary results)**. On average, the per capita rural WURC in coastal provinces rose from 28.7 to 44.8 m^3/person (78.6 to 122.7 l/person/day), while that in inland provinces from 31.8 to 38.9 m^3/person (87.1 to 106.6 l/person/day).

Hence, significant trends of per capita WURC were discovered nationwide, with decreases in urban areas and increases in rural areas. Due to much faster socioeconomic development, the coastal provinces had greater per capita WURC on average in both urban and rural areas. In the context of China’s demographic changes, the rural areas were the greatest contributor to the rising per capita total WURC at both national and provincial scales.

3.3. Energy: urban and rural areas sharing throne

From a national perspective, the values of per capita total ERCERC showed a significant increasing trend during 2003-2012 **(Table S.17)**. Per capita total ERCERC climbed from 0.42 t/person in 2003 to 0.85 t/person in 2012 **(Table S.17)**. Unlike per capita WURC, significant increasing trends were detected in both urban and rural areas **(Table S.18-S.19)**. The urban and rural values grew from 0.60 and 0.31 to 0.99 and 0.70 t/person, respectively **(Table S.18-S.19)**. Despite the fact that urban ERCERC shares had significant increasing changes and their values were constantly greater than the rural ones throughout the study period **(Supplementary results)**, there was no evident shift between urban and rural areas over the dominance of per capita total ERCERC at the national scale.

Significant increasing trends were also found in the provincial values of per capita total ERCERC, excluding 4 inland provinces (Xinjiang, Qinghai, Ningxia, and Guizhou) **(Fig. 3 and Table S.17)**. This was consistent with similar significant changes in the provincial total ERCERC **(Supplementary results)**. On average, the per capita total ERCERC in coastal and inland provinces went up from 0.43 and 0.41 to 0.90 and 0.83 t/person, respectively.

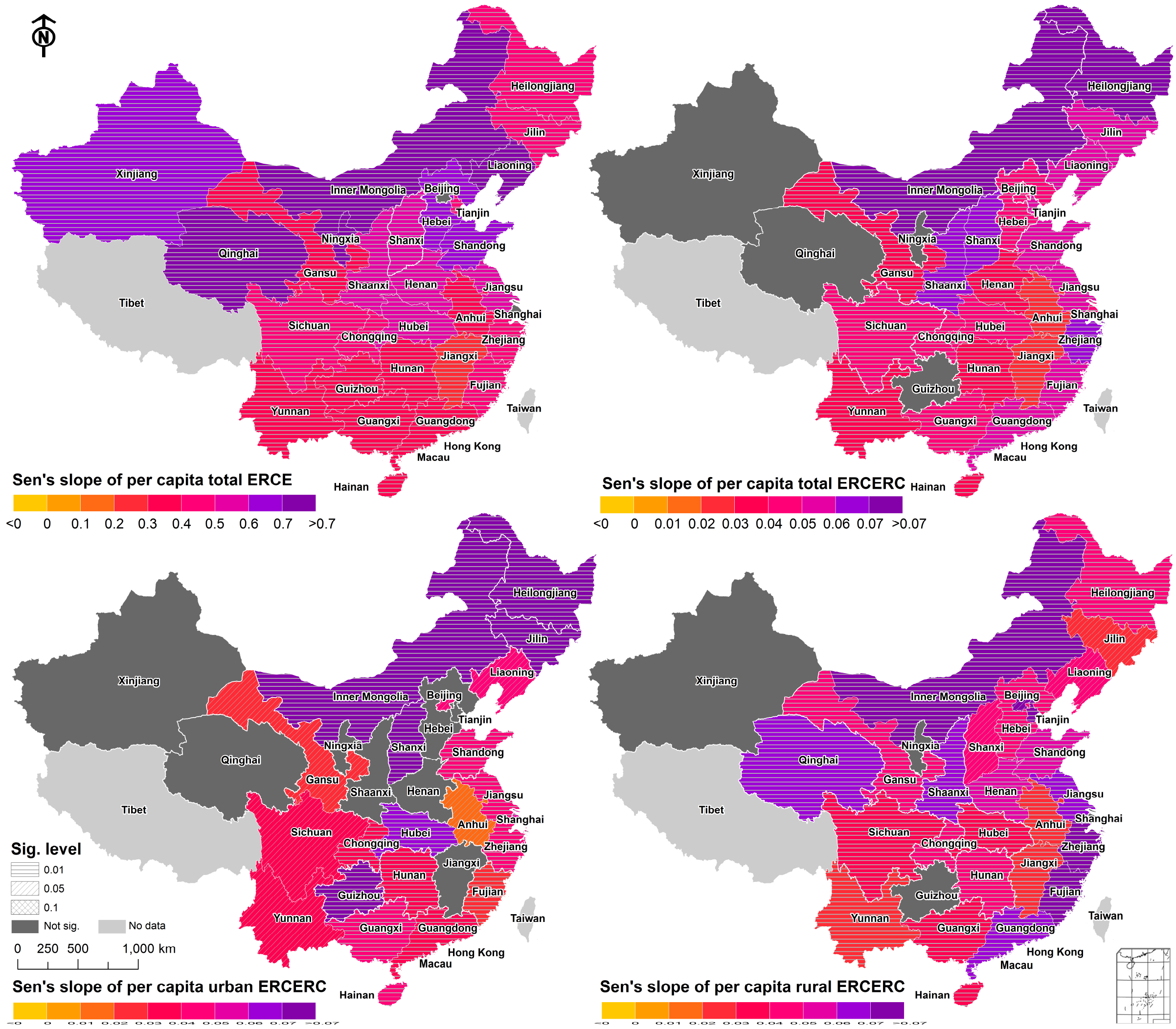

Fig. 3. China's provincial per capita energy-related CO_2 emissions of residential consumption (ERCERC, t/person) during 2003-2012: Results of Mann-Kendall test and Sen's slope. Data of per capita total energy-related CO_2 emissions (ERCE) and per capita total ERCERC are available in Table S.16-S.17. Data for urban and rural areas are available in Table S.18-S.19.

Regarding per capita ERCERC in urban and rural areas at the provincial scale, the urban values showed significant increasing trends in 64% (7 out of 11) of coastal provinces and 47% (9 out of 19) of inland provinces **(Fig. 2 and Table S.18)**. This was different from the significant changes of the urban ERCERC discovered in the same provinces, among which only Shanghai (coastal province) as well as Shanxi, Hubei, and Guizhou (inland provinces) had consistent changes in both urban and rural areas **(Supplementary results)**. On average, per capita urban ERCERC in coastal and inland provinces grew from 0.57 and 0.66 to 0.89 and 1.24 t/person, respectively. On the other hand, the rural values also showed significant increasing trends in 73% (8 out of 11) of coastal provinces and 68% (13 out of 19) of inland provinces **(Fig. 2 and Table S.19)**. There was a lack of consistency in the changes of the rural ERCERC in the same provinces, except for Qinghai and Guangxi (inland provinces) **(Supplementary results)**. On average, per capita rural ERCERC in coastal and inland provinces rose from 0.30 and 0.31 to 0.76 and 0.59 t/person, respectively.

Consequently, there was strong evidence of significant increasing trends of national and provincial per capita ERCERC in urban and rural areas, both of which greatly contributed to the rising per capita total ERCERC at national and provincial scales.

3.4. High correlation between water and energy

At the national scale, a significant positive correlation appeared between the per capita total WURC and per capita total ERCERC during 2003-2012 (r = 0.8287, p < 0.001) **(Table S.20)**. There was also a significant positive correlation between the per capita rural WURC and per capita rural ERCERC (r = 0.9235, p < 0.001), however, a significant negative correlation was detected in urban areas (r = -0.9754, p < 0.001) **(Table S.20)**.

By province, the per capita total WURC and per capita total ERCERC manifested significant positive correlations in 27% (3 out of 11) of coastal provinces and 21% (4 out of

19) of inland provinces ($p < 0.01$) **(Fig. 4 and Table S.20)**. Beijing (coastal province) exclusively showed a significant negative correlation during this ten-year period ($r = -0.8360$, $p < 0.01$) **(Fig. 4 and Table S.20)**. In terms of urban areas, significant negative correlations were found in 36% (4 out of 11) of coastal provinces and 16% (3 out of 19) of inland provinces ($p < 0.01$), whereas there were significant positive correlations in Beijing (coastal province) and Inner Mongolia (coastal province) ($p < 0.01$) **(Fig. 4 and Table S.20)**. With regard to rural areas, only significant positive correlations were discovered, in 55% (6 out of 11) of coastal provinces and 32% (6 out of 19) of inland provinces ($p < 0.01$) **(Fig. 4 and Table S.20)**.

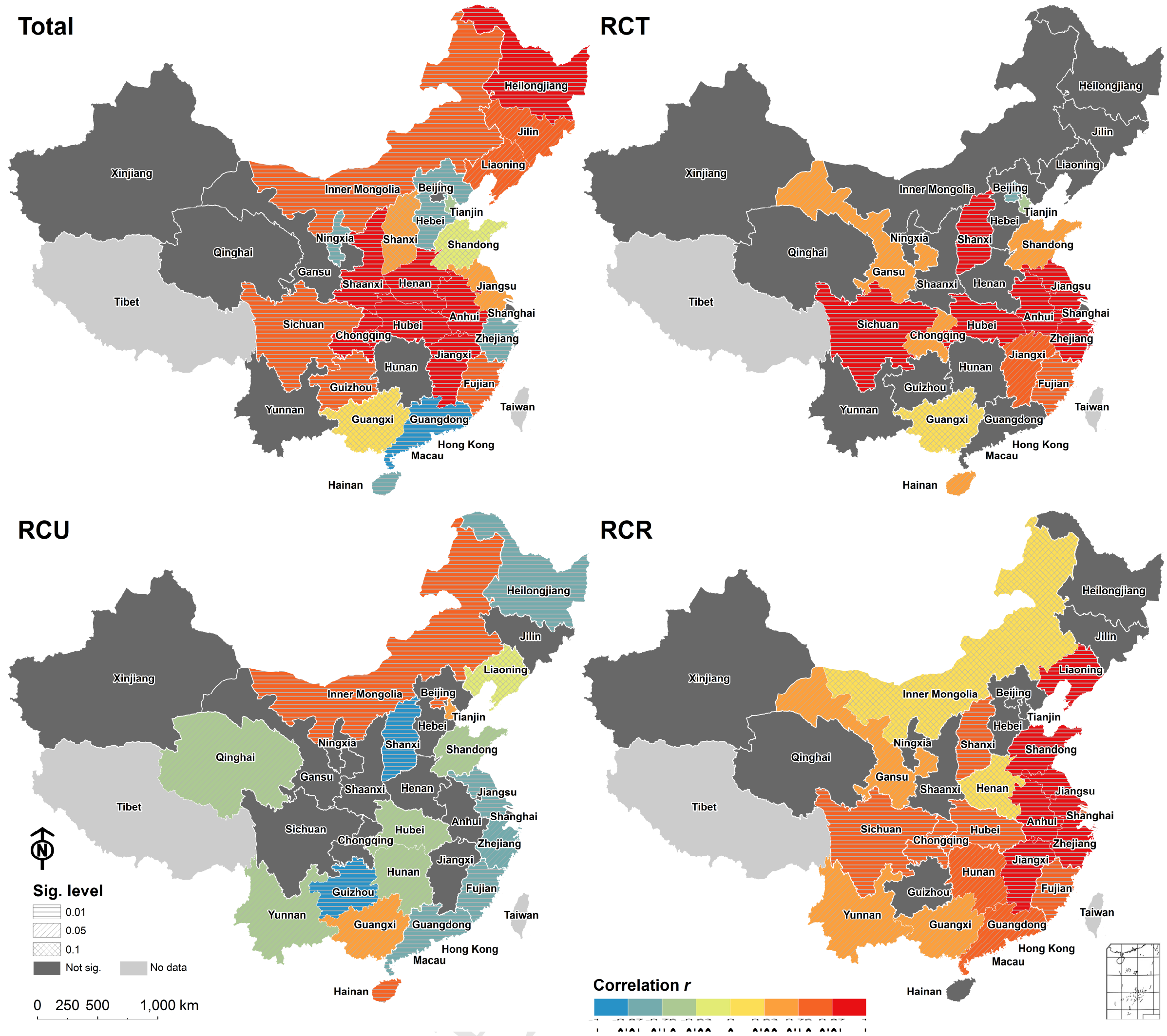

Fig. 4. China's provincial per capita water use of residential consumption (WURC) and per capita energy-related CO_2 emissions of residential consumption (ERCERC) during 2003-2012: Correlation coefficients (*r*) and their significance levels. Total, RCT, RCU, and RCR denote per capita total water use vs. per capita total energy-related CO_2 emissions, per capita total WURC vs. per capita total ERCERC, per capita urban WURC vs. per capita urban ERCERC, and per capita rural WURC vs. per capita rural ERCERC, respectively. Their data are available in Table S.20.

Therefore, this suggests the inclusion of per capita WURC and per capita ERCERC as national indicators for policy-making targets of China's water and energy security in the context of its determination in striving for sustainable urbanization.

4. Discussion

There was strong evidence of distinct spatial patterns of per capita WURC and per capita ERCERC among China's coastal and inland provinces over 2003-2012. This indicates how the country's recent urbanization development has impacted residential water use and energy consumption and how its concurrent national polices influence water and energy security for residential consumption. These patterns result from both natural and anthropogenic effects **(Cai et al., 2017a; Veldkamp et al., 2017)**.

China's urbanization development has tended to be located in fertile areas with good access to international markets **(Christensen et al., 2016)**, which is in line with the fact that coastal provinces are located in plains and connected to ports. Also due to this fact, China's national policies since the 1978 economic reform have been in favor of coastal provinces' socioeconomic development, which has led to their soaring urbanization progress **(Cai et al., 2016)**.

In contrast, the degree of inland provinces' urbanization is lagging behind, although significant increasing trends were detected **(Fig. 1)**. What is more important, the tendency of the population flow from rural to urban areas, not only occurred within each inland province but also was largely towards coastal provinces' urban areas **(Fig. 1)**. Hence, China's rapid urbanization, which is directly related to the expansion of urban areas and growth of the urban population **(Cai et al., 2017a)**, has substantially affected the extent of residential water use and energy consumption, in particular with coastal provinces experiencing much more stress.

Facing this unprecedented urbanization progress, WURC has been emerging as the dominant concern in China's municipal water supply planning and management during our study period, owing to the fact that it involves a huge capital commitment as well as an equity issue between urban and rural areas with wide social implications **(Zhang and Brown, 2005)**. In general, more coastal provinces had significant increasing total WURC and corresponding per capita total WURC than inland provinces, by both absolute and proportional amount **(Supplementary results)**. Hence, more urbanized provinces need more water to meet the demand of growing population for residential consumption.

However, it was surprising to find that per capita urban WURC manifested significant decreasing trends, regardless of coastal or inland provinces **(Fig. 2)**. These unexpected results are rooted in aforementioned China's water pricing reforms that were set in force in 2002 to reduce WURC in urban areas **(Zhong and Mol, 2010)**. These reforms have targeted adoption of increasing block rate price structures in place of commonly used uniform rate structures, motivated by the responsiveness of water demand to higher prices **(Dalhuisen et al., 2003; Saglam, 2015; Zhang et al., 2017)**. Zhang et al. **(2017)** pointed out that there was a 3-4% annual urban WURC reduction in the short-run and 5% in the longer-term, based on 28 China's cities that adopted increasing block rate tariffs during 2002-2009, which is not completely consistent with the results of our broader spatio-temporal analysis **(Supplementary results)**. Nevertheless, the effectiveness of the increasing block rate tariffs should not be underestimated, when taking the ceaselessly growing urban population into account **(Fig. 1 and Tables S.1-S.2)**.

In contrast, almost half of coastal and inland provinces had significantly increasing per capita rural WURC, while the amount of the rural WURC did not change much **(Fig. 1, 2, and S.1)**. These results are likely to be closely linked to socioeconomic controls, including income and education **(Sankarasubramanian et al., 2017)**. The study by Sankarasubramanian et al. **(2017)** demonstrated that per capita WURC in the U.S. has increased in urban counties relative to rural ones and in counties with higher income and education. They also argued the need for frequent updates, perhaps monthly to annual, of WURC data for identifying effective strategies, such as increasing block rate tariffs **(Sankarasubramanian et al., 2017)**. Heretofore, China and the U.S. appear to confront the same delicate issue, i.e. how to control and alleviate per capita urban and rural WURC in various geographic settings under a changing climate. Especially in the context of reaching the United Nations' Sustainable Development Goal no. 6 (to ensure access to water and sanitation for all) by 2030, China could learn useful lessons and experiences from other countries that have achieved a mature stage in the urbanization process, as well as join forces with them to optimize policy-making strategies and their implementation **(Steensig, 2017)**.

Many studies have revealed a positive link between China's urbanization and ERCERC **(Zha et al., 2010; Feng et al., 2011; Jiang and Lin, 2012; Sun et al., 2014; Yuan et al., 2015)**. Our analysis shared the same outcome. Per capita ERCERC approximately doubled nationwide in total, in urban areas and in rural areas during this ten-year urbanization **(Fig. 3)**. In general, coastal provinces had much greater per capita ERCERC than inland provinces in both urban and rural areas, which is in accordance with the fact that coastal provinces' ERCERC increased substantially in both absolute and proportional terms (total ERCERC/total

ERCE) **(Supplementary results)**. When taking a close look at all 21 actual fuel types consumed in China, heat and electricity (H&E) were the greatest contributors to ERCERC **(Table S.21)**. On average, inland provinces' urban and rural H&E shares climbed from 52.1% and 31.8% in 2003 to 61.9% and 44.7% in 2012 respectively, while coastal provinces' shares maintained a relatively high consumption level, from 62.1% and 61.8% in 2003 to 63.1% and 61.7% in 2012 respectively **(Table S.22-S.23)**. Accordingly, inland provinces were still in the increasing phase of ERCERC owing to urbanization.

Given the dominance of coal in China's energy production structure for a long time, coal has been occupying an absolutely dominant proportion of energy sources for H&E production, particularly in rural areas **(Aldhous, 2005; Zha et al., 2010; Feng et al., 2011; Hu and Cheng, 2017)**. It is also worth noting that there is an interesting phenomenon in China's heat consumption. Only the urban households of cities located north of the Yangtze River are able to use central heating provided and controlled by local governments in winter **(Sun et al., 2014)**. This leads to a unique spatial pattern of heat consumption among China's provinces **(Table S.25-S.26)**, which is in line with the fact that many northern provinces have been experiencing severe fossil-fuel-related outdoor/ambient air pollution by fine particulate matter (<2.5 μm: PM2.5), along with growing ERCE **(Ramaswami et al., 2017)**. During our study period, there were no specific national policies initiated for aiming to alleviate ERCERC, it is therefore apparently the critical reason why China's per capita ERCERC showed significant increasing trends nationwide.

Thanks to China's commitment to clean energy and climate protection made during the 2009 United Nations Climate Change Conference (known as the Copenhagen Summit) **(Cai**

et al., 2016), a series of initiatives have been proposed and implemented. In July 2012, China launched a pilot run of residential tiered electricity pricing reforms in all the provinces expect Xinjiang, which is seen as the first step towards a thorough power sector reform **(Zhang and Qin, 2015)**. In March 2014, the National New-type Urbanization Plan (2014–2020), consisting of 17 indicators from four components (urbanization level, basic public services, infrastructure, and resource and environment), was released by the State Council of China as the first national policy to steer China's urbanization process onto a human-centered, environmentally friendly, and sustainable path **(Chen et al., 2016; Cai et al., 2017a)**. To implement this plan, the National Development and Reform Commission of China initiated a new action plan in the same month to develop 1000 low-carbon cities **(Liu and Qin, 2016)**. On the basis of the Paris Agreement of 2015, China's regional pilot cap-and-trade programs are now being implemented as part of its current climate policy, which signals that China has been making efforts for the absolute ERCE cuts **(Bretschger and Zhang, 2017)**. These measures are ambitious and promising, however, it is too early to envision what progress can be achieved and by when **(Zhang and Qin, 2015)**.

In spite of the fact that urbanization and industrial transition are expected to co-occur, it is of prime importance and necessity to have a comprehensive understanding of characteristics of residential water use and energy consumption in the rapid urbanization process, for developing effective strategies and appropriate policy-making targets of China's water and energy security **(Liu and Yang, 2012; Zhang and Qin, 2015; Chen et al., 2016; Ramaswami et al., 2017)**. Our results indicated the huge difference between per capita WU/ERCE and per capita WURC/ERCERC. On one hand, the national and provincial values of per capita total WU/ERCE that includes WU/ERCE in primary, secondary, and tertiary industry were approximately 10 times greater on average than those values of per capita total WURC/ERCERC **(Table S.8-S.9 and S.16-S.17)**. On the other hand, the changes of per capita total WU/ERCE manifested diverse trends nationwide due to China's industrial transition, in comparison with those of per capita total WURC/ERCERC **(Fig. 2-3 and S.1-S.2)**. This further led to different correlations of per capita total WU/ERCE and per capita total WURC/ERCERC in each province **(Fig. 4 and Table S.20)**. Our proposed potential national indicators, per capita WURC and per capita ERCERC, have thus fulfilled the purpose of identifying the effects of demographic transition on China's water and energy security, which is in accordance with reflecting our findings against its concurrent national policies.

5. Conclusions

We conducted, for the first time, an integrated and quantitative spatio-temporal analysis of the impacts of China's urbanization on two potential national indicators for policy-making targets of its water and energy security, namely per capita water use of residential consumption and per capita energy-related CO_2 emissions of residential consumption. Our study, conducted over the period 2003-2012, provided strong evidence of the significant impacts of the demographic changes on per capita water use of residential consumption and per capita energy-related CO_2 emissions of residential consumption. Its highlights can be summarized as follows: (1) Rural areas dominated the per capita water use of residential consumption at both national and provincial scales, with a significant increasing trend, while the shares of water use of residential consumption and the per capita water use of residential consumption in urban areas decreased; (2) the per capita energy-related CO_2 emissions of residential consumption was significantly augmented in both urban and rural areas nationwide; (3) the per capita total and rural water use of residential consumption and per capita total energy-related CO_2 emissions of residential consumption had a significant positive correlation, but urban areas had a significant negative correlation.

As national indicators for policy-making targets, it is crucial to quantify them for the timelines set in long-term action plans. Given our results indicating a significant positive correlation between per capita total WURC and per capita total ERCERC, it would be highly useful and advisable to synchronize these two potential national indicators for policy-making targets in every stage of the timeline to contribute most to China's water and energy security in the context of its determination in striving for sustainable urbanization **(Liu and Yang, 2012; Cai et al., 2016; Chen et al., 2016)**.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at XXX.

Impacts of urbanization on water use and energy-related CO_2 emissions of residential consumption in China: A spatio-temporal analysis during 2003-2012

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Highlights

- We assessed the impacts of China's urbanization on water-energy security.
- An integrated and quantitative spatio-temporal analysis was performed.
- Growing residential water consumption was found in rural areas nationwide.
- Both urban and rural areas had soaring residential energy consumption nationwide.
- Significant correlations of residential water and energy consumption were detected.