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Published in:
Applied Energy

DOI:
10.1016/j.apenergy.2016.09.069

Published: 01/12/2016

Document Version
Publisher's PDF, also known as Version of record

Please cite the original version:
Cai, J., Yin, H., & Varis, O. (2016). Impacts of industrial transition on water use intensity and energy-related carbon intensity in China: A spatio-temporal analysis during 2003–2012. *Applied Energy*, *183*, 1112-1122. https://doi.org/10.1016/j.apenergy.2016.09.069

Applied Energy 183 (2016) 1112–1122

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Impacts of industrial transition on water use intensity and energy-related carbon intensity in China: A spatio-temporal analysis during 2003–2012

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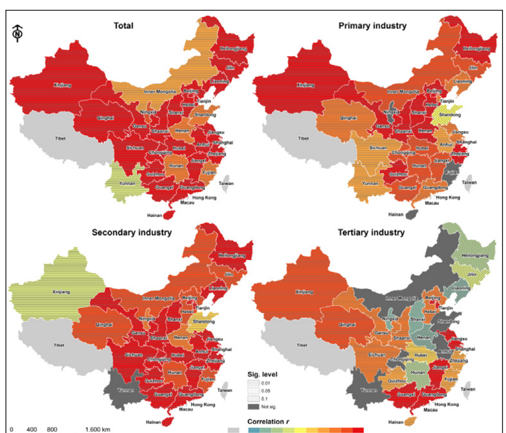
HIGHLIGHTS

- We assessed the impacts of China's industrial transition on water-energy security.
- An integrated and quantitative spatio-temporal analysis was performed.
- Primary industry appeared to dominate the water use intensity.
- Secondary industry dominated in affecting the total carbon intensity nationwide.
- The total water use and carbon intensity had a significant positive correlation.

GRAPHICAL ABSTRACT



High correlation between water use intensity and energy-related carbon intensity in China's different industries

ARTICLE INFO

Article history:
Received 4 May 2016
Received in revised form 10 September 2016
Accepted 24 September 2016
Available online 28 September 2016

Keywords:
Industrial transition
Water use intensity
Energy-related carbon intensity
CO_2 emissions
Policy-making
China

ABSTRACT

China faces a complicated puzzle in balancing the country's trade-offs among water and energy security, economic competitiveness, and environmental sustainability. It is therefore of prime importance to comprehend China's water and energy security under the effect of its economic structural changes. Analyses of this issue still remain few and far between, and a comprehensive picture has not been available that would help understand the recent evolution of China's economic structure as well as its spatial features and links to water and energy security, and policy-making. Consequently, we addressed these information gaps by performing an integrated and quantitative spatio-temporal analysis of the impacts of China's industrial transition on water use intensity and energy-related carbon intensity. Those two factors are national indicators for policy-making targets of its water and energy security. Primary industry appeared to dominate the water use intensity although its relative share decreased, and the water use intensity of primary industry continued to be far higher than that of secondary and tertiary industries. In contrast, secondary industry dominated the total energy-related carbon intensity at both national and provincial scales. Besides, the total water use intensity and energy-related carbon intensity had a significant positive correlation.

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http://dx.doi.org/10.1016/j.apenergy.2016.09.069
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Nomenclature

CC_i	CO_2 emission factor of fuel type i
C_m	national total CO_2 emissions of year m
C_{mkji}	CO_2 emissions from the combustion of fuel type i in sector j of province k of year m
ERCE	energy-related CO_2 emissions
ERCI	energy-related carbon intensity
F'_{mkji}	physical quantity of the final consumption of fuel type i in sector j of province k of year m
FF_{mi}	energy factor of fuel type i of year m
F_{mkji}	standard quantity of the final consumption of fuel type i in sector j of province k of year m
GDP	gross domestic product
G_m	gross rate of coal consumption for electricity generation of year m
GNI	gross national income
i	fuel type consumed by each sector
j	industrial or residential sector of China's CO_2 emissions
k	province of China
L_{mkji}	loss of fuel type i in sector j of province k of year m
N_{mkji}	non-CO_2-emission amount of fuel type i in sector j of province k of year m
O_i	fraction of carbon oxidized of fuel type i
p	significance level
PI	primary industry
Q	Sen's slope
r	Pearson's correlation coefficient
RMB	Renminbi, the official currency of China
SI	secondary industry
T	theoretical rate of coal consumption for electricity generation
TCE	tonne of coal equivalent
TI	tertiary industry
WU	water use
WUI	water use intensity

1. Introduction

Just like the two cerebral hemispheres of the brain, water and energy are tightly interlinked. They are both critical to human well-being and sustainable socioeconomic development [1,2]. Throughout the world, the perennially increasing demand for water and energy is rooted in demographic and economic growth, changing lifestyles, as well as evolving consumption patterns [3]. This development has increased the vulnerability of water and energy systems at local, regional, and national scales across the planet during the past several decades [4–6]. The water and energy situation is particularly challenging in countries undergoing rapid economic growth and accelerated industrial transition. Typical to such conditions is that water environment and aquatic ecosystems are highly stressed and modern energy services remain largely underdeveloped, but are subjected to soaring demand [3]. Among those countries, China is a representative example.

China has been tackling a quite challenging water-energy trilemma since the 1978 economic reform [7–9]. Balancing the trade-offs among three major concerns, namely water and energy security, economic competitiveness, as well as environmental sustainability [10–13] has been very demanding. In that struggle, China's unfortunate choice has been to apply the well-known philosophy *pollute first, clean up later* in order to prioritize securing its long-enduring high economic growth. This has yielded a severe nationwide deterioration of environment and ecosystems [13–16]. The soaring concerns on the steadily worsening environmental situation have led to the development that sustainability has been increasingly taken into account as an overarching principle for water and energy policy-making. A milestone of this development was China's 10th Five-Year Plan on national economy and social development that was set in force in 2001. Accordingly, China has ever since been intending to boost its service-oriented green economy and high-value-added industrial profile, aiming to contribute to long-term sustainable water and energy security [7,17]. Therefore, it is of prime necessity and importance to examine the impacts of China's economic structural changes on its water and energy security.

By now, a variety of studies have scrutinized China's water security (e.g., Xia and Zhang [18], Ren et al. [19], and He et al. [20]) and energy security (e.g., Bambawale and Sovacool [21], Wu et al. [22], and Zhao and Liu [23]) at either regional or national scales. These studies indicate that the definition and themes of water and energy security are not only diverse, owing to the fact that their nature is polysemic and multidimensional, but also dynamic and evolving as circumstances change over time [13,24–26]. With regard to the theme of the industrial transition, to our knowledge, only few studies have addressed its impact on China's water security [7] and energy security [27] at national scale. As China is geographically a vast country, it is to be expected that a high level of spatial heterogeneity exists among different provinces. Thus, it is critical to assess China's water and energy security within the context of its local socioeconomic development, with a policy-relevant spatio-temporal resolution.

Apart from the close interlinkage of water and energy, they are also highly interdependent, with choices made and actions taken in one domain having direct and indirect as well as positive and negative consequences on the other [3]. Besides, the choices made and actions taken for water and energy can impact other sectors, and vice versa [3]. Thereby, in terms of formulating long-sighted polices, water and energy security should be considered as an ensemble, rather than in isolation. The emerging concept of water-energy nexus has been recognized during the past decade for embracing and exploiting the aforementioned interlinkage and interdependency between water and energy, along with their externalities [6,28]. Heretofore, an extensive number of studies using the water-energy nexus have been conducted to analyze the interaction of water consumption and energy production, i.e. whereas energy is required for the provision of water services, water resources are required in the production of energy [29–31]. With regard to the latest case studies in China, Huang et al. [32] developed a bottom-up model to integrate China's energy system with water resources, projecting water demand in power sector, and assessing the impacts on power generation portfolio out to the year 2050 by China's Intended Nationally Determined Contributions to greenhouse gas emission reductions and water constraints. Duan and Chen [33] proposed a water-energy element nexus for identifying China's international energy trade and analyzing its impact on water scarcity in China. Chen and Chen [34] used a system-based framework from an urban network perspective for water-energy nexus to synthesize the interwoven connections between energy consumption and water use in Beijing. Despite the innovative development of water-energy-nexus methodologies and technologies, there is still a lack of studies that illustrate China's water-energy nexus in broader terms, from the point of view of its economic competitiveness and national policies for water and energy security. Hence, there is a pressing need for analyzing the impacts of China's industrial transition on its water and energy security in an integrated and rigorous way.

Due to the diversity and ongoing evolution of the definition and themes of water and energy security, their indicators are highly dependent on the shifting national foci, concerns, and perceptions. In today's China, water use intensity (WUI) and energy-related carbon intensity (ERCI) can be seen as the most representative indicators of water and energy security, respectively, in the context of China's economic structural changes. On one hand, WUI, namely water withdrawal (water use (WU)) per unit of gross domestic product (GDP), is one of three national indicators (known as "redlines") for the most stringent water resources management, listed in the *Number 1 Central Document* in 2011, which is China's most important policy document for that year and beyond [10,16,35]. The measures aiming to improve WUI by 2030 have been issued in the action plans of the central government [35–37]. On the other hand, ERCI, namely energy-related CO_2 emissions (ERCE) per unit of GDP, is also one of China's national indicators for clean energy and climate protection, which was announced during the 2009 United Nations Climate Change Conference (known as the Copenhagen Summit) [9,38–39]. The measures aiming to reduce ERCI by 2010 and 2015 have been issued in the 11th and 12th Five-Year Plans respectively [40–41]. Additionally, it is of great interest to investigate the relationship between WUI and ERCI, owing to the fact that both of them are national indicators for policy-making targets of China's water and energy security, and influenced by its industrial transition.

Our principal aim was to comprehensively understand (1) how China's recent development in economic structure has influenced water and energy security in the context of its water-energy nexus, with a policy-relevant spatial resolution; and (2) how China's national policy-making for water and energy security could benefit from identifying the relationship between WUI and ERCI. Filling these knowledge gaps involved conducting a quantitative spatio-temporal analysis of WUI and ERCI under the effect of China's industrial transition during 2003–2012. The specific objectives were to (1) quantify China's industrial transition at national and provincial scales; (2) assess possible trends of national and provincial WUI and ERCI changes in primary, secondary, and tertiary industries; and (3) analyze the correlation between WUI and ERCI in different industries at national and provincial scales.

2. Material and methods

2.1. Industrial and socioeconomic development classification

According to the composition of GDP, China's economic activities are categorized into the following three strata of industry: (1) Primary industry (PI) refers to agriculture, forestry, animal husbandry, and fishery; (2) secondary industry (SI) refers to industry (mining, manufacturing, as well as production and supply of electricity, gas, and water) and construction; and (3) Tertiary industry (TI) refers to all other economic activities not included in the PI or SI, such as various public and private services (services to households, education, research, health, social security, social welfare, culture, sports, entertainment, public management, social organizations, management of water conservancy, environment and public facilities, and business services) and information technology (information transmission, computer services, and software) (Table S.1).

The level of China's economic development can be classified by per capita gross national income (GNI), using the Atlas method, which is widely and systematically available [42]. Over the period 2003–2012, all the thresholds for four classification categories (low income, lower middle income, upper middle income, and high income) have been annually increased (Tables S.2 and S.3). Therefore, in this study, the level of China's economic development was dynamically assessed, taking this increase into account.

Additionally, the annual GDP deflator was used to eliminate the impact of price inflation or deflation during 2003–2012 [43].

2.2. Estimation of water use

China's total water withdrawal during this ten-year period consisted of water use in PI, SI, and water use for residential sector as well as for environment and ecosystems [44–53]. According to the bulletin of first national census for water [54], the amount of water use in TI can be estimated at 35% of the total amount of the residential water use.

2.3. Estimation of energy-related CO_2 emissions

Contrary to existing studies estimating China's CO_2 emissions from fuel combustion [9,17,23,39,55], 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. This estimation was performed using Eq. (1):

$$
\begin{aligned}
C_m &= \sum_{k=1}^{30}\sum_{j=1}^{4}\sum_{i=1}^{21} C_{mkji} \\
&= \sum_{k=1}^{30}\sum_{j=1}^{4}\sum_{i=1}^{21} F_{mkji} \times CC_i \times O_i \qquad (1)\\
&= \sum_{k=1}^{30}\sum_{j=1}^{4}\sum_{i=1}^{21} F'_{mkji} \times FF_{mi} \times CC_i \times O_i
\end{aligned}
$$

where C_m is the national total CO_2 emissions of year m (m = 2003, 2004, ..., 2012) (t); k is the province of China (k = 1, 2, ..., 30); j is the industrial or residential sector of China's CO_2 emissions, in which the numbers of 1, 2, 3, and 4 denote PI, TI, residential consumption, and SI 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} is the CO_2 emissions from the combustion of fuel type i in sector j of province k of 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} is the standard quantity of the final consumption of fuel type i in sector j of province k of year m (TCE); F'_{mkji} is the physical quantity of the final 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 kW h); 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 kW h).

With regard to SI, a certain amount of carbon-based fuels are only used as raw materials (or feedstock) for products (e.g. plastics) and consequently do not emit CO_2 [56]. On the other hand, heat and electricity are generally used in the manufacture process, which results in their inevitable loss. However, this amount of loss 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 as

$$\begin{aligned}
C_m &= \sum_{k=1}^{30}\sum_{j=1}^{3}\sum_{i=1}^{19} F'_{mkji} \times FF_{mi} \times CC_i \times O_i \\
&+ \sum_{k=1}^{30}\sum_{j=1}^{3}\sum_{i=20}^{21} (F'_{mkji} + L_{mkji}) \times FF_{mi} \times CC_i \times O_i \\
&+ \sum_{k=1}^{30}\sum_{j=4}\sum_{i=1}^{19} (F'_{mkji} - N_{mkji}) \times FF_{mi} \times CC_i \times O_i \\
&+ \sum_{k=1}^{30}\sum_{j=4}\sum_{i=20}^{21} (F'_{mkji} + L_{mkji}) \times FF_{mi} \times CC_i \times O_i \\
&= \sum_{k=1}^{30}\sum_{j=1}^{3}\sum_{i=1}^{19} F'_{mkji} \times FF_{mi} \times CC_i \times O_i \\
&+ \sum_{k=1}^{30}\sum_{j=4}\sum_{i=1}^{19} (F'_{mkji} - N_{mkji}) \times FF_{mi} \times CC_i \times O_i \\
&+ \sum_{k=1}^{30}\sum_{j=1}^{4}\sum_{i=20}^{21} (F'_{mkji} + L_{mkji}) \times FF_{mi} \times CC_i \times O_i
\end{aligned} \tag{2}$$

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 kW h); and N_{mkji} is the non-CO_2-emission amount of fuel type i in sector j of province k of year m (t or 10^4 m^3).

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 [7,39], it is useful to convert the physical quantity of electricity generation into TCE, using coal equivalent calculation. Thus, Eq. (2) can be developed as

$$\begin{aligned}
C_m &= \sum_{k=1}^{30}\sum_{j=1}^{3}\sum_{i=1}^{19} F'_{mkji} \times FF_{mi} \times CC_i \times O_i \\
&+ \sum_{k=1}^{30}\sum_{j=4}\sum_{i=1}^{19} (F'_{mkji} - N_{mkji}) \times FF_{mi} \times CC_i \times O_i \\
&+ \sum_{k=1}^{30}\sum_{j=1}^{4}\sum_{i=20} (F'_{mkji} + L_{mkji}) \times FF_{mi} \times CC_i \times O_i \\
&+ \sum_{k=1}^{30}\sum_{j=1}^{4}\sum_{i=21} (F'_{mkji} + L_{mkji}) \times \frac{G_m}{T} \times FF_{mi} \times CC_i \times O_i
\end{aligned} \tag{3}$$

where G_m is the gross rate of coal consumption for electricity generation of year m (g/kW h); T is the theoretical rate of coal consumption for electricity generation, whose value is 122.9 g/kW h [57].

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, jurisdictions Tibet, Hong Kong, Macau, and Taiwan were excluded from the analysis. Accordingly, data were collected on 30 provinces in mainland China. To ease interpretation, these 30 provinces (k in Eq. (1)) are categorized into 2 regions as follows [55,58–59]:

(1) Coastal China with 11 provinces from Northeast China (Liaoning) and East China (Beijing, Tianjin, Hebei, Shandong, Jiangsu, Shanghai, Zhejiang, Fujian, Guangdong, Hainan);
(2) Inland China with 19 provinces from 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 the WUI and ERCI indicators during this 10-year period, a non-parametric statistical method, namely the Mann-Kendall test, was used [60–62]. Unlike ordinary least squares regression, the Mann-Kendall test is less affected by missing values and uneven data distribution, as well as are relatively robust towards extreme values and serial dependence [63,64]. To identify the magnitude of each trend, Sen's slope (Q) was calculated [62,65,66]. It is a non-parametric linear regression and less affected by gross data errors or outliers [64,67,68].

2.5. Data

The annual provincial data of (i) total GDP as well as GDP of PI, SI, and TI, (ii) GNI, (iii) total population, (iv) GDP deflator, and (v) total water withdrawal as well as water withdrawal of PI, SI, and water use for residential sector during the study period were collected from the China statistical yearbooks [44–53].

The data of (vi) F'_{mkji}, (v) FF_{mi}, (vi) L_{mkji}, (vii) N_{mkji}, and (viii) G_m during the study period were collected from the China energy statistical yearbooks [69–78], while the data of (ix) CC_i, and (x) O_i from the China national greenhouse gas inventory [57].

3. Results

3.1. Quantification of national and provincial industry transition

China's national GDP manifested a significant increasing trend during 2003–2012 (Table S.4). The GDP values in each province also indicated a significant increasing trend (Fig. 1 and Table S.4). In relation to per capita GNI (Tables S.2 and S.3), the provinces located in coastal China had much faster socioeconomic development than those in inland China. Accordingly, coastal China was capable of maintaining a relatively high GDP growth level throughout the study period, while inland China as a developing region was still in the accelerating phase of the GDP growth.

From an industrial structure perspective, a significant decreasing trend of the national GDP share was only detected in PI (Tables S.5–S.7). So evidently the drops of China's GDP share of PI were redistributed to the shares of SI and TI. When considering the GDP share by province, PI indicated significant decreasing trends in all provinces except three in inland China (Fig. 1 and Table S.5). The PI shares of coastal and inland China went down on average from 10.7% and 17.2% in 2003 to 7.5% and 12.2% in 2012 respectively. Secondly, the GDP shares of SI developed in opposite directions in coastal and inland China. Coastal China's 3 provinces had significant decreasing trends, whereas the significant increasing trends were discovered in 11 provinces from inland China and Fujian (coastal China) (Fig. 1 and Table S.6). Thirdly, the GDP shares of TI demonstrated significant increasing trends in 8 provinces, including 6 coastal and 2 inland (Fig. 1 and Table S.7). At the same time, significant decreasing trends were found in 7 provinces from inland China (Fig. 1 and Table S.7).

In striving for speedy GDP growth, China thus mostly experienced the industrial transition from PI towards SI and TI nationwide during 2003–2012. Being in different phases of socioeconomic development and consequent GDP level, coastal China as the more developed region, outpaced inland China in the transition. Coastal China's industrial transition in general evolved definitively from traditional PI and SI towards advanced TI. Meanwhile, inland China still dominantly relied on SI to fuel its economic growth, which was correspondingly supported by the shrinking GDP share of TI during this ten-year period. Heretofore, the differences in industrial transition would result in quite

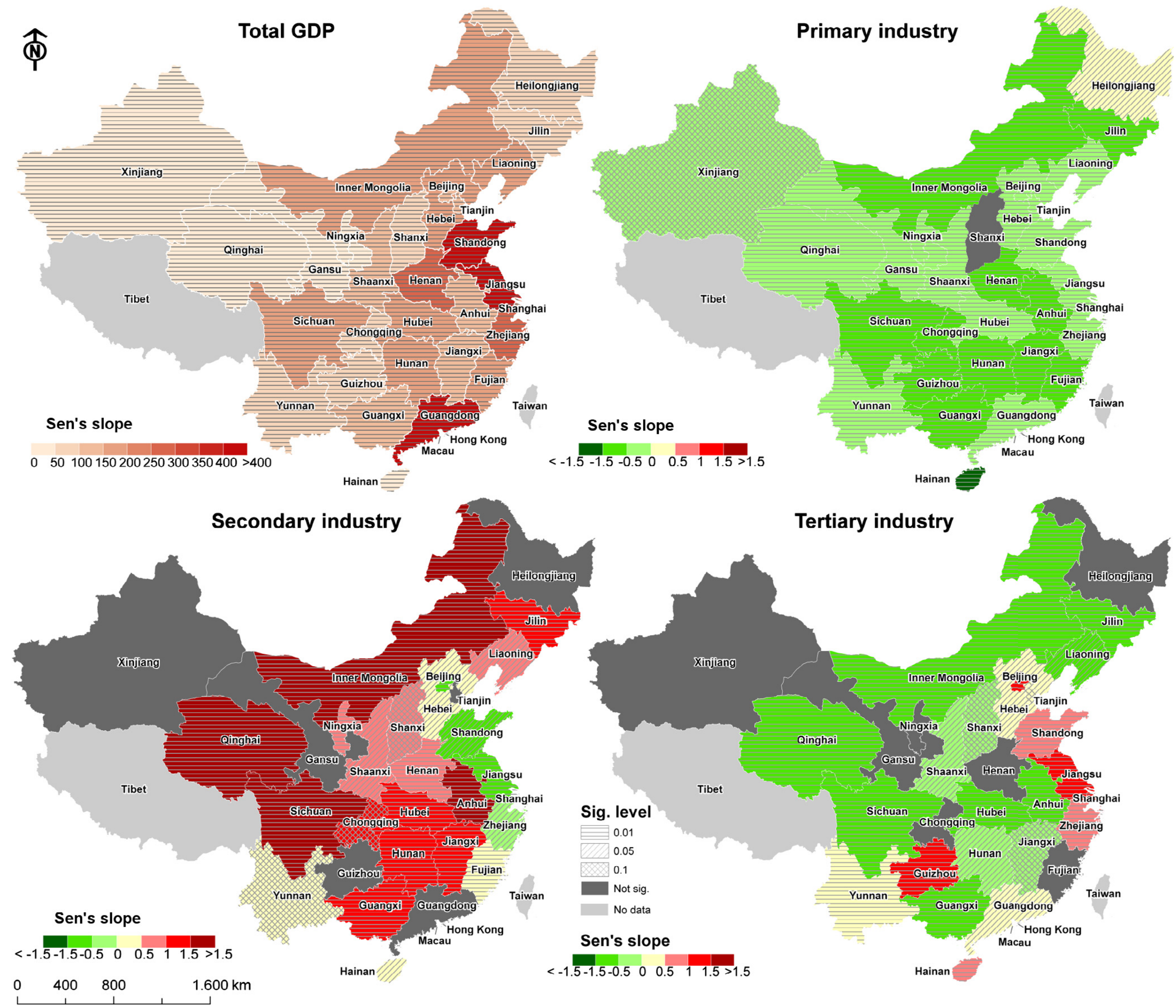

Fig. 1. Results of Mann-Kendall test and Sen's slope for China's provincial gross domestic product (GDP) during 2003–2012. (1) Data of total GDP (10^9 RMB) are available in Table S.4; (2) Primary, secondary, and tertiary industry indicates GDP share of primary, secondary, and tertiary industry (%), respectively. Their data are available in Tables S.5–S.7 respectively; (3) The scale difference of Sen's slope between total GDP and GDP share of each industry is due to the dimensional difference of their data.

diverse scenarios of its impact on WUI and ERCI at the provincial scale.

3.2. Water: dominance of primary industry

For China as a whole, the total WUI values showed a significant decreasing trend during 2003–2012, i.e. the total WUI was ceaselessly improved from 401 $m^3/10^4$ RMB (Renminbi, the official currency of China) in 2003 to 106 $m^3/10^4$ RMB in 2012 (Table S.8). The WUI values for each industry also indicated significant decreasing trends, although they varied from each other substantially (Tables S.9–S.11). The WUI values of PI, SI, and TI were continuously reduced from 1804, 179, and 42 $m^3/10^4$ RMB in 2003 to 666, 47, and 11 $m^3/10^4$ RMB in 2012 respectively (Tables S.9–S.11). The largest contribution was from PI, which clearly demonstrated that the WUI of PI was the key issue to drag the total WUI down at the national scale.

With regard to the total WUI values by province, significant decreasing trends were found in all provinces (Fig. 2 and Table S.8). The huge difference between coastal and inland China, however, stood out. The total WUI values in coastal China sank on average from 271 to 71 $m^3/10^4$ RMB, while those values in inland China from 727 to 185 $m^3/10^4$ RMB. The most extreme cases were Xinjiang (inland China) and Beijing (coastal China), the former having the highest total WUI during this ten-year period with the values 36–44 times greater than those of the latter (Fig. 2 and Table S.8).

In terms of the provincial industrial WUI values, significant decreasing trends were detected in three industries as well (Fig. 2 and Tables S.9–S.11). The PI's WUI values dropped on average from 1611 to 650 $m^3/10^4$ RMB in coastal China, whereas the drop in inland China was from 3171 to 1053 $m^3/10^4$ RMB. In contrast, the relative gap of the WUI values was smaller between SI and TI. The WUI values of SI and TI in coastal China were diminished on average from 144 to 39 $m^3/10^4$ RMB (SI) and from 33 to 9 $m^3/10^4$ RMB (TI), while those values in inland China were from 258 to 62 $m^3/10^4$ RMB (SI) and 58 to 14 $m^3/10^4$ RMB (TI). The WUI of PI was highest, as expected due to its direct use of natural

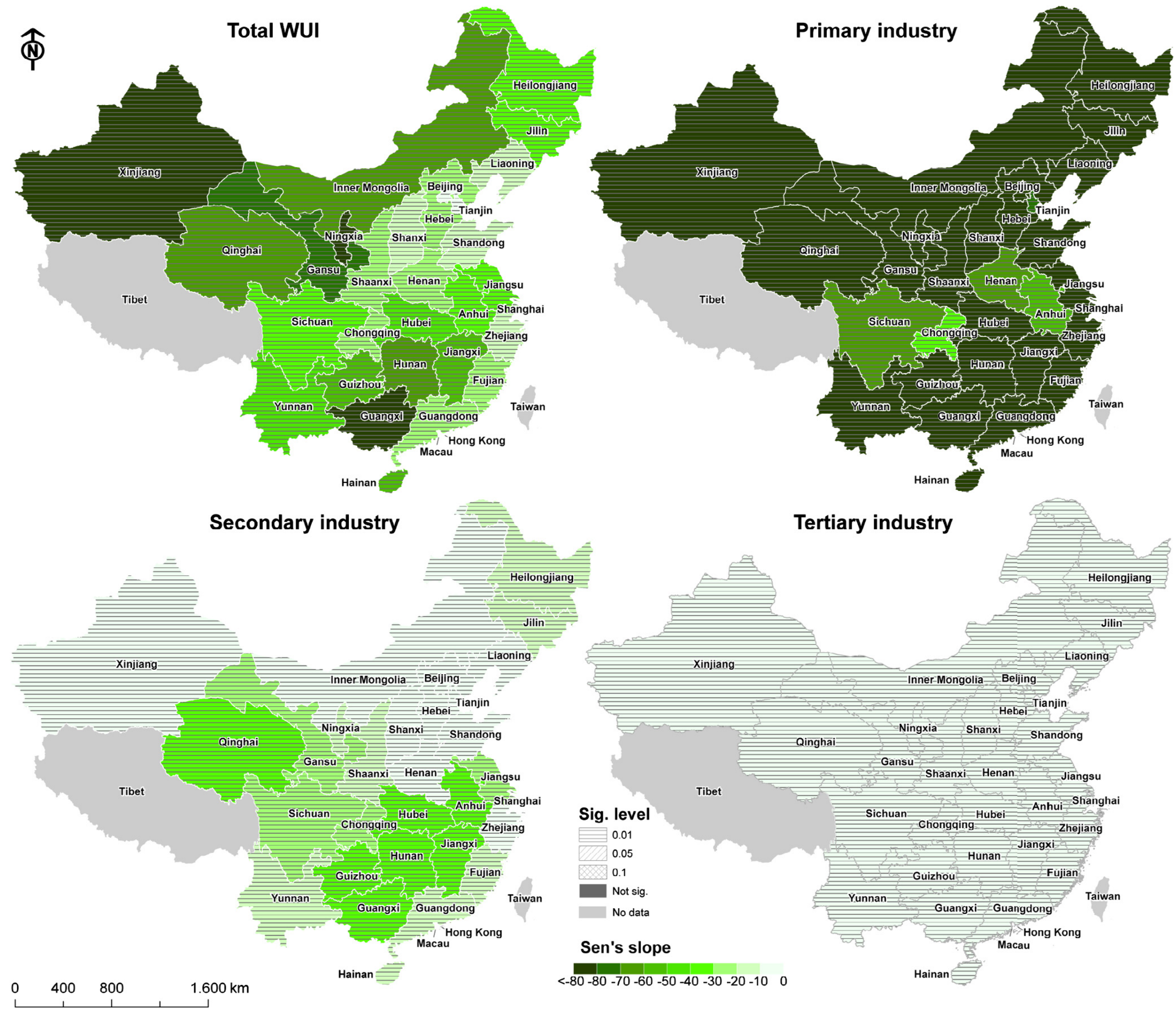

Fig. 2. Results of Mann-Kendall test and Sen's slope for China's provincial water use intensity (WUI, $m^3/10^4$ RMB) during 2003–2012. Data of total WUI are available in Table S.8. Data for each industry are available in Tables S.9–S.11.

resources. PI consistently had the greatest share of both national and provincial WU over time, despite its decreasing contribution to GDP in most provinces (Supplementary results).

3.3. Energy: dominance of secondary industry

Total ERCI's nationwide values showed a significant decreasing trend during this ten-year period (Table S.12). The total ERCI eased from 3.38 t/10^4 RMB in 2003 to 1.78 t/10^4 RMB in 2012 (Table S.12). Regarding the ERCI values of PI, SI, and TI, significant decreasing trends were detected (Tables S.13–S.15). In comparison with the industrial WUI values, the industrial ERCI values shrank with the same order of magnitude (PI from 0.85 to 0.43 t/10^4 RMB; SI from 5.15 to 2.62 t/10^4 RMB; and TI from 1.02 to 0.64 t/10^4 RMB) (Tables S.13–S.15). It can thereby be portrayed that the ERCI of SI dominated the total ERCI at the national scale.

Except for Yunnan (inland China), significant decreasing trends were found in the provincial total ERCI values (Fig. 3 and Table S.12). In general, inland China had higher ERCI than coastal China. The total ERCI values went down on average from 2.93 to 1.54 t/10^4 RMB in coastal China and from 5.13 to 2.43 t/10^4 RMB in inland China.

From an industrial structure perspective, the changes of the ERCI values differed from each other by province. Regarding PI, significant decreasing trends were determined in 25 provinces, excluding Tianjin, Fujian, and Hainan, from coastal China, as well as Inner Mongolia and Ningxia, from inland China (Fig. 3 and Table S.13). The ERCI values in coastal China were on average reduced from 1.28 to 0.71 t/10^4 RMB, while in inland China from 1.33 to 0.53 t/10^4 RMB. In terms of SI, 27 provinces had significant decreasing trends, except Fujian (coastal China) as well as Xinjiang and Yunnan (inland China) (Fig. 3 and Table S.14). The ERCI values sank on average from 4.57 to 2.32 t/10^4 RMB in coastal China and from 8.71 to 3.73 t/10^4 RMB in inland China. In contrast, significant decreasing trends in TI were only discovered in about half of all provinces, including 9 from coastal China and 7 from inland China (Fig. 3 and Table S.15). Coastal China's ERCI values dropped on average from 1.07 t/10^4 RMB in 2003 to 0.59 t/10^4 RMB in 2012, whereas in inland China they went down from 1.34 to 0.83 t/10^4 RMB. Heretofore, it was detected that SI dominated the total ERCI

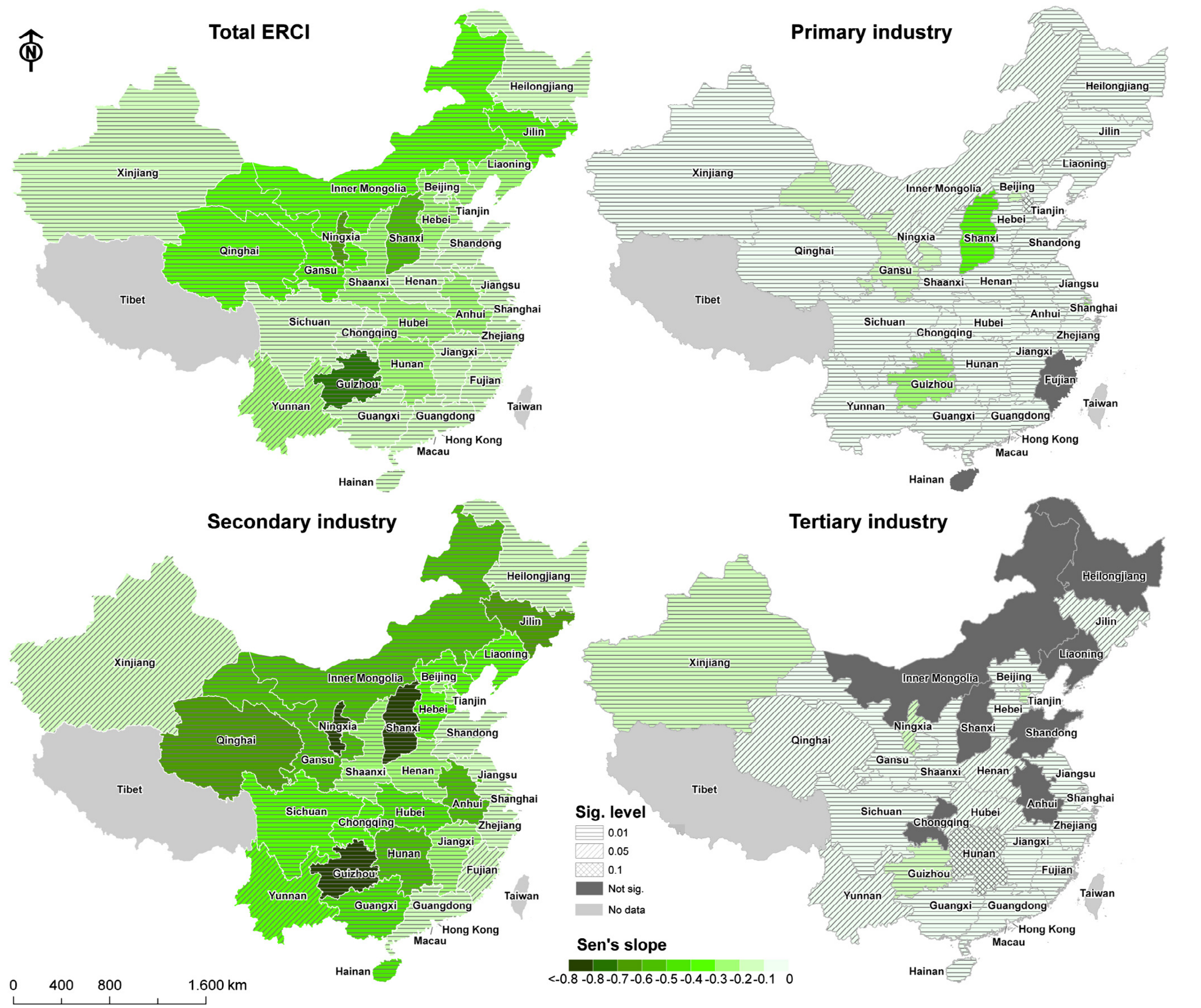

Fig. 3. Results of Mann-Kendall test and Sen's slope for China's provincial energy-related carbon intensity (ERCI, t/10^4 RMB) during 2003–2012. Data of total ERCI are available in Table S.12. Data for each industry are available in Tables S.13–S.15.

at both national and provincial scales. This is consistent with the fact that SI had the greatest share of both national and provincial ERCE, regardless of temporal changes (Supplementary results).

3.4. High correlation between WUI and ERCI in different industries

At the national scale, a significant positive correlation appeared between the total WUI and ERCI during 2003–2012 (Pearson's correlation coefficient $r = 0.9879$, $p < 0.001$) (Table S.16). Significant positive correlations were also detected between the WUI and ERCI in PI ($r = 0.9715$, $p < 0.001$), SI ($r = 0.9949$, $p < 0.001$), and TI ($r = 0.9742$, $p < 0.001$) respectively during this ten-year period (Table S.16).

At the provincial scale, significant positive correlations between the values of the total WUI and ERCI were apparent both in coastal and inland China ($p < 0.01$) (Fig. 4 and Table S.16). In contrast, the variability of the r values was quite high among different industries. Firstly, significant positive correlations in PI ($p < 0.01$) were found in 26 provinces, excluding Shandong, Fujian, and Hainan from coastal China as well as Ningxia (inland China) (Fig. 4 and Table S.16). Secondly, the correlations in SI ($p < 0.01$) were generally consistent with the national correlation, with Yunnan (inland China) being an exception (Fig. 4 and Table S.16). Thirdly, significant positive correlations in TI ($p < 0.01$) were only discovered in half of all provinces, where 6 and 9 provinces are located in coastal and inland China respectively, corresponding to those in which decreasing ERCI trends were observed (Fig. 4 and Table S.16).

As an additional analysis, both the WUI and ERCI are among the national indicators for policy-making targets of China's water and energy security, it is therefore of prime interest and importance to estimate their quantitative relationship. The total WUI was defined as independent variable in regression analysis (Fig. 1.S and Table 1). In comparison with the ERCI values (1.81 and 1.75 t/10^4 RMB by 2015 and 2020 respectively) calculated on the basis of China's national policy documents, the ERCI values (1.66 and 1.47 t/10^4 RMB by 2015 and 2020 respectively) simulated by regression analysis showed reasonable agreement (Fig. 1.S and Table 1). This provided additional verification that the total WUI and ERCI as China's national indicators for water and energy security had a significant positive correlation.

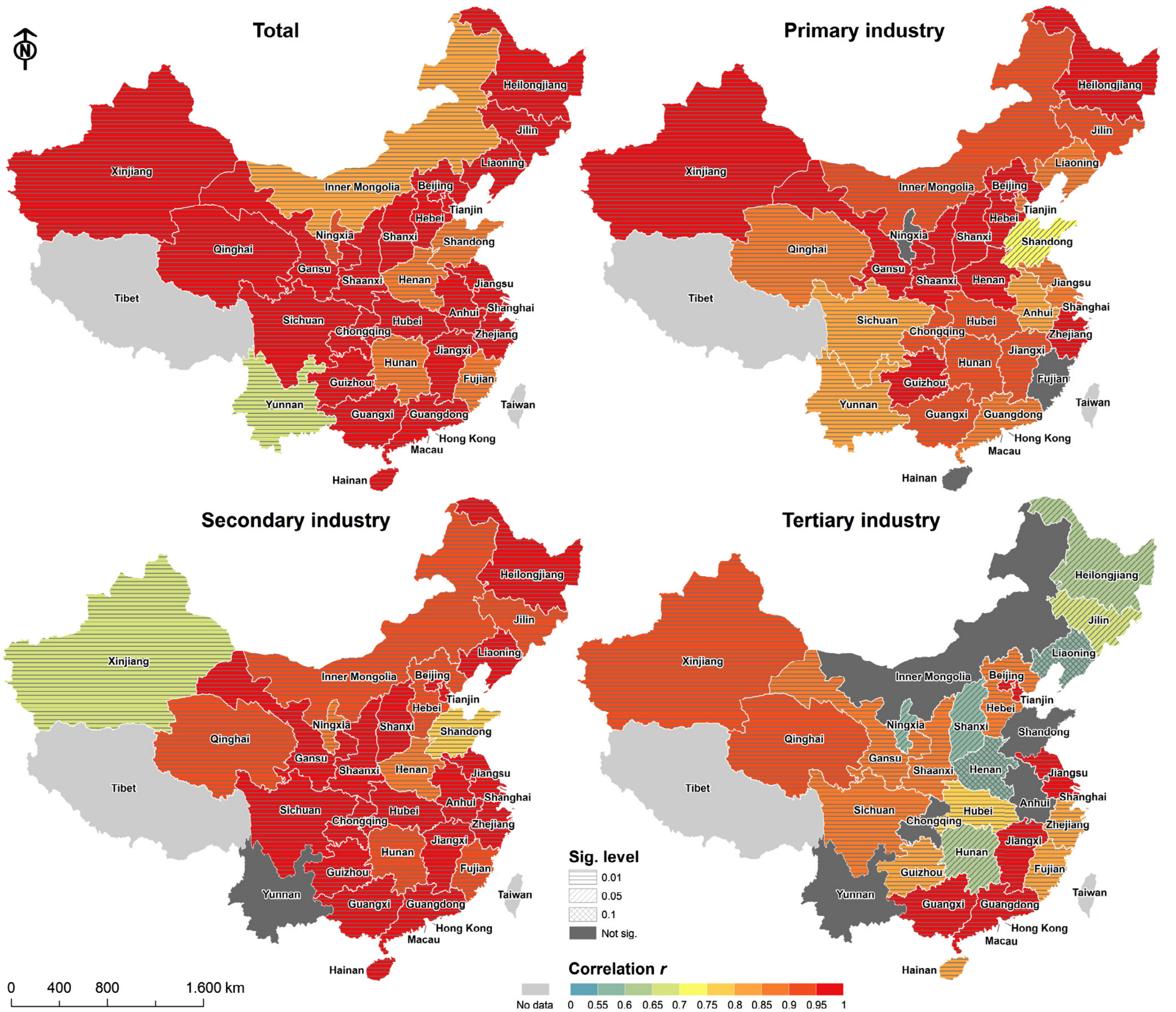

Fig. 4. Correlation coefficients (r) and their significance levels of total water use intensity (WUI) vs. total energy-related carbon intensity (ERCI) as well as WUI vs. ERCI in three industries during 2003–2012 for China's provinces.

Table 1
China's national policy-making targets for water use intensity (WUI) and energy-related carbon intensity (ERCI) in 2015, 2020, and 2030. (a) The ERCI values were taken from [38,39,41] for 2015 and 2020 (not available for 2030), corresponding to reductions of 17% from 2010 and 45% from 2005, respectively. (b) The ERCI values in 2015, 2020, and 2030 were estimated by the WUI values respectively in regression analysis (Fig. S.1).

Policy	Indicator	Timeline	Target	
Water security	WUI	2030	40 $m^3/10^4$ RMB [36]	
		2020	65 $m^3/10^4$ RMB [36]	
		2015	83 $m^3/10^4$ RMB [10,36]	
Energy security	ERCI	2030	–[a]	1.16 $t/10^4$ RMB[b]
		2020	1.75 $t/10^4$ RMB[a]	1.47 $t/10^4$ RMB[b]
		2015	1.81 $t/10^4$ RMB[a]	1.66 $t/10^4$ RMB[b]

4. Discussion

Our analysis showed strong evidence of the significant impacts of the industrial transition on the provincial WUI and ERCI over 2003–2012. Besides, the notable variation among provinces with regard to the transition and its impact on WUI and ERCI was clearly portrayed.

Due to the advantages of geographical location and national policy support, coastal China has greatly benefited from economic reform, so that its socioeconomic development, such as industry transition and per capita GNI, soared. In contrast, inland China severely lagged behind in moving away from PI. Accordingly, the trend in China's coastal provinces was from PI to SI and furthermore to TI. This redistribution of economic activities improved the WUI remarkably, and thus the efficiency of water use rose steeply. In the light of their total WUI values in 2012, 8 out of 11 provinces were ahead in accomplishing their national target; they exceeded the 2015 goal already by 2012, and some even achieved the 2020 or 2030 goals (Tables 1 and S.8). By the advance of several TI's sectors such as financial intermediation, information transmission, computer services, and software (Tables S.1 and S.8), they have boosted a more service-oriented green economy and higher-value-added industrial profile. This obviously helps in striving towards local sustainable water security in the long term. At the same time, inland China, which is less developed and has kept aiming to secure high economic growth by SI, generally had the greater WU share in PI than coastal China. The pertinent dominance of PI and its disproportionally low GDP generation for the high WU share was the critical reason why the total WUI lagged badly behind in most of inland China.

Given the fact that coal has dominated the energy consumption structure for a long time to fuel China's economic growth, the ERCE in SI should remain the primary driving factor determining the total ERCI at both national and provincial scales in the few coming decades [38,39,55]. However, for some more developed provinces like Beijing and Shanghai, the reductions of the SI's ERCE share were redistributed to the share in TI, alleviating the total ERCI markedly (Tables S.23 and S.24). On the basis of their values in 2012, 72.7% provinces of coastal China accomplished the national target by 2020 in advance, whereas only 10.5% provinces of inland China achieved the goal by 2015 (Tables 1 and S.12). Our results thereby indicated a huge gap of the ERCI levels between coastal and inland China.

During our study period, China's policy-making on either adjusting industrial structure or improving water and energy security were in general isolated from each other, because an appropriate way to balance the trade-offs of its water-energy trilemma has not yet been available. As a consequence, the industrial transition has not yet yielded an efficient and coordinated relaxation of WUI and ERCI, and the national reducing WUI and ERCI targets have not been updated adequately as the industrial transition progressed. Heretofore, it is critical to improve policy integration related to industrial transition, water and energy security, as well as environmental sustainability.

Owing to the fact that China has been intending to steer its economy toward a more sustainable growth mode, featuring slower but higher quality, service-sector driven growth, it would be rational to consider sustainable economic competitiveness as the priority in addressing China's water-energy trilemma, in coordination with sustainable water and energy security at the forefront. Our results showed that the industrial structure changes had quite significant impacts on the WUI and ERCI. Consequently, the core of the policy-making should be shifted to accelerating the ongoing transition. In particular more attention should be paid to enhance policies on the industrial transition in order to efficiently, in a coordinated manner, alleviate WUI and ERCI. For instance, in the light of China's national policies for the most stringent water resources management, effective irrigation ratio has been listed as one of three "redlines" with specific targets by 2015, 2020, and 2030 [7,10,35–37]. The measures to fulfill this goal are expected to be targeted to the development of irrigation schemes and water-saving irrigation technologies for enhancing crop water productivity [10,79]. Another of the straightforward measures is to take initiatives, like *Made in China 2025* [80], for upgrading the manufacturing industry. Pushing strongly forward and even accelerating the innovation-driven transformation on agricultural modernization, would help improve the nationwide WUI of PI.

The imbalance of socioeconomic development and the variability within the industrial transition among China's provinces stems from their geographical and socioeconomic heterogeneity. So it would be of prime importance and necessity to encourage flexibility in making and implementing national policies, which would be custom tailored to local circumstances. For example, the newly released action plans by the State Council of China, namely *Made in China 2025* [80] and *Internet Plus* [81], emphasize the priorities in SI and TI respectively. Being in line with pursuing sustainable economic competitiveness, inland China could turn the overall industrial transition into the specific sectoral transition in SI to decrease its WUI and ERCI, by focusing on the upgrading of the manufacturing industry. On the other hand, coastal China as a more developed region could route the industrial structure changes from one-directional toward more comprehensive development. It has been evidently illustrated based on the aim of *Internet Plus* [81] and embodied new features. Coastal China could integrate the Internet such as mobile Internet, cloud computing, and big data with traditional industries, including manufacturing, agriculture, and energy, as well as create a new engine for China's economic growth by 2025 [81].

Policy-making is a dynamic process and its effects ought to be reviewed regularly in order to ensure the adequacy of any follow-up procedures. According to our results, a number of provinces in 2012 accomplished reducing national WUI and/or ERCI targets by 2015, 2020, or even 2030 in advance. This is a very promising achievement, and it should be better taken into account to schedule the renewal of the national targets in China's 14th Five-Year Plan and other long-term action plans. Furthermore, our results demonstrated that the total WUI and ERCI as national indicators for policy-making targets portrayed a significant positive correlation. Hence, it would be highly useful and advisable to synchronize these two national targets in every stage of the timeline in order to contribute most to China's water and energy security. Furthermore, it would be advisable to extend the policy setting from supply-side factors such as those indicated by WUI and ERCI to include also the demand side.

5. Conclusions

We conducted, for the first time, an integrated and quantitative spatio-temporal analysis of the impacts of China's industrial transition on two national indicators for policy-making targets of its water and energy security, namely water use intensity and energy-related carbon intensity. Our study, conducted over the period 2003–2012, demonstrated strong evidence of the significant impacts of the industrial transition on water use intensity and energy-related carbon intensity and its highlights can be portrayed as follows: (1) Primary industry appeared to dominate the water use intensity although its relative share decreased, and the water use intensity of primary industry continued to be far higher than that of secondary and tertiary industries; (2) secondary industry dominated in affecting the total energy-related carbon intensity at both national and provincial scales; and (3) the total water use intensity and energy-related carbon intensity had a significant positive correlation.

This consequently led to our policy-making recommendations. On one hand, policy-making, industrial transition, back to back with water and energy security are deeply intertwined in the context of China's socioeconomic development. This underlines the crucial importance of better understanding their interlinkages and interdependencies in order to lead China out of its water-energy trilemma. On the other hand, only customized policy-making along with its corresponding measures is able to advance and deepen the national and provincial industrial transition for sustainable economic competitiveness, and also tackle the bottlenecks of alleviating the national and provincial water use intensity and energy-related carbon intensity for sustainable water and energy security. Furthermore, the significant positive correlation between the total water use intensity and energy-related carbon intensity has given some useful and advisable insights into the next step in policy target setting. It would be to not only synchronize these two national targets in every stage of the timeline in order to contribute most to China's water and energy security, but also extend water use intensity and energy-related carbon intensity towards turning the tide away from the still growing total volume of water use and energy-related CO_2 emissions.

Acknowledgements

This study was funded by Aalto University. Special thanks go to Dr. Joseph Guillaume for his proofreading. The thorough and insightful comments of editors and anonymous reviewers are greatly appreciated.

Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.apenergy.2016.09.069.

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