Official Journal of the World Water Council
Water Policy

Water Policy Vol 24 No 2, 345 doi: 10.2166/wp.2022.182

An analysis of the relationship between water-energy-food system and economic growth in China based on ecological footprint measurement

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ABSTRACT

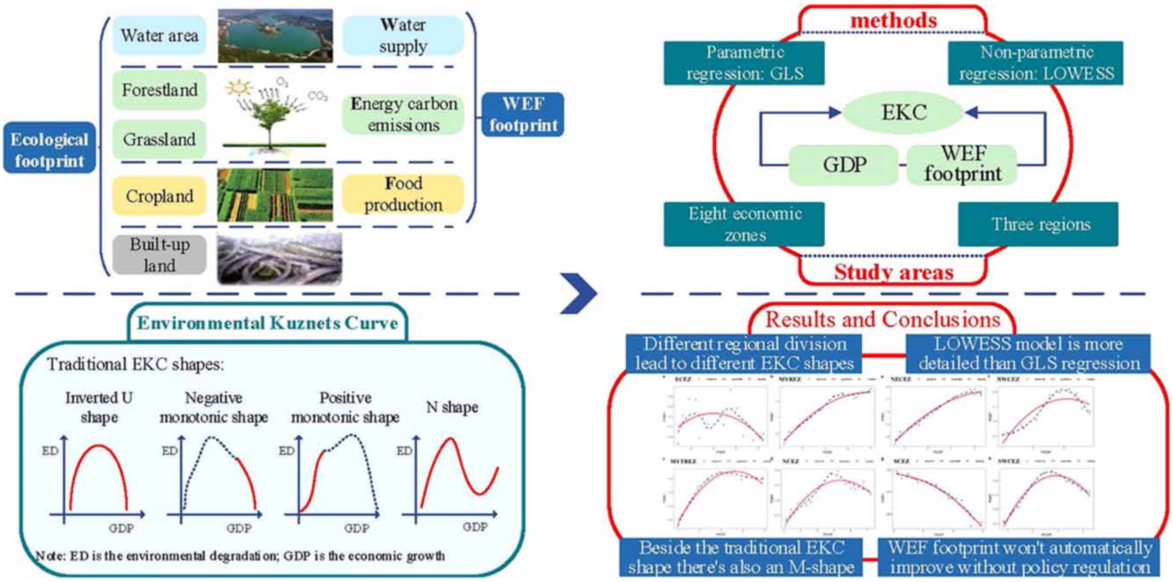
With the acceleration of urbanization, the demand for water, energy and food (WEF) keeps increasing. However, the infrastructure construction leads to a sharp decline of cultivated land, water area and forest land, so the importance of ecological space management should be recognized. Based on ecological footprint theory, this paper proposes the WEF footprint and first attempts to explicitly examine the relationship between economic growth and WEF footprint by investigating the existence of an Environmental Kuznets Curve (EKC). GLS regression and the LOWESS model are used to explore the economic growth and WEF footprint nexus in the eight economic zones and the three regions of China. The results indicate that besides the traditional EKC shapes, an M-shape exists, and the proportion of the M-shape curve (12.5%) is lower than the traditional EKC (87.5%). The results showed that the LOWESS model may be more conducive to reflect the real relationship between economic growth and WEF footprint. According to the analysis, the policy suggestions are put forward to promote the sustainable development of the water-energy-food system. In addition, the study can provide some ideas for solving the contradiction of land use.

Key words: Ecological footprint, Eight economic zones, EKC hypothesis, National resource, Three regions, Water-energy-food system

HIGHLIGHTS

- Using ecological footprint measurement to study water-energy-food system.
- EKC hypothesis is used to investigate the relationship between the WEF footprint and economic growth, and policy suggestions are further put forward.
- LOWESS model and GLS regression are both introduced to test the EKC hypothesis.

GRAPHICAL ABSTRACT



1. INTRODUCTION

Water, energy, and food are important resources in meeting people's basic living needs and sustaining worldwide economic development, which are inextricably interrelated and interdependent. Many scholars regard water-energy-food (WEF) as a system (Bazilian *et al.*, 2011; Dubreuil *et al.*, 2013; Zhang & Vesselinov, 2017). With the rapid growth of the world economy, the demand for natural resources keeps rising, and it is expected that by 2030, the global demand for water, energy and food will increase by 30, 50, and 50%, respectively (Chen *et al.*, 2020). However, water, energy, and food supply will face severe challenges due to the competition for land use (Haber, 2007). Sustaining food production, freshwater supply, and energy carbon emissions also undermine the capacity of ecosystems inevitably (Foley *et al.*, 2005). As the largest developing country globally, China continues to increase the built-up land for infrastructures such as housing, industry, and transportation, which would lead to a sharp decline in cultivated land, water area, and forestland (Xie *et al.*, 2018). Wackernagel & Galli (2012) proposed that the biological production areas, such as cultivated land, water area and forestland, can be measured by ecological footprint. Hassan *et al.* (2019) and Mikkelson (2021) discovered that economic growth increases the ecological footprint with the environmental degradation. Khan (2017) and Ahmed *et al.* (2021) proposed the EKC relationship between ecological footprint and income in Pakistan and Japan, respectively. Ulucak *et al.* (2022) pointed out that the human capital accumulation is the unique driver of economic growth, which is useful to reduce the ecological footprint. Harris (2019) proposed a new approach rather than the ecological footprint to measuring ecological deficits. Based on the above studies of economy and ecological footprint, we further study the relationship between Chinese economic development and ecological footprint of water-energy-food system.

The ecological footprint was first put forward by Rees & Wackernagel (1996). In their research, the land is a carrier of natural ecological space and is, therefore, inseparable from all human activities. The nature of ecological footprint is the aggregation of productive land and water area occupied by specific human activities (Ferng, 2001). The ecological footprint monitors the stress of human activities on nature by calculating the occupation of productive land (Rees & Wackernagel, 1996). The most current researches on ecological footprint are mainly focused on single resource footprint (Stöglehner, 2003; Hoekstra, 2009), water-food footprint (Vanham & Bidoglio, 2013; Chini *et al.*, 2017; Marston *et al.*, 2018), and water-energy footprint (Xu *et al.*, 2019a, 2019b). As mentioned above, water, energy and food is a holistic system. In this regard, we further propose the ecological footprint of the water-energy-food system. The ecological footprint of the water-energy-food system (WEF footprint) can be used to calculate the occupation of productive areas by water, energy, and food based on ecological footprint theory, such as (1) the water area with the function of storing and supplying fresh water for all water consumption in production activities, services, and daily life (Huang *et al.*, 2008); (2) the forest land and grassland required for absorbing carbon dioxide emissions from energy consumption (Fang *et al.*, 2007); (3) the cultivated land required for all food production (Figure 1).

Environmental Kuznets Curve (EKC) hypothesis originated from Kuznets' seminal study (1955), claims that there exists an inverted U-shaped relationship between economic growth and environmental degradation. The inverted U-shaped curve means that environmental quality deteriorates in the initial stages of economic growth and improves in the later stages of economic growth. This means that environmental degradation rises first and then falls as the economy grows. Most of the studies in the literature generally use CO_2 emissions as environmental degradation to investigate the EKC hypothesis (Kaika & Zervas, 2013a; Fujii & Managi, 2016; Shi *et al.*, 2018). However, CO_2 emissions can only represent the impact of energy consumption on the environment rather than the overall environmental degradation (Charfeddine & Mrabet, 2017; Ulucak & Bilgili, 2018). The ecological footprint indicator is a more comprehensive measure of environmental degradation (McDonald & Patterson, 2004; Borucke *et al.*, 2013) as it refers to the consumption of the environment demanded by people and monitors the stress of human activities on nature. Recent studies confirmed the EKC hypothesis and found that there is an 'inverted U' shaped curve between the ecological footprint and economic growth (Kaika & Zervas, 2013b; Charfeddine, 2017; Ulucak & Lin, 2017; Dogan *et al.*, 2020).

In the current researches of the ecological footprint, the EKC hypothesis is commonly tested by the parameter estimation method of the ordinary regression, such as the GLS regression (Charfeddine & Mrabet, 2017). GLS regression generally supposes that there exists a specific functional form, and the function coefficients are estimated using statistical methods. However, non-parametric or semi-parametric models may be more robust

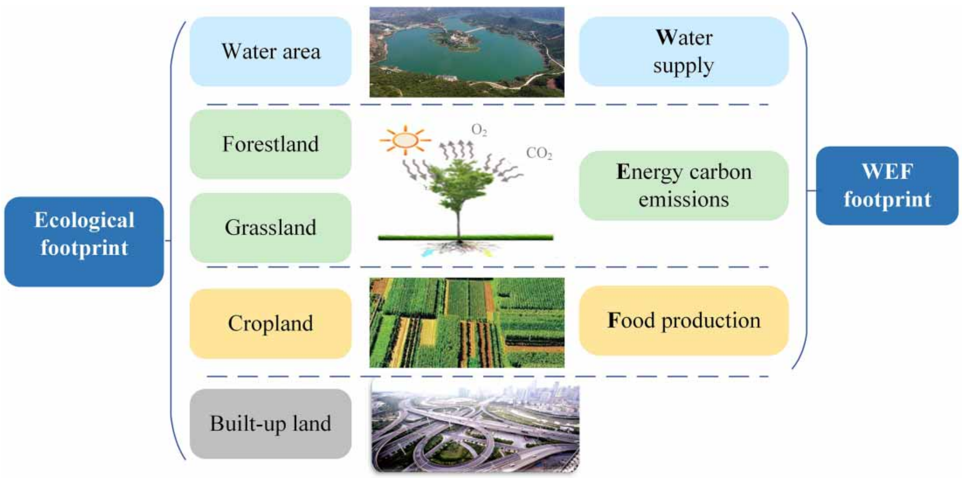


Fig. 1 | The ecological footprint and the WEF footprint.

than GLS regression which may deviate from reality under the condition of no specific functional form (Millimet *et al.*, 2003; Paudel *et al.*, 2005). LOWESS model, one of the most common non-parametric estimation models, does not require a specific function form. It estimates the relationship between dependent variables and independent variables through a best-fit curve, considering all local scattered points. Cai *et al.* (2020) and Lawell *et al.* (2018) used a non-parametric estimation model (LOWESS) to analyze the EKC relationship between water pollution and economic growth. However, the LOWESS model cannot analyze the panel data theoretically. Therefore, in this paper, the LOWESS model and GLS regression are both introduced to better analyze the EKC relationship between the WEF footprint and economic growth.

Although former studies had put forward the concept of the natural resource footprint based on the ecological footprint theory and used it to test the EKC hypothesis, which are only preliminary conceptual researches using simple GLS regression analysis (Ulucak & Bilgili, 2018). These researches only focus on one or two resources rather than the WEF system holistically. In this paper, we regard the water, energy, and food as a whole system and put forward the concept of WEF footprint. GLS regression and the LOWESS model are used to analyze the EKC relationship between Chinese WEF footprint and economic growth. The LOWESS model may be more conducive to reflecting the detail of the real relationship between the economic growth and WEF footprint. Through the detailed analysis of the results, we put forward some valuable policy suggestions to promote the sustainable development of the water-energy-food system of China. Therefore, this work is important and meaningful for regulating water-energy-food security in China, promoting the construction of ecological civilization and realizing sustainable development.

2. DATA AND METHODS

2.1. Study area and data

The area in our study covers 31 provinces in China. Hong Kong, Macao, and Taiwan are not considered because the data cannot be fully obtained. The 31 provinces in mainland China can be divided into either the eight economic zones (Figure 2) or the three regions (Figure 3) based on the suggestion of the Department of Development Strategy in the Development Research Center of the State Council in the People's Republic of China.

In Figure 2, the eight economic zones, including the Eastern Coastal Economic Zone (ECEZ), the Southern Coastal Economic Zone (SCEZ), the Northern Coastal Economic Zone (NCEZ), the Northeastern Comprehensive Economic Zone (NECEZ), the Middle Yellow River Economic Zone (MYREZ), the Middle Yangtze River Economic Zone (MYTREZ), the Northwestern Comprehensive Economic Zone (NWCEZ) and the Southwestern Comprehensive Economic Zone (SWCEZ), are developing unevenly. The ECEZ, SCEZ and NCEZ belong to economically developed regions. Commonly, their GDP has long been accounted for more than half of the overall GDP of the whole country with the advantages of superior natural conditions, a high level of science and technology, and good infrastructure. Followed by the NECEZ, MYTREZ and MYREZ, the level of economic development is inferior to the three coastal areas. In addition, the SWCEZ and NWCEZ have always been the regions with the lowest GDP for many years due to the lack of infrastructure and the backward level of science and technology. The three regions (Figure 3), namely the eastern, the central and the western, respectively represent the economically developed region, the sub-developed region and the undeveloped region. Although the three regions are different from the eight economic zones, there exists a corresponding relationship among them geographically.

Taking the eight economic zones and three regions as the research objects, we can compare the differences in the results caused by different regional divisions. In addition, we can further observe the changes in the WEF footprint with the economic growth since these regions represent different levels of economic development.

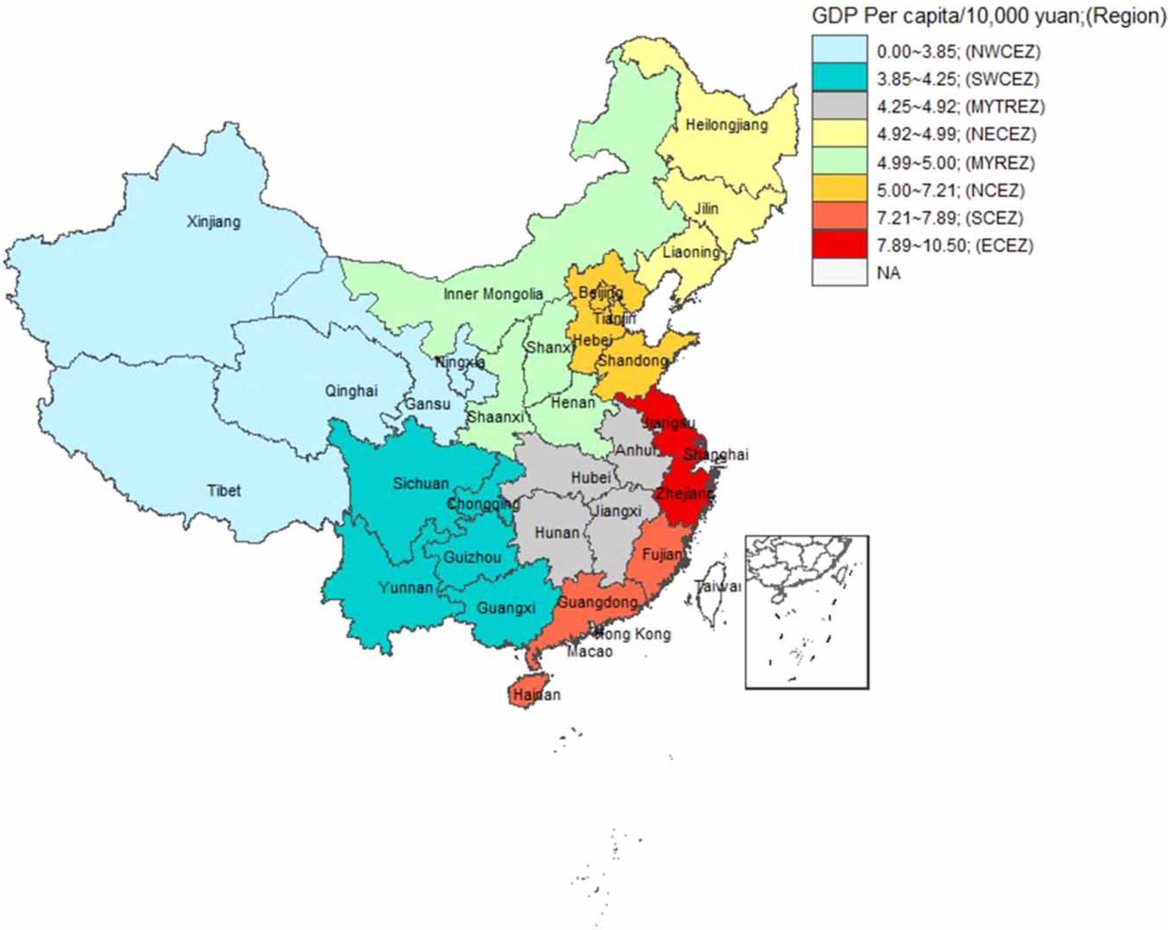


Fig. 2 | Eight economic zones in China and their member provinces.

The data of water use, GDP and population are obtained from China Statistical Yearbooks (Statistics, 2005–2017c). We get the data on energy use from China Energy Statistics Yearbook (Statistics, 2005–2017a). In addition, the data of cultivated land used as a proxy for food consumption is achieved from China Rural Statistical Yearbook (Statistics, 2005–2017b). The datasets of the WEF footprint include the cross-sectional data of the eight economic zones and the panel data of the three regions, which are both based on the estimation from 2005 to 2017.

According to Huang *et al.* (2008), the water footprint is defined as the water area with the function of storing and supplying fresh water in accordance with the calculation of production, domestic and ecological water use. In the consumption of food products, the occupation of cultivated land includes the land needed for the production of grains, legumes and potatoes. The ecological occupation of energy, that is, energy footprint, includes the demand for land to sequestrate carbon emitted from coal, crude oil, coke, gasoline, kerosene, diesel, fuel oil, natural gas and other energy consumptions. Since there is no direct statistics on carbon dioxide emissions of various energy categories, we calculate carbon dioxide emissions by using the method proposed by IPCC (2006). The equivalence factor of the ecologically productive area is obtained from the World Wildlife Fund (WWF). In each year, the average carbon sequestration capacity of woodland and grassland were 41 t/ha and 3.46 t/ha,

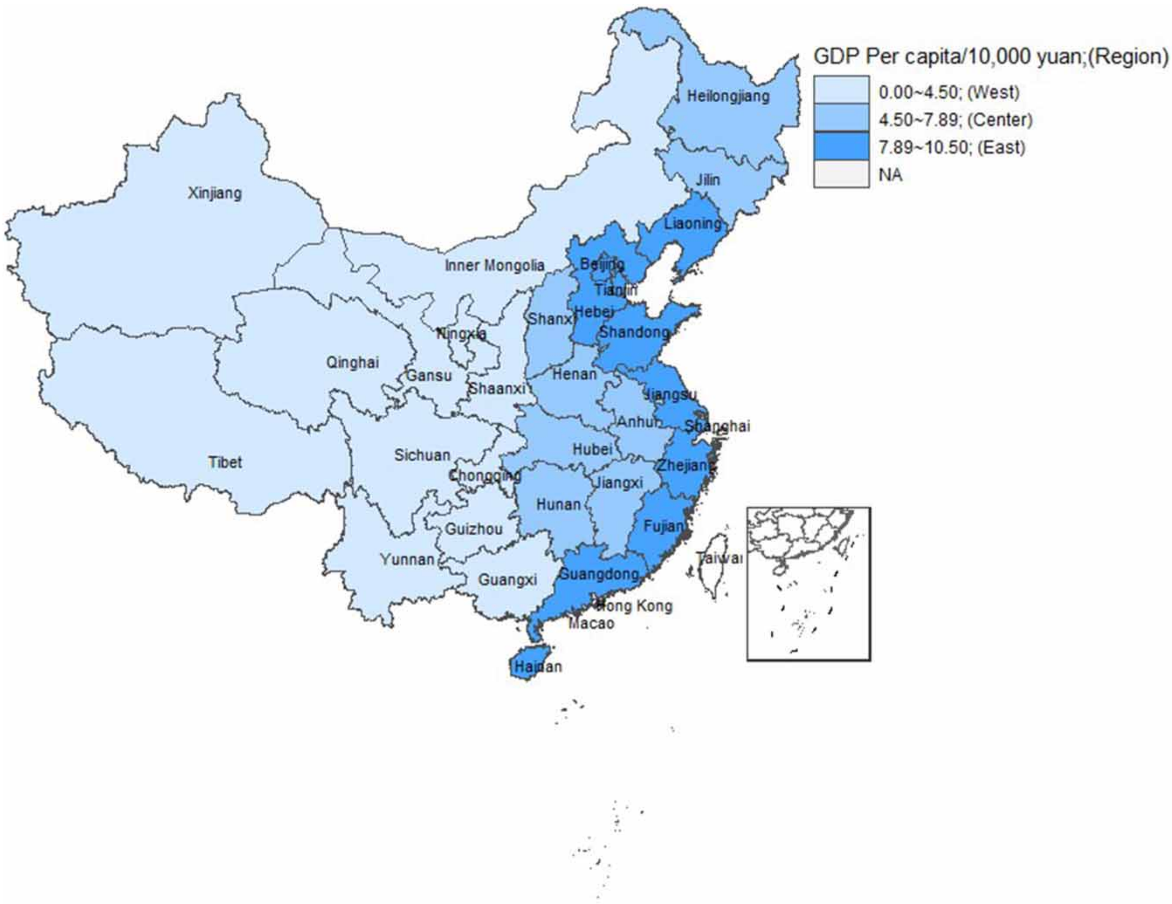


Fig. 3 | Three regions and their member provinces.

respectively, and the carbon sequestration capacity of cultivated land was not significant and usually set to zero (Fang *et al.*, 2007). Considering the area of woodland and grassland, the energy ecological footprint is converted into 93% of woodland and 7% of grassland for carbon sequestration in this paper.

2.2. Quantification of ecological footprint

Ecological footprint, also known as 'ecological occupation', represents the demand for ecological space occupied by specific human activities. These activities include the production and consumption of various goods and services by a particular group of people in a certain period. Specifically, the ecological footprint can be calculated based on the idea that natural resource consumption and pollutant emissions can be converted into geographical space. And then estimating the geographical space occupied by human beings to maintain their own survival (Xiong & Li, 2019). The primary method in the study can be expressed as Equation (1):

$$EF_{mz} = H_z \cdot \sum\nolimits_w (k_{mz} \cdot Q_{mz}/p_{mz}) \tag{1}$$

where EF is the ecological footprint, H is the population, z is the region, w is the type of consumption project, m is the type of production land, Q is the level of per capita consumption, the parameter p is the annual average productivity of the land (kg/ha) and k is a factor converting different types of productive land into uniform and comparable production areas with equal productivity.

2.3. Parametric regression

This study constructs a simplified model regarding the GDP per capita as the explanatory variable, which tests the correlations between variables rather than the corresponding causation (Katz, 2015). In this study, the generalized least squares (GLS) regression is introduced to analyze both the panel data and the cross-sectional data. We selected the panel data to analyze since it can account for the strong heteroscedasticity in the data. The panel data also contain both cross-section data and time-series information and reflect the characteristics and changing rules of variables in time and space. However, it is inappropriate to utilize the non-parametric method described in the next subsection to analyze the panel data in theory. Therefore, the cross-sectional data is introduced to address the limitation. In addition, in order to maintain the economic significance of the estimation coefficient, the per capita form of the WEF footprint is chosen as the dependent variable in this study rather than the logarithmic form of the WEF footprint.

We construct the EKC model including the gross domestic product (GDP) of the constant prices to observe economic growth. The model can be expressed as Equation (2):

$$PWEF_{it} = \beta_0 + \beta_1 PGDP_{it} + \beta_2 PGDP_{it}^2 + \beta_3 PGDP_{it}^3 + \varepsilon_{it} \tag{2}$$

where *PWEF* is the WEF footprint per capita, *PGDP* is the GDP per capita, ε represents the error term, the subscript i and $\beta = [\beta_0, \beta_1, \beta_2, \beta_3]$ represent the region and the estimated parameters respectively. The national level, the eight economic zones and the three regions all take the per capita WEF footprint (PWEF) as a dependent variable for regression estimation.

2.4. Non-parametric regression

Parametric models generally suppose that there exists a specific functional form, and the function coefficients are estimated using statistical methods. Some scholars hold the opinion that non-parametric or semi-parametric models may be more robust than parametric models under the condition of the misspecification of functional forms (Millimet *et al.*, 2003; Paudel *et al.*, 2005). Unlike parametric estimation, non-parametric regression does not require a specific functional form. It estimates the relationship between dependent variables and independent variables through a best-fit curve. The LOWESS (locally weighted scatterplot smoothing) adopted in this paper widely used the non-parametric regression method developed by Cleveland in 1979.

The LOWESS method can solve the smoothing problem very well (Montgomery *et al.*, 2012). The basic idea of the LOWESS model is described as: for the observation (Y_i, X_i) in the sample sequence, regarding Y and the data in the adjacent range of X_i as the dependent variable and independent variable of the regression model, respectively, and taking the fitting value about X_i of the regression equation as the smooth value Y_i^s of Y_i. Finally, the smooth fitting curve is obtained by repeating the above process until each pair (Y_i, X_i) is regressed. Considering that the observations far away from X_i make little contribution to smoothing Y_i, the cubic weighting function is commonly used as the weighting function, and the cubic weight function is written as follows (Montgomery *et al.*, 2012):

$$W_{(t)} = \begin{cases} (1-t^3)^3 & 0 \le t < 1 \\ 0 & \text{otherwise} \end{cases} \tag{3}$$

The weights are estimated after the normalization of the distances on a targeted value (Equation (4)):

$$W\left(\frac{|x_0 - x_j|}{\Delta(x_0)}\right)$$
$$W(\mathrm{t}) \tag{4}$$

where x_0 is a particular point of interest, x_j is the point in the certain adjacent range, $\Delta(x_0)$ is the distance between the farthest point in the adjacent range and x_0, $W(\mathrm{t})$ is the cubic weighting function.

3. RESULTS

3.1. The EKC validation in eight economic zones

The GLS regression and the LOWESS model were carried out on the data of 31 provinces. Table 1 shows the results of the GLS regressions; Figure 4 shows the quadric curve from GLS regression and lowess curve from the LOWESS model in each economic zone.

The GLS regression results for the eight economic zones except the ECEZ are consistent, because the quadratic form is significant at the 5% level and the quadratic coefficient is negative (Table 1). The EKC relationship verifies the existence of an inverted U-shaped curve for each economic zone. There are four situations under the GLS regressions: first, the linear form and quadratic form are significant at the 5% level, the cubic form is not significant, and the R-squared values for the linear form are lower than the quadratic form. Consequently, the PWEF increases first and then decreases with the increase of PGDP, and shows an inverted U-shaped curve in the economic zones of MYREZ, NCEZ, NECEZ, SCEZ, and SWCEZ. Revisiting the GLS regression results of MYREZ, NECEZ and SCEZ, the R-squared value in linear form, is slightly lower than the respective R-squared value in quadratic form. Nevertheless, the quadratic form of these three economic zones is significant at the levels of 0.05%, 0.5 and 4%, respectively, while the linear form is significant at the 0.0002% level. All of these indicate that the PWEF demonstrates a monotonic curve with the increase of PGDP, which implies that the inverted U-shaped curve may have not reached or has passed the turning point; second, sometimes (e.g., in MYTREZ), the linear form, quadratic form and cubic form are all significant at the 1% level, and the quadratic form has the lowest level of significance, which supports that the PWEF increases first and then decreases with the growth of PGDP, and shows an inverted U-shaped curve again; third, in some cases (e.g., in NWCEZ), the linear form, quadratic form and cubic form are all significant at the 1% level, and the R-squared values for the cubic form is the highest, which means that with the growth of PGDP, the PWEF keep stable and even begin to increase slightly after an initial decline; fourth, specifically in ECEZ, the linear form, quadratic form and cubic form are not significant, which indicate that there is no apparent relationship between PWEF and PGDP under GLS regression in this situation.

The GLS results seem to support the existence of the EKC hypothesis and the inverted U-shaped relationship between PWEF and PGDP reasonably. However, the reliability of such a conclusion will be questioned when GLS results are compared with the results obtained from non-parametric regression.

In Figure 4, the GLS regression and the LOWESS model are both utilized to display the relationship between PWEF and PGDP. There are three situations under the two models: first, the difference in the shape of the curve in the same economic zone, such as ECEZ. In ECEZ, the PWEF increases first and then decreases with the increase of PGDP under the GLS regression, showing an inverted U-shape curve. While under the LOWESS model, the relationship between PWEF and PGDP exhibits an M-shaped curve, which has never previously been observed in EKC studies. It reflects that the PWEF fluctuations in different stages of the PGDP in ECEZ; second, there

Table 1 | GLS regression: WEF footprint (PWEF) per capita of eight economic zones.

Independent variable	Linear	Quadratic	Cubic	Linear	Quadratic	Cubic	Linear	Quadratic	Cubic	Linear	Quadratic	Cubic
	ECEZ			MYREZ			MYTREZ			NCEZ		
Constant	1.32***	1.27***	1.24***	0.9***	0.73***	0.71***	1.06***	0.88***	0.75***	0.86***	0.71***	0.74***
	(0.02)	(0.04)	(0.13)	(0.03)	(0.04)	(0.1)	(0.03)	(0.02)	(0.04)	(0.02)	(0.03)	(0.11)
GDP	−0.001	0.02	0.03	0.08***	0.22***	0.23*	0.04***	0.2***	0.37***	0.01***	0.09***	0.06
	(0)	(0.01)	(0.07)	(0.01)	(0.03)	(0.11)	(0.01)	(0.02)	(0.05)	(0)	(0.02)	(0.08)
GDP^2		−0.002	0.00		−0.02***	−0.03		−0.03***	−0.09***		−0.01***	0.00
		(0)	(0.01)		(0)	(0.04)		(0)	(0.02)		(0)	(0.02)
GDP^3			0.00			0.00			0.01***			0.00
			(0)			(0)			(0)			(0)
R-squared	0.03	0.21	0.21	0.91	0.98	0.98	0.63	0.96	0.98	0.48	0.82	0.83
F-statistic	0.29	1.29	0.79	113.91	199.23	119.79	18.58	106.53	163.79	9.99	23.53	147.54
	0.6	0.32	0.53	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00
	NECEZ			NWCEZ			SCEZ			SWCEZ		
Constant	1.23***	0.99***	1.27***	2.43***	2.1***	2.91***	1.1***	1.04***	1.04***	0.88***	0.77***	0.78***
	(0.03)	(0.07)	(0.2)	(0.05)	(0.12)	(0.17)	(0.01)	(0.03)	(0.09)	(0.02)	(0.02)	(0.04)
GDP	0.11***	0.27***	−0.02	0.1***	0.42***	−0.81***	−0.02***	0.01	0.00	0.02***	0.14***	0.12*
	(0.01)	(0.05)	(0.2)	(0.02)	(0.11)	(0.25)	(0)	(0.01)	(0.06)	(0.01)	(0.02)	(0.07)
GDP^2		−0.02***	0.07		−0.07**	0.49***		−0.003**	0.00		−0.02***	−0.02
		(0.01)	(0.06)		(0.02)	(0.11)		(0)	(0.01)		(0)	(0.03)
GDP^3			−0.01			−0.08***			0.00			0.00
			(0.01)			(0.01)			(0)			(0)
R-squared	0.94	0.97	0.98	0.66	0.82	0.95	0.89	0.93	0.93	0.49	0.92	0.92
F-statistic	178.11	194.35	147.54	21.7	22.19	61.44	86.3	63.85	38.32	10.64	54.53	32.87
	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00

Note: Coefficient results are presented with robust standard errors in parenthesis. The symbols *, **, *** represent statistical significance at the 10, 5, and 1% levels respectively.

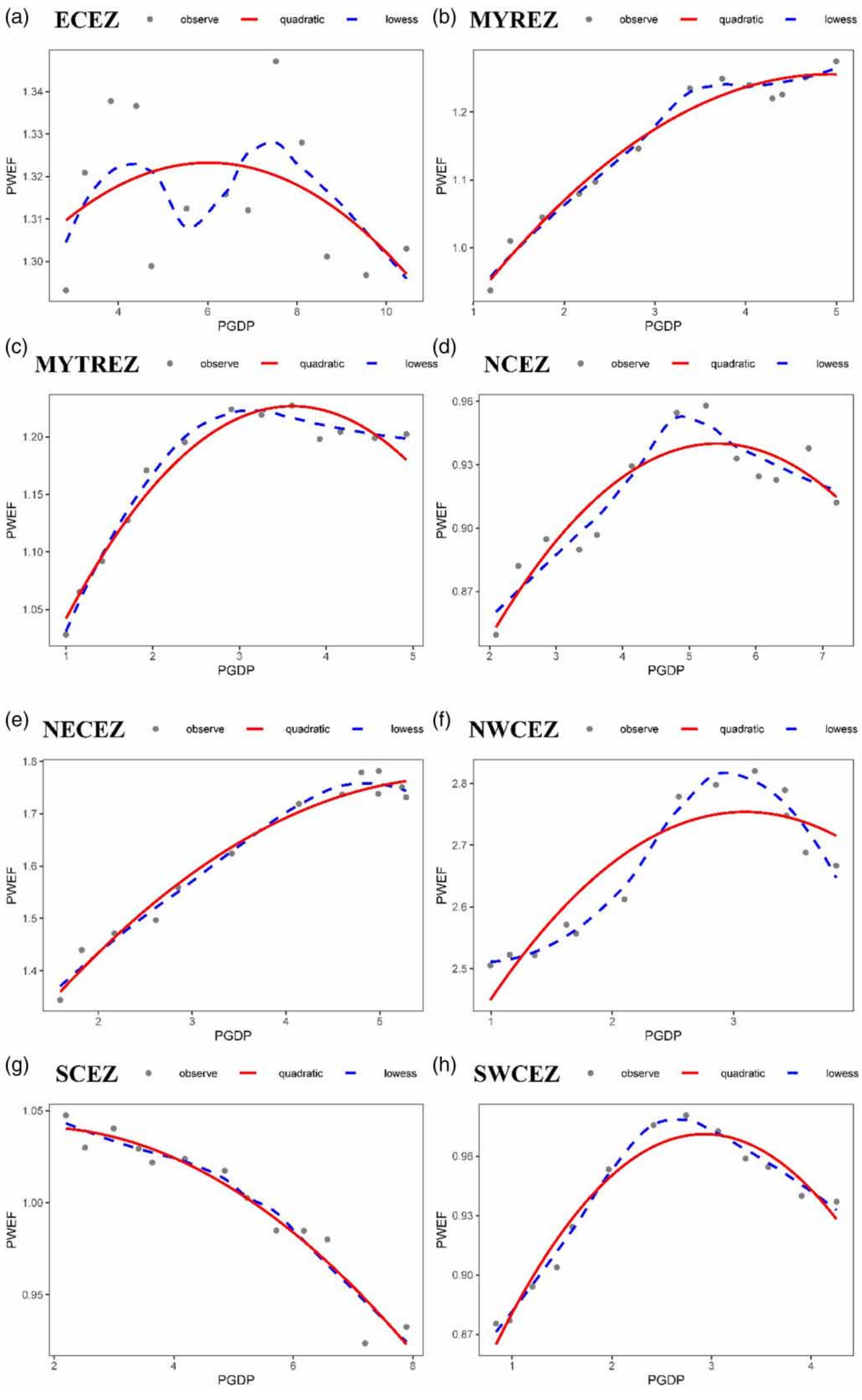


Fig. 4 | Validation of EKC relationship between PWEF and PGDP under GLS regression and LOWESS model.

exists the same EKC shape with a different turning point in the same economic zone, such as MYTREZ, NCEZ, NWCEZ and SWCEZ. In these regions, the PWEF increases first and then decreases with the increase of PGDP under the GLS regression and LOWESS model, showing the same EKC shape of an inverted U-shape with different turning points. In MYTREZ, the turning point of the quadratic curve is on the right side of the lowess curve. While in the other three regions, the turning point of the quadratic curve is lower than the lowess curve, which indicates that with the increase of PGDP, the actual turning point of PWEF is higher than that of the quadratic curve; third, there exist the similar curve shape in the same economic zone with no obvious turning point, such as MYREZ, NECEZ and SCEZ. In MYREZ and NECEZ, the PWEF fluctuates in a small range and presents a steady monotonically increasing trend with the PGDP increase under the LOWESS model, while under the GLS regression, the PWEF increases first with the increase of PGDP and then decreases after reaching the turning point. In addition, the PWEF decreases in SCEZ with the increase of PGDP, showing a negative monotonic shape with no obvious turning point under the LOWESS model, while under the GLS regression, the PWEF decreases in SCEZ with the increase of PGDP, showing an inverted U-shape and the turning point has passed.

After continuous and in-depth development, the traditional EKC has been expanded from an inverted U-shape curve to a negative monotonic shape curve, positive monotonic shape curve and N-shape curve. According to the above analysis, although traditional parametric regressions find some evidence of an EKC, these results are not confirmed by the non-parametric test theoretically. The results from the traditional statistical analysis may simply be a result of the functional form used in the regressions and would not adequately illustrate the relationship between the PWEF and PGDP. The non-parametric test represented by the LOWESS model demonstrates various curves of the relationship between the PWEF and PGDP. Besides the traditional EKC, there is also an M-shaped curve. Al-Mulali *et al*. (2016) and Pal & Mitra (2017) proposed that the hypothesis of EKC is not sufficient in many cases. According to the analysis, we verify the insufficiency of the EKC hypothesis in demonstrating the relationship between the PWEF and PGDP similarly. This analysis suggests that although many economic zones may have such an EKC, not all eight economic zones have such curves.

3.2. The EKC validation in three regions

Although the cross-sectional data can be analyzed by GLS regression and the LOWESS model, there is the potential weakness that the cross-sectional data cannot demonstrate the trend over a period of time compared with the panel data.

Descriptive statistics for the whole country and the three regions are provided in Table 2. It can be seen from Table 3, the GLS regression results of the whole country are consistent with the EKC hypothesis, indicating that the PWEF increases first and then decreases with the increase of PGDP. Because the quadratic form is significant at the 1% level, and the coefficient of a quadratic function is negative, the cubic function is not significant. In the east, the linear form is significant at the 2% level, while the quadratic function is significant at the 7% level, which indicates the initial increase and the subsequent decrease of PWEF are both quite gentle with the increase of PGDP under the GLS regression. Additionally, the cubic form is not significant. Similar to the east, the linear form of the center is significant at the 2% level, while the square of the PGDP variable in the quadratic form is significant only at a 5% level, which further support the more obvious inverted U-shaped curve than the east. Moreover, the cubic form is not significant again. A strong linear relationship is found in the case of the west. The linear form is significant at the 1% level, while the quadratic form and the cubic form are not significant, which present a positive monotonic shape with the increase of the PGDP. The R-squared values are relatively low since the panel data do not consider factors such as technical level, urbanization, education level, geography and climate. At the same time, these factors play an important role in explaining the relationship between PWEF and PGDP.

Table 2 | Descriptive statistics of variables: the whole country and the three regions.

Three Regions	Variables	Obs	Min	Max	Mean	SD
Whole country	WEF	403	0.42	5.09	1.36	0.83
	GDP	403	0.53	12.90	3.80	2.38
East	WEF	143	0.42	1.72	1.03	0.28
	GDP	143	1.08	12.90	5.55	2.74
Center	WEF	104	0.70	2.67	1.32	0.44
	GDP	104	0.88	6.01	2.93	1.28
West	WEF	156	0.66	5.09	1.68	1.17
	GDP	156	0.53	7.19	2.77	1.52

Note: PWEF = WEF footprint (ghm^2) per capita; PGDP = Gross Domestic Product (RMB 10,000) per capita.

4. DISCUSSION

By analyzing cross-sectional and panel data and using both GLS regression and LOWESS model, this paper finds that five types of curve shapes exist between the PWEF and PGDP, including the positive monotonic shape, negative monotonic shape, N-shape, inverted U-shape and M-shape. The results of the study indicate not only the traditional EKC shapes, usually found in relevant studies, but also an M-shape curve. Although the proportion of the M-shape curve (12.5%) is lower than the traditional EKC (87.5%) under the LOWESS model, this proportion cannot be ignored. Initially, due to the growth of population and low production efficiency, the WEF footprint increased seriously. The WEF footprint would decline when the economy has developed to a certain degree. The reason is that the local governments are able to care about the ecological protection and pay more attention to technological innovations with the economic support. Predictably, with the continuing development of the economy, society and population, the demand for water, energy, and food will increase, and the next inverted U-shape will also start. The M-shape further indicates that the WEF footprint fluctuates in the inverted U-shaped cycle with the development of the social economy.

By comparing the eight economic zones with the three regions, this paper finds that although they correspond to each other geographically, their EKC results are quite different. Geographically, the eastern region includes ECEZ, SCEZ, NCEZ, and Liaoning province in NECEZ, the western region includes SWCEZ, NWCEZ, and Shanxi, Inner Mongolia provinces in MYRZ, and the central region corresponds to MYTRZ, Heilongjiang, Jilin provinces of NECEZ and Shanxi, Henan provinces of MYRZ. Figure 5 shows that the economic development of the eastern region and the central region whose inverted U-shape curve supports the EKC hypothesis significantly. The eight economic zones that correspond to the eastern and central regions, the GLS regression results display two shapes: the unspecified shape and the inverted U-shape curves, while the LOWESS model yields four shapes: the inverted U-shape, rising shape, decline shape and M-shape. Moreover, the western region shows the rising shape curve, while in the eight economic zones corresponding to the western region, GLS regression results display two shapes: the N-shape and inverted U-shape, and there are also two shapes concluded by the LOWESS model: the inverted U-shape, and rising shape. Based on the above analysis, it can be concluded that different regional divisions and statistical methods will result in different shape curves.

The EKC theory proposed that environmental degradation initially increases and then decreases with the economy's development, demonstrating an inverted U-shape curve. In line with Ulucak & Bilgili (2018), this paper uses

Table 3 | GLS regression: WEF footprint (PWEF) per capita of the three regions.

Dependent variable	Whole country ($n = 403$)			East ($n = 143$)			Centre ($n = 104$)			West ($n = 156$)		
Independent variable	Linear	Quadratic	Cubic	Linear	Quadratic	Cubic	Linear	Quadratic	Cubic	Linear	Quadratic	Cubic
Constant	1.49***	1.22***	1.02***	1.14***	0.98***	1.05***	1.08***	0.7***	0.71	1.21***	1.22***	0.62
	(0.08)	(0.13)	(0.2)	(0.05)	(0.1)	(0.19)	(0.11)	(0.22)	(0.51)	(0.19)	(0.34)	(0.65)
GDP	−0.03**	0.1*	0.27*	−0.02**	0.04	0.001	0.08**	0.38**	0.36	0.17***	0.16	0.9
	(0.02)	(0.06)	(0.15)	(0.01)	(0.03)	(0.10)	(0.03)	(0.16)	(0.57)	(0.06)	(0.22)	(0.71)
GDP^2		−0.01***	−0.05*		−0.005*	0.002		−0.05**	−0.04		0.002	−0.24
		(0.01)	(0.03)		(0.003)	(0.02)		(0.03)	(0.19)		(0.03)	(0.22)
GDP^3			0.002			−0.0003			−0.001			0.02
			(0.002)			(0.001)			(0.02)			(0.02)
R-squared	0.01	0.03	0.03	0.04	0.06	0.07	0.05	0.09	0.09	0.05	0.05	0.06
F-statistic	3.94	5.35	4.08	6.06	4.79	3.22	5.91	4.93	3.25	8.03	3.99	3.06
	0.05	0.01	0.01	0.02	0.01	0.02	0.02	0.01	0.02	0.01	0.02	0.03

Note: Coefficient results are presented with robust standard errors in parenthesis. The symbols *, **, *** represent statistical significance at the 10%, 5%, and 1% levels respectively.

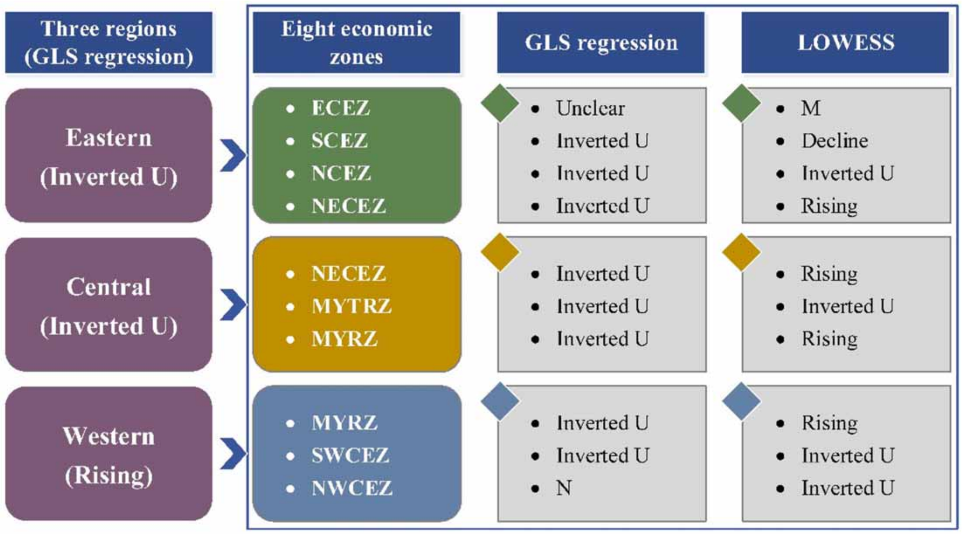


Fig. 5 | Comparison of the curve shapes of the eight economic zones and the three regions under GLS regression and LOWESS model.

ecological footprint as a proxy for environmental degradation. Will the WEF footprint be consistent with the traditional EKC theory and improve with the development of the economy automatically? In Figures 4 and 5, although the NECEZ belongs to the more developed eastern region and central region geographically, the results of the LOWESS model show a rising shape curve, which reflects that the WEF footprint has not significantly been improved or even been worse with the development of the economy. While SWCEZ and NWCEZ regions in the economically undeveloped western region show an inverted U-shape curve which reflects that the status of the WEF footprint begins to improve. Consequently, in the economically developed zones of China, an inverted U-shape curve reflects that the WEF footprint will not always improve as it does in some of the economically undeveloped areas. It can also be concluded that the economic development can bring technological progress, but technological progress will not automatically improve the ecological environment. Actually, the improvement of the ecological environment also needs the guidance of government policies and the pursuit of high quality of life (Zhang *et al.*, 2017).

5. CONCLUSIONS

This paper introduces the ecological footprint measurement to research the water-energy-food system, and the WEF footprint is proposed. The study area focuses on eight economic zones and three geographical regions of China where the influence of different regional divisions is analyzed with the use of statistical techniques in view of the WEF footprint indicator. In addition, the generalized least squares regression (GLS) and non-parametric regression model (LOWESS) are applied to research the relationship between the WEF footprint and economic growth. On this basis, we draw the main conclusions of this paper and further give the policy suggestions:

Firstly, according to the analysis of the eight economic zones and the three regions, different regional divisions will lead to different shapes of the relationship curve between the WEF footprint and economic growth. The phenomenon is naturally caused by the imbalance of the economic development of each province and the differences among the main bodies (e.g., water, energy, food and buildings) that occupy the study area. Therefore, the local governments should utilize ecologically appropriate techniques to formulate ecological policies and plans according to the water, energy, and food status of provinces. In addition, the provinces should actively cooperate to narrow the regional economic gap. The governments of the provinces also need to monitor the environmental quality and further formulate relevant policies to ensure that the ecological footprint by the different main bodies is within an appropriate range.

Secondly, in the process of analyzing the EKC relationship between the WEF footprint and economic development by utilizing the GLS regression and LOWESS model, it is found that the shape of the curves obtained by the traditional GLS model may be affected by the form of the function, while the LOWESS model without the specific function form can fit the smooth curve taking into account all local scattered points. Compared with GLS regression, the LOWESS model would reflect the relationship between the WEF footprint and economic growth in more detail. Therefore, the governments should not only formulate the policies according to the law of development, but also focus on the actual situation to constantly adjust and improve the direction of the policies. In addition, the government should pay more attention to the guiding significance of statistical methods in policy-making. The proposed methodology of GLS regression joint LOWESS model can be used by government officials, relevant policy experts and scientists to analyze the EKC relationship between ecological footprint and economic development.

Finally, the above analysis discovers that the WEF footprint will not change automatically with the development of the economy and further supports the necessity of the government's participation theoretically. However, only depending on the cooperation of local governments is not enough, because of the interest competition among local governments (Overton, 2017). Therefore, the top-level design and policies from the national government are important and necessary. The policies, such as comprehensive promoting the development of the Yangtze River Economic Belt, and promoting the ecological protection and high-quality development of the Yellow River Basin, are both good examples and implemented orderly and commendably (Jiang *et al.*, 2021). In addition, the government should encourage enterprises to improve their energy efficiency and develop more renewable energies (Hong *et al.*, 2013).

In this paper, the WEF footprint and its methodology were studied based on the EKC hypothesis. The novelty of this work is the implementation of the ecological footprint methodology of the whole water-energy-food system. Moreover, the LOWESS model and GLS regression are both introduced to test the validity of the EKC hypothesis of Chinese WEF footprint and economic growth. In addition, the research on the WEF footprint will provide some ideas for solving the contradiction of land use in the process of urbanization. Also, the research is significant to protect biodiversity and achieve sustainable development. It should be admitted that: (1) similar to some EKC studies, the quantitative conclusions of this paper are insufficient. (2) The LOWESS model is only applicable to the cross-sectional data theoretically. Future studies will use more appropriate estimation methods to reach more quantitative conclusions.

ACKNOWLEDGMENTS

We would like to acknowledge the support of the Major Project of National Social Science Foundation of China (Grant No. 19ZDA084). We appreciate the editor and anonymous reviewers for their beneficial comments and suggestions that improve the quality of this paper.

DATA AVAILABILITY STATEMENT

All relevant data are available from an online repository or repositories (https://login.cnki.net/).

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First received 1 August 2021; accepted in revised form 18 January 2022. Available online 2 February 2022