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Threshold eff ect of economic growth on domestic waste production: evidence from China

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Abstract: Since the implementation of the compulsory sorting of domestic waste policy in China, the participation rate of residents is low, which leads to the unsatisfactory result of terminal reduction of domestic waste. Therefore, the problem of domestic waste reduction still needs to rely on source reduction. Based on the panel data of 29 provincial capitals in China from 2009 to 2018, this study conducts a comprehensive threshold effect test on per capita GDP and other influencing factors of domestic waste production, conducts panel threshold regression for the factors with threshold value, and explores the nonlinear relationship between per capita GDP and domestic waste production under the influence of different threshold variables. The results show that when the urban population density is less than 272 people/km^2, the increase of 1% of per capita GDP will lead to a decrease of 0.251% in the domestic waste production, otherwise, it will lead to an increase of 0.249%; when the per capita consumption expenditure is less than the threshold value of 10,260 yuan/year, the influence coefficient of per capita GDP is 0.155, which increases to 0.207 above the threshold. When the share of tertiary industry is taken as the threshold variable, the two threshold values are 61% and 71% respectively. Through the analysis of control variables, it has been found that population size and amount of courier per capita have significant positive effects on domestic waste production, while gas permeability and the number of non-governmental organizations have significant negative effects.

Introduction

The survey report "What a Waste 2.0" released by the World Bank in 2018 suggests that the global municipal solid waste amounted 2.01 billion tons in 2016. The East Asia and Pacific regions produce the most waste by far, accounting for 23% of the world's total. The report also predicts that by 2030, East Asia, Europe and North America will produce 602, 440, 342 million tons of waste, respectively, a growth by 28.6%, 12.2% and 18.3% from 2016. Among these, China's waste production and growth rate are particularly noteworthy. According to the *China Statistical Yearbook*, from 1999 to 2019, the total urban domestic waste in China increased from 113.0181 million tons in 1998 to 228.018 million tons in 2018, with an increase rate of 101.75% within only 20 years. The urban domestic waste production is growing rapidly, posing a great threat to the environment. The survey data of the Ministry of Housing and Urban-rural Development (MOHURD) indicates that more than two-thirds of China's cities are facing the dilemma of garbage siege, and a quarter of cities have no suitable place to stack garbage. At present, incineration and landfill are the main domestic waste disposal methods in China. The National Bureau of Statistics of China declare that the incineration volume of domestic waste was 121.201 million tons in 2019, a year-on-year increase of 19%. The landfill treatment volume of domestic waste was 109.48 million tons, a year-on-year decrease of 6.5%. The leachate, sulphur dioxide and particulate matter generated from such treatment have caused a series of environmental problems such as land pollution, water pollution and air pollution (Pang et al. 2004, Jiang 2019). The reduction of domestic waste is an important issue that cannot be ignored in the study of urban construction and sustainable development. It includes the reduction of source production and the end-of--pipe control (Singh and Raj 2018, Song and Dai 2020). In terms of end-of-pipe control of domestic waste, China mainly implements the policy of compulsory sorting of domestic waste. In March 2017, National Development and Reform Commission (NDRC) and the Ministry of Housing and Urban-rural Development (MOHURD) issued the Implementation Scheme of Domestic Waste Classification System. After Shanghai implemented the mandatory domestic waste sorting policy from July 1, 2019, other cities have also started to carry out the policy gradually, and the academic research on China's domestic waste sorting and treatment mechanism is increasing (Du and Huang 2019, Wang et al. 2020b). However, there are some problems in the four stages of domestic waste sorting: in the stage of sorting and delivery, the problems are that the realization of waste sorting mainly depends on the government to push, whereas residents and enterprises have weak sense of responsibility (Liu and Dai 2022); in the stage of sorting collection and transportation, many cities are facing the problem of centralized transportation (Yang et al 2019), which leads to the remixing of previous effective sorting resulting in waste of resources; in the stage of sorting disposal, China's waste sorting and treatment capacity is still insufficient. Let us take the disposal of kitchen waste, which accounts for more than 60% of the total domestic waste, as an example: the research report on the development of China's waste sorting industry from 2019 to 2021 demonstrates that the average daily output of urban kitchen waste in 2018 was more than 1,000 tons, but 82.6% of cities do not have the capacity to deal with such a large amount of waste. The above research studies show that there is no substantive progress in waste sorting in China, and there still exists major problems in end-of-pipe treatment. Therefore, it is necessary to reduce the domestic waste from the source.

The existing research studies on reducing waste from the source are mainly based on the influencing factors of domestic waste production in single or multiple provinces, including population size, population density, the per capita consumption expenditure, share of tertiary industry, gas permeability, investment in urban appearance and environmental sanitation, etc. The researchers consistently find out that gas permeability and investment in urban appearance and environmental sanitation have a negative impact on the domestic waste production (Xu et al. 2019, Huangfu and Li 2018, Wang et al. 2020a), while other factors have a positive one (Nicolli and Lafolla 2012, Xu et al. 2013, Drew et al. 2013, Han et al. 2018). However, for per capita GDP, which is one of the important factors, most scholars find out that it has nonlinear relationship with the domestic waste production, but there is a dispute on what a nonlinear relationship it is. Different research studies provide different results, including a U-shaped relationship (Madden et al. 2019, Cui and Wang 2018), an inverted N-shaped relationship (Du et al. 2019), and an N-shaped relationship (Cheng et al. 2020). With the rapid development of domestic e-commerce, express packaging has gradually become a large part of urban solid waste. In addition, the non--governmental organizations and social networks in cities may have a certain impact on residents' environmental protection behavior, and then change the domestic waste production. The previous research did not take the abovementioned factors into consideration.

To research the nonlinear relationship between per capita GDP and domestic waste production, scholars mainly establish multiple equations of per capita GDP (Mao et al. 2018) or panel threshold regression model (Qin and Ge 2019). The former may be unable to accurately identify the inflection point and solve the problem of endogeneity of variables (Jia and Huang 2015, Ren 2018) and the variables used fail to optimize over time. Therefore, on the basis of existing literature, this study includes two new variables that have a huge impact on the amount of garbage generation in modern life, namely, the amount of express delivery per capita and the number of non-governmental organizations. The study also conducts a comprehensive threshold effect test on the per capita GDP (Qin and Ge 2019) and other influencing factors, and carries out panel threshold regression on the factors with threshold values to explore the non-linear relationship between per capita GDP and domestic waste production under the influence of different threshold variables. The main influencing factors and their magnitude of waste production under modern lifestyle are deeply studied. The researchers also put forward more targeted policy suggestions for waste source reduction that are applicable to modern living conditions.

Variables and methods

Explanation of variables and data sources

This study uses the panel data of 29 provincial capitals and municipalities directly under the central government (complete data on Taiwan, Xinjiang, Macao, Tibet, and Hong Kong are not available therefore excluded in the study) from 2009 to 2018. The explained variable is the amount of domestic waste. Because these data cannot be obtained directly, this paper uses the urban waste removal amounts which are collected from *the China Urban Construction Statistical Yearbooks* to represent the annual domestic waste production of each city. The core variable is per capita GDP. In order to eliminate the impact of prices, the per capita GDP of each city is converted into the actual per capita GDP with 2009 as the base year (Wang et al. 2010). The variable data is also collected from *the China Urban Construction Statistical Yearbook*. Two factors of domestic waste production are introduced based on previous studies: (1) per capita express delivery: the increase of express delivery means that there will be more waste caused by express packaging. Since there is no mandatory express packaging recycling standard in China, the increase of express packaging waste may directly affect the production of local urban domestic waste; (2) number of non-governmental organization: the behavior of residents producing domestic waste in daily life may be affected by interactive groups. Therefore, the variables and their descriptive statistics in this study are shown in Table 1 and Table 2.

In this study, multiple factors affecting the amount of domestic waste production are chosen, which may cause multicollinearity problems, thus adversely affecting the empirical analysis results. In order to avoid this problem, VIF test is carried out (The software used in the full text is stata15). If the value of VIF exceeds 10, it indicates that there is an obvious multicollinearity problem. VIF test results are shown in Table 3. Among the 9 variables, the maximum VIF value is 7.690, the average VIF value is 4.450, and the VIF value is significantly less than 10. Hence, possible multicollinearity problems can be excluded and empirical analysis can be conducted.

To preliminarily investigate the degree of correlation among variables, this study conducted correlation analysis on the explained variable, explanatory variable and control variables, and the results are shown in Table 4. The correlation coefficient between variables reached a significant level, and the amount of *msw* generated was significantly positively correlated with per capita GDP, which preliminarily indicated that the level of regional economic development would affect the amount of *msw* generated. In addition, control variables including population size (*pop*), per capita express delivery (*del*), population density (*den*), number of non-governmental organizations (*ngo*), per capita consumption expenditure (*exp*), proportion of tertiary industry (*sti*), city appearance, environmental health investment (*inv*), and gas permeability (*gas*) are significantly correlated with domestic waste production, which shows that the choice of control variables in the model is representative to some extent.

Panel threshold regression model

Assuming the existence of threshold effect, this study discusses the nonlinear relationship between per capita GDP and domestic waste production with different population size (*pop*), per capita express delivery(*del*), population density

Table 1. Variables and data sources

Variable type	Variable	Symbol	Unit	Data source
Explained variable	Domestic waste production	*msw*	10kt	China urban construction statistical yearbooks
Core explanatory variable	Per capita GDP	*pgdp*	yuan	China urban statistical yearbook
control variable	Population	*pop*	–	China urban statistical yearbook
	Per capita express delivery	*del*	piece	State Post Bureau
	Population density	*den*	person/km^2	Statistical yearbooks of each city
	Number of non-governmental organizations	*ngo*	–	China civil affairs statistic yearbook
	Per capita consumption expenditure	*exp*	yuan	Statistical announcement of each city
	proportion of the tertiary industry	*sti*	%	China urban statistical yearbook
	Investment in city appearance and environmental sanitation	*inv*	10k yuan	China urban construction statistical yearbook
	Gas permeability	*gas*	md	China urban construction statistical yearbook

Table 2. Descriptive statistics of variables

Variable	N	Mean	SD	Min	Max
msw	290	211.3	178.2	23.71	975.1
pgdp	290	63740	24863	21945	162658
pop	290	790.1	584.8	155.5	3404
del	290	32.31	62.91	1	546
den	290	652.6	416.5	132.0	2306
ngo	290	3465	2866	452	19029
exp	290	18827	5340	8717	35974
sti	290	0.535	0.0990	0.362	0.810
inv	290	74201	201775	180	1971974
gas	290	0.613	0.205	0.248	1.030

Table 3. VIF test results

Variable	VIF	1/VIF
exp	7.690	0.130
pop	6.370	0.157
ngo	5.820	0.172
del	5.620	0.178
pgdp	5.460	0.183
gas	3.100	0.322
sti	2.610	0.383
den	1.890	0.529
inv	1.510	0.661
Mean	VIF	4.450

(*den*), number of non-governmental organizations (*ngo*), per capita consumption expenditure (*exp*), per capita GDP (*gdp*), share of tertiary industry (*sti*), investment in urban appearance and environmental sanitation (*inv*), gas permeability (*gas*), etc. In this study, a single threshold model and a double threshold model are established respectively:

$$\begin{aligned} \mathrm{Ln}msw_{it} &= \ln\alpha + \beta_1 \ln pop_{it} + \beta_2 \ln del_{it} + \beta_3 \ln den_{it} + \\ &+ \beta_4 \ln ngo_{it} + \beta_5 \ln exp_{it} + \beta_6 \ln sti_{it} + \beta_7 \ln inv_{it} + \beta_8 \ln gas_{it} + \\ &+ \theta_1 \ln gdp_{it} I(q_{it} \le \delta) + \theta_2 \ln gdp_{it} I(q_{it} > \delta) + \varepsilon_{it} \end{aligned} \quad (1)$$

$$\begin{aligned} \ln msw_{it} &= \ln\alpha + \beta_1 \ln pop_{it} + \beta_2 \ln del_{it} + \beta_3 \ln den_{it} + \\ &+ \beta_4 \ln ngo_{it} + \beta_5 \ln exp_{it} + \beta_6 \ln sti_{it} + \beta_7 \ln inv_{it} + \beta_8 \ln gas_{it} + \\ &+ \theta_1 \ln gdp_{it} \mathrm{I}(q_{it} \le \delta_1) + \theta_2 \ln gdp_{it} \mathrm{I}(\delta_1 < q_{it} \le \delta_2) + \\ &+ \theta_3 \ln gdp_{it} \mathrm{I}(q_{it} > \delta_2) + \varepsilon_{it} \end{aligned} \quad (2)$$

Where, msw_{it} refers to the explained variable, *it* means the domestic waste production of province *i* in the year of *t*; q_{it} refers to the threshold variable, respectively expressed with population size (*pop*), per capita express volume (*del*), population density (*den*), number of non-governmental organizations (*ngo*), per capita consumption expenditure (*exp*), per capita GDP (*gdp*), share of tertiary industry (*sti*), investment in urban appearance and environmental sanitation (*inv*) and gas permeability (*gas*); δ refers to the estimated threshold value; β_1_β_8 refer to the coefficient of control variables; θ_1, θ_2 and θ_3 refer to the impact of per capita GDP in different intervals of domestic waste production; I (∗) is an indication function, its value is 1 when the condition is met, otherwise it is 0; ε_{it} refers to an random disturbance term.

Results and discussion

Stationary test and cointegration test of variables

This study uses LLC and ADF-Fisher to test whether variables are stable, so as to avoid the result of pseudo regression in threshold regression (Zhao et al. 2016). The null hypothesis of the test is that there is a unit root in panel data, which means that the variables are not stationary. The alternative assumption is that there is no unit root, i.e., the variables are stationary. The test results are shown in Table 5; the explanatory variables and the explained variable in this study are stable in the LLC test, while in the ADF-Fisher test, the population size, per capita consumption expenditure and the share of tertiary industry are non-stationary variables, but all variables after the first-order difference have passed the stability test, indicating that these three variables are stable in the first-order difference. Then, this study adopts the Kao test to tell whether there are long-term stable relationships between variables. The primary hypothesis is that long-term stable relationships between all variables exist, and the alternative hypothesis is that there are no long-term stable relationships. The test results show the values of five statistics, three of them reject the null hypothesis at the 1% level of this set of data, indicating that there are long-term stable relationships between variables, and the next step of threshold regression research can be carried out.

Model selection and practical tests

Based on Bollen & Brand (2010), Yang et al. (2020) and Zhong & Lian (2010), this study conducts selection and testing of panel models.

(1) Testing individual effect. Tests are performed between the fixed effects model and the Pool-OLS model. For fixed-effect models, the F statistic reported in the last line of regression results is to test whether all individual effects are significant as a whole. The results of this study show that the P-value of F statistic is 0, and the test results show that the fixed-effect model is superior to the Pool-OLS model.

(2) Testing the time effect. Breusch and Pagan Lagrangian Multiplier test is used to test between the random effect model and the Pool-OLS model. The results show that the random effect model is better than the Pool-OLS model when the P-value is 0.

(3) Tests between random effects and fixed effects. The results of Hausman test show that the P value of Hausman test is 0.0271, which strongly rejects the null hypothesis and indicates that fixed-effect model should be adopted (see Table 6).

Then, according to Hoyos & Sarafidis (2006), the cross-section correlation of panel data is tested. Table 7 shows that Expect Frees' test, Pesaran's CD test and Friedman's test accept the assumption of cross-sectional independence, so there is no cross-sectional correlation in panel data.

Table 4. Correlation analysis of variables

	msw	*pop*	*del*	*den*	*ngo*	*exp*	*sti*	*pgdp*	*inv*	*gas*
msw	1									
pop	0.746***	1								
del	0.589***	0.241***	1							
den	0.612***	0.466***	0.472***	1						
ngo	0.792***	0.854***	0.467***	0.403***	1					
exp	0.633***	0.311***	0.869***	0.356***	0.544***	1				
sti	0.359***	-0.115**	0.568***	0.158***	0.104*	0.561***	1			
pgdp	0.561***	0.221***	0.807***	0.420***	0.400***	0.844***	0.388***	1		
inv	0.479***	0.298***	0.289***	0.293***	0.309***	0.333***	0.251***	0.373***	1	
gas	0.334***	-0.268***	0.503***	0.219***	-0.0600	0.477***	0.635***	0.551***	0.386***	1

Note: *, **, and *** indicate the significance level is 10%, 5%, and 1%, respectively.

Table 5. Stationary test and cointegration test of variables

Variable	LLC		ADF-Fisher		Test results
	Horizontal sequence	First-order difference	Horizontal sequence	First-order difference	
ln*msw*	-14.8440*** (0.0000)	-21.7920 *** (0.0000)	4.8836** (0.0203)	20.6025*** (0.0000)	stable
ln*pgdp*	-8.7223*** (0.0000)	-16.2701*** (0.0000)	9.0955*** (0.0010)	24.5783*** (0.0000)	stable
ln*pop*	-47.7919*** (0.0000)	-23.6937*** (0.0000)	2.7111 (0.2172)	14.0365*** (0.0005)	stable in the first-order difference
ln*del*	-8.1614*** (0.0006)	-22.0954*** (0.0000)	3.7086* (0.0607)	18.8152*** (0.0000)	stable
ln*den*	-7.3443*** (0.0000)	-26.7039*** (0.0000)	3.2328* (0.0882)	15.0110*** (0.0000)	stable
ln*ngo*	-7.7864*** (0.0000)	-13.6585*** (0.0000)	-0.0035* (0.0607)	11.9121*** (0.0009)	stable
ln*exp*	-9.8744*** (0.0000)	-15.8276*** (0.0000)	6.7067 (0.4146)	16.1658*** (0.0017)	stable in the first-order difference
ln*sti*	-6.2986*** (0.0003)	-10.1182*** (0.0000)	-0.1282 (0.5350)	15.3945*** (0.0000)	stable in the first-order difference
ln*inv*	-13.2022*** (0.0000)	-20.0095*** (0.0000)	15.2101*** (0.0000)	22.4110*** (0.0000)	stable
ln*gas*	-16.1867*** (0.0000)	-18.1119*** (0.0000)	8.9635*** (0.0023)	22.5415*** (0.0000)	stable
Kao test	Modified Dickey-Fuller t		-0.1696(0.4327)		co-integration relation existed
	Dickey-Fuller t		-3.7257*** (0.0001)		
	Augmented Dickey-Fuller t		-0.9870 (0.1618)		
	Unadjusted modified Dickey-Fuller t		-4.3552*** (0.0000)		
	Unadjusted Dickey-Fuller t		-6.3074*** (0.0000)		

Note: *, **, and *** indicate the significance level is 10%, 5%, and 1%, respectively, the number in () is the p-value of the statistic.

Table 6. Model selection and test results

Variable	FEM	REM	Pool-OLS
ln*pgdp*	0.1212 (1.52)	0.1108 (1.44)	0.0360 (0.43)
ln*pop*	0.6754*** (2.85)	0.7222*** (7.25)	0.7043*** (12.91)
ln*del*	0.0824*** (2.95)	0.0465* (1.82)	-0.0218 (-0.90)
ln*den*	0.2323 (0.86)	0.169-** (2.28)	0.1516*** (4.91)
ln*ngo*	0.1326 (1.63)	0.1303* (1.86)	0.2262*** (4.58)
ln*exp*	-0.1466 (-1.05)	-0.1039 (-0.77)	0.0985 (0.70)
ln*sti*	-0.1378 (-0.81)	0.0646 (0.42)	0.5510*** (4.36)
ln*inv*	0.0007 (0.10)	0.0014 (0.19)	-0.0004 (-0.03)
ln*gas*	0.4210*** (3.37)	0.6172*** (5.92)	0.8201*** (11.67)
_cons	-1.7702 (-0.77)	-1.6412 (-1.27)	-2.7254** (-2.50)
AdjR^2			0.8949
F-statistics	46.97***[0.0000]	674.65***[0.0000]	274.39***[0.0000]
F test that all u_i=0:	17.42***[0.0000]		
Breush&Pagan LM		370.44***[0.0000]	
Hausman	18.79**[0.0271]		

Note: *, **, and *** indicate the significance level is 10%, 5%, and 1%, respectively, the number in () is the value of T statistic, the number in [] is the p-value of the statistic.

Threshold effect test

The study investigates the nonlinear impact of per capita GDP on domestic waste from two aspects: the first is the impact of per capita GDP itself, and the second is to explore the relationship between these two variables by taking population size, per capita express delivery, population density, number of non-governmental organizations, per capita consumption expenditure, share of tertiary industry, investment in urban appearance and environmental sanitation and gas permeability as threshold variables.

Before conducting threshold regression, threshold effect test needs to be carried out to determine whether the variables have a threshold value and what is the number of threshold values (He and Wang 2018). This paper uses Stata15.0 to test the threshold effect with the indicators including per capita GDP, population size, per capita express delivery, population density, number of non-governmental organizations, per capita expenditure, share of tertiary industry, investment in urban appearance and environmental sanitation and gas permeability as threshold variables. The test results are shown in Table 8.

From the table, it suggests that only the share of tertiary industry passes the significance test of the two threshold values. The two threshold variables of the per capita consumption expenditure and population density have passed the significance test of a single threshold value, and the other variables have not passed the significance test of a single threshold value. The results show that there is no nonlinear relationship between per capita GDP and domestic waste production by taking per capita GDP as the threshold variable. Under the influence of the amount of per capital express delivery, the number of non-governmental organizations and the investment in urban appearance and environmental sanitation, the relationship between the two is relatively stable; while under the influence of the share of tertiary industry, per capita expenditure and population density, the relationship between the two will change suddenly. The threshold variables and confidence intervals are shown in Table 9.

The threshold values are shown in the LR value chart which takes the share of tertiary industry as an example. It is

Table 7. Cross-sectional dependence test results

Pesaran's CD test	Pesaran's test of cross sectional independence = 0.328, Pr = 0.7427
	Average absolute value of the off-diagonal elements = 0.411
Frees' test	Frees' test of cross sectional independence = 3.312
	Critical values from Frees' Q distribution alpha = 0.10 : 0.2559 alpha = 0.05 : 0.3429 alpha = 0.01 : 0.5198
Friedman's test	Friedman's test of cross sectional independence = 10.151, Pr = 0.9992

Table 8. Threshold effect test results

Variable	**Single threshold**	**Double threshold**
	F-statistics	F-statistics
ln*pgdp*	9.14 (0.5133)	–
ln*pop*	27.13 (0.1933)	–
ln*del*	14.35 (0.2833)	–
ln*den*	29.88* (0.0833)	24.04 (0.2867)
ln*ngo*	24.28 (0.1067)	–
ln*exp*	46.91*** (0.0000)	7.05 (0.6600)
ln*sti*	26.41* (0.0833)	19.26* (0.0767)
ln*inv*	9.52 (0.1967)	–
ln*gas*	10.30 (0.7100)	–

Note: *, **, and *** indicate the significance level is 10%, 5%, and 1%, respectively.

Table 9. Threshold estimates and confidence intervals

Explanatory variable	Threshold variable	Threshold value 1	95% confidence interval	Threshold value 2	95% confidence interval
ln*pgdp*	ln*den*	5.6066	[5.5105, 5.7545]	–	–
	ln*exp*	9.2360	[9.1913, 9.2760]	–	–
	ln*sti*	-0.4887	[-0.4938, -0.4860]	-0.3320	[-0.3507, -0.2992]

inferred from Figure 1 and Figure 2 that there are two threshold values for the share of tertiary industry, which changes the impact of per capita GDP on the domestic waste production.

Analysis of panel threshold regression results of domestic waste production

According to the results of threshold effect tests, the panel threshold regression is carried out with population density, per capita consumption expenditure and the share of tertiary industry as threshold variables. The regression results are shown in Table 10.

Population density

When the population density is taken as the threshold variable, the relationship between per capita GDP and domestic waste production represents a "U" shape. For the cities with population density higher than 272 people/km^2, every 1% increase in per capita GDP will lead to a decrease of 0.251% in the domestic waste production; otherwise, it will lead to an increase of 0.249%. In 2018, the cities with population density less than 272 people/km^2 included Ha'erbin, Yinchuan, Lanzhou, Xining, Kunming and Hohhot. Currently, these cities are mainly focusing on economic development, and the problem of domestic waste can be ignored temporarily.

Table 11 reflects the cities' threshold values of population density. In 2009, the population density of Ha'erbin, Yinchuan, Lanzhou, Xining, Kunming, and Hohhot did not exceed the threshold value, the increase of per capita GPD of that year can reduce the domestic waste production apparently. The provinces such as Beijing, Fuzhou and 23 cities in total, have population density higher than the threshold of 272 people/km^2, the growth of per capita GDP brought a significant increase in domestic waste production. The cities with population density higher than the threshold value in 2018 are as same as those in 2009. Despite changes of population density over 10 years, there was no city whose population density increased to a level above the threshold value or decreased to a level below the threshold value. Therefore, it is hard to adjust the relationship between per capita GDP and domestic waste production by regulating the population density. At present, the per capita GDP of Ha'erbin, Yinchuan, Lanzhou, Xining, Kunming, and Hohhot has negative influence on domestic waste production and it is unnecessary to consider the issue of domestic waste while developing the economy. By comparing the above 6 cities' population density of 2009 and that of 2018, this study show that the population density of Kunming and Xining has increased and is approaching the threshold value. Therefore, it is necessary to prepare beforehand to deal with the positive impact of per capita GDP on domestic waste production.

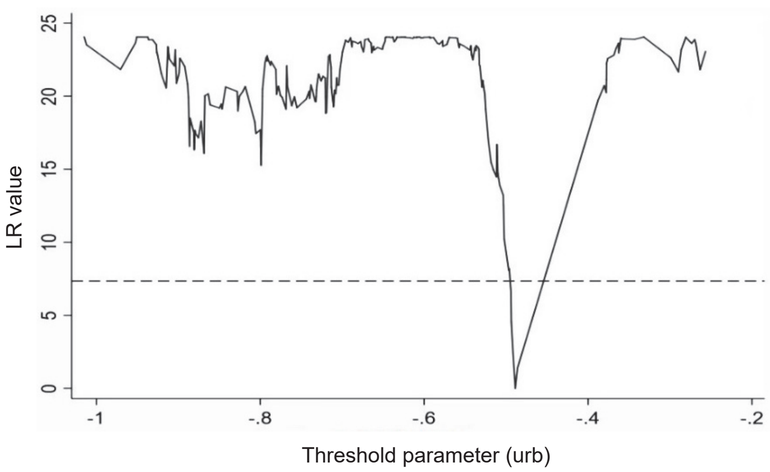

Fig. 1. Likelihood ratio function of the first threshold

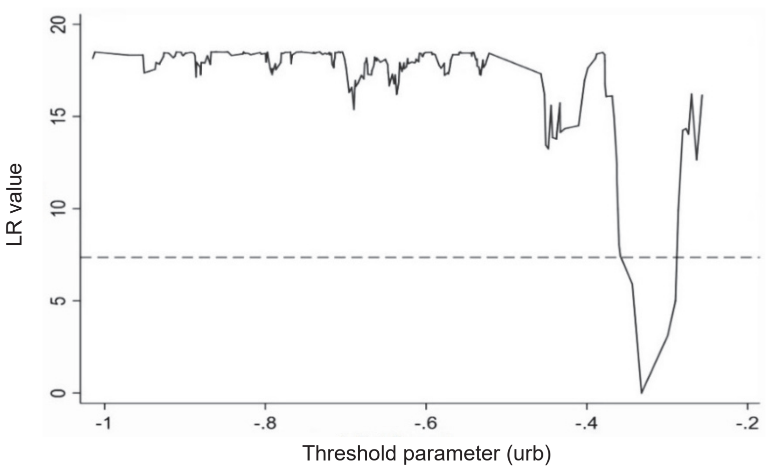

Fig. 2. Likelihood ratio function of the second threshold

Per capita consumption expenditure

When the per capita consumption expenditure is taken as the threshold variable, the domestic waste production shows a stepped growth with the increase of per capita GDP. After exceeding 10,260 yuan, with the increase of the per capita consumption expenditure, the increase of 1% of per capita GDP leads the impact on domestic waste production increase from 0.155% to 0.207%. It shows that if other factors are controlled, the increase of the per capita consumption expenditure will lead to further increase of domestic waste production.

Table 12 shows the threshold values for the per capita consumption expenditure in each city. In 2009, the per capita consumption expenditure only in Shijiazhuang and Xining were below the threshold value. The growth coefficient of domestic waste production due to per capita GDP growth of that year was quite small. The per capita consumption expenditures of other cities were above the threshold value of 10,260 Yuan, and the coefficient of domestic waste production increased with the per capita GDP growth in that year. In the year of 2018, the per capita consumption expenditure of all cities exceeded the threshold value, and the per capita GDP growth of all cities brought substantial increase in domestic waste production. Therefore, in terms of consumption, residents should develop green and circular consumption habits to mitigate the negative impact of per capita GDP growth on domestic waste."

Share of tertiary industry

When the share of tertiary industry is taken as the threshold variable, the domestic waste production increases in stages with the increase of per capita GDP. The threshold values of the share of tertiary industry are 61% and 71%. When the threshold value is below 61%, the coefficient of per capita GDP is 0.194; when it is between 61% and 71%, the coefficient of per capita GDP is 0.178, and when it is above 71%, the coefficient of per capita GDP is 0.2; the impact of per capita GDP on domestic waste production is the smallest when the threshold is between 61% and 71%. In 2018, cities with share of tertiary industry between 61% and 71% included Shanghai,

Table 10. Result of panel threshold regression

Variable	den(a1=272)	exp(a1=10260)	Variable	sti(a1=61%, a2=71%)
ln*pop*	0.607** (2.68)	0.774*** (3.49)	ln*pop*	0.743*** (3.33)
ln*del*	0.0366 (1.30)	0.0669* (2.55)	ln*del*	0.0754** (2.83)
ln*den*	0.247 (0.96)	0.242* (1.96)	ln*den*	0.271 (1.06)
ln*ngo*	-0.155* (-1.99)	0.0140 (0.18)	ln*ngo*	0.104 (1.31)
ln*exp*	0.0341 (0.25)	0.0662* (1.49)	ln*exp*	-0.235 (-1.79)
ln*sti*	0.0244 (0.15)	-0.0725 (-0.46)	ln*sti*	0.154* (1.91)
ln*inv*	0.00173 (0.25)	0.00263 (0.39)	ln*inv*	0.00162 (0.24)
ln*gas*	-0.356** (-2.98)	-0.416*** (-3.57)	ln*gas*	-0.474*** (-3.96)
ln*pgdp* (r≤a1)	-0.251* (-2.41)	0.155* (2.09)	ln*pgdp* (r≤a1)	0.194* (2.56)
ln*pgdp* (r>a1)	0.249** (3.13)	0.207** (2.74)	ln*pgdp* (a1<r≤a2)	0.178* (2.36)
–	–	–	ln*pgdp* (r>a2)	0.200** (2.61)
N	290	290	N	290
Trend	U-shaped	Staged increase	Trend	Staged increase
R^2 (overall)	0.8027	0.8357	R^2(overall)	0.8436
F-statistics	42.55	53.36	F-statistics	46.28
P-value	0.0000	0.0000	P-value	0.0000

Note: *, **, and *** indicate the significance level is 10%, 5%, and 1%, respectively, the number in () is the value of T statistic.

Table 11. Threshold values for population density of each city

Threshold interval (person/km^2)	Cities (2009)	Cities (2018)
den<272	Ha'erbin, Yinchuan, Lanzhou, Xining, Kunming, Hohhot	Ha'erbin, Yinchuan, Lanzhou, Xining, Kunming, Hohhot
den>272	Beijing, Fuzhou, Guangzhou, Haikou, Hangzhou, Jinan, Nanjing, Naning, Shanghai, Shenyang, Shijiazhuang, Tianjin, Hefei, Nanchang, Taiyuan, Wuhan, Changchun, Changsha, Zhengzhou, Chengdu, Guiyang, Xi'an, Chongqing.	Beijing, Fuzhou, Guangzhou, Haikou, Hangzhou, Jinan, Nanjing, Naning, Shanghai, Shenyang, Shijiazhuang, Tianjin, Hefei, Nanchang, Taiyuan, Wuhan, Changchun, Changsha, Zhengzhou, Chengdu, Guiyang, Xi'an, Chongqing.

Hohhot, Ha'erbin, Lanzhou, Hangzhou, Taiyuan and Xi'an. The per capita GDP of those cities has smallest impacts on domestic waste production; for the cities with share of tertiary industry above 71% including Beijing, Haikou, Guangzhou and the cities with share of tertiary industry below 61%, the share of tertiary industry shall be properly adjusted to ease the environmental pressure of per capita GDP.

Table 13 shows the threshold values of tertiary industry share in each city. In 2009, only Haikou and Beijing exceeded the first threshold value of the share of tertiary industry, with Beijing even exceeding the second threshold value and Haikou is in the interval with the smallest coefficient of per capita GDP. In 2014, the seven cities including Shanghai, Hohhot and Ha'erbin exceeded the first threshold value, while Haikou and Guangzhou also exceeded the second one and Guangzhou directly moved from the first threshold value to the interval above the second threshold value. In that year, all cities took on a rising trend in terms of the share of tertiary industry. For the cities with such share lower than the first threshold value or higher than the second threshold value, the development progress of the tertiary industry shall be adjusted. For cities with the share of tertiary industry between 61% and 71%, such share shall be maintained. The quality of the tertiary industry in all cities needs to be improved, and the domestic waste production should be reduced by adopting green production and reducing the use of disposable articles.

No matter which variable is taken as the threshold variable, the population size has a significant positive impact on domestic waste production. With the expansion of urban population, the demand and consumption of daily necessities will also increase, so will the domestic waste production; gas permeability has a significant negative impact on the domestic waste production. With the increase of residents' domestic gas consumption rate, the use of coal is decreasing, which reduces the production of coal ash and domestic waste; different from the previous conclusions, this study finds that the impact of the investment in urban appearance and environmental sanitation on the domestic waste production is not significant. Since the previous studies took provinces or regions as the research objects, whereas the objects of this study are the provincial capital cities, the conclusions of this index are slightly different. This study regards that the investment in urban appearance and environment sanitation has a limited impact on the reduction of urban domestic waste. It is the residents who are the key factors for domestic waste reduction, and their awareness of green consumption and recycling may contribute to the reduction of domestic waste.

When the population density is taken as the threshold variable, the per capita express delivery has no significant impact on the domestic waste production, but when the per capita consumption expenditure and the share of tertiary are taken as the threshold variables, they have significant positive impacts on the domestic waste production. With the development of transportation and e-commerce, express packaging waste is increasing, which brings increasing pressure on the urban environment. When the population density is taken as the threshold variable, the number of non-governmental organizations has a significant negative impact on the domestic waste production. As a part of social capital, the number of non-governmental organizations inhibits the domestic waste production. This shows that the communication function of social groups consisting of residents has a certain impact on the improvement of the environmental protection awareness and reduction of domestic waste at the source.

Robustness test

In order to further test the robustness of regression results of economic growth on domestic waste production, per capita disposable income (*udi*) is used to test the robustness of the model instead of per capita GDP, and the test results are

Table 12. Threshold values for per capita consumption expenditure of each city

Threshold interval (Yuan)	Cities (2009)	Cities (2018)
exp<10260	Shijiazhuang, Xining	
exp>10260	Beijing, Fuzhou, Guangzhou, Haikou, Hangzhou, Jinan, Nanjing, Nanning, Shanghai, Shenyang, Ha'erbin, Yinchuan, Lanzhou, Tianjin, Hefei, Nanchang, Taiyuan, Wuhan, Changchun, Changsha, Zhengzhou, Chengdu, Guiyang, Xi'an, Chongqing, Kunming, Hohhot.	Beijing, Fuzhou, Guangzhou, Haikou, Hangzhou, Jinan, Nanjing, Nanning, Shanghai, Shenyang, Shijiazhuang, Tianjin, Hefei, Nanchang, Taiyuan, Wuhan, Changchun, Changsha, Chengdu, Guiyang, Xi'an, Chongqing, Ha'erbin, Yinchuan, Lanzhou, Xining, Kunming, Hohhot.

Table 13. Threshold values for share of tertiary industry of each city

Threshold interval	Cities (2009)	Cities (2018)
sti<61%	Fuzhou, Jinan, Nanjing, Nanning, Shenyang, Shijiazhuang, Tianjin, Hefei, Nanchang, Wuhan, Changchun, Changsha, Zhengzhou, Chengdu, Guiyang, Chongqing, Yinchuan, Xining, Kunming, Guangzhou, Shanghai, Hohhot, Ha'erbin, Lanzhou, Hangzhou, Taiyuan, Xi'an	Fuzhou, Jinan, Nanjing, Nanning, Shenyang, Shijiazhuang, Tianjin, Hefei, Nanchang, Wuhan, Changchun, Changsha, Zhengzhou, Chengdu, Guiyang, Chongqing, Yinchuan, Xining, Kunming
61%<sti<71%	Haikou	Shanghai, Hohhot, Ha'erbin, Lanzhou, Hangzhou, Taiyuan, Xi'an
sti>71%	Beijing	Beijing, Haikou, Guangzhou

shown in Table 14. Test results show that the proportion of tertiary industry (*sti*), population density (*de*n) and per capita consumption expenditure (*exp*) have threshold values and pass the significance test. The symbols of variables' coefficients are basically the same, difference between the coefficients are small, and the regression results are almost consistent with the original model, indicating that the threshold regression model is robust.

Finally, this study uses the panel data of China's provincial capital cities, so there is no considering spatial correlative factors of domestic waste production, while this is a possible research direction. Using provincial data and incorporating factors into spatial models could be taken into consideration in the future, which will be the new contribution of further research.

Conclusions

Based on the panel data of 29 provincial capitals in China from 2009 to 2018, this paper conducts a comprehensive threshold effect test with population size, per capita express delivery, population density, number of non-governmental organizations, per capita consumption expenditure, per capita GDP, share of tertiary industry, investment in urban appearance, and environmental sanitation and gas permeability as threshold variables, and explores the threshold effect of per capita GDP on the domestic waste production in China. The conclusions are as follows:

(1) When the population density is taken as the threshold variable, the impact of per capita GDP on the domestic waste production takes on a "U" shape. The threshold value of population density is 272 persons/km^2. When the population density is below the threshold value, the per capita GDP has a negative impact on the domestic waste production, and when it is above the threshold value, the impact will be positive.

(2) When the per capita consumption expenditure is taken as the threshold variable, the domestic waste production increases in stages with the increase of per capita GDP. The threshold of the per capita consumption expenditure is 10,260 yuan/year. 1% increase of the per capita GDP will lead to an increase of domestic waste production from 0.155% to 0.207%.

(3) When the share of tertiary industry is taken as the threshold variable, the domestic waste production increases in stages with the increase of per capita GDP. The per capita GDP has the smallest impact on domestic waste production when the share of tertiary industry is between 61% and 71%.

(4) With different threshold variables, the population always has a significant positive impact on the domestic waste production. The domestic waste production increases with the growth of population size. Gas permeability always has a significant negative impact on domestic waste production. The higher the gas permeability, the less domestic waste is produced; the investment in city appearance and environmental sanitation has no significant impact on domestic waste production.

(5) When the per capita consumption and the share of tertiary industry are taken as the threshold variables, the per capita express delivery has a significant positive impact on domestic waste production and the latter increases with the increase of the former. When

Table 14. Robustness check results of panel threshold regression

Variable	den(a1=272)	exp(a1=10260)	Variable	sti(a1=61%, a2=71%)
ln*pop*	0.4472**(1.91)	0.7404***(3.37)	ln*pop*	0.5772**(2.59)
ln*del*	0.1039***(2.96)	0.1230***(3.96)	ln*del*	0.1512***(4.55)
ln*den*	0.1196(0.46)	0.1981(0.79)	ln*den*	0.2010(0.79)
ln*ngo*	0.2936***(3.56)	0.0812(1.03)	ln*ngo*	0.2091(1.31)
ln*exp*	0.1202(0.78)	0.3063**(2.03)	ln*exp*	-0.0457(-0.31)
ln*sti*	0.1854(1.13)	-0.1782(-1.14)	ln*sti*	0.1655*(1.94)
ln*inv*	0.0007(0.10)	0.0024(0.36)	ln*inv*	0.0013(0.19)
ln*gas*	-0.4839***(-4.05)	-0.4215***(-3.68)	ln*gas*	-0.4592***(-3.95)
ln*udi* (r≤a1)	-0.2286* (-1.60)	0.2585*(1,76)	ln*udi* (r≤a1)	0.3342**(2.26)
ln*udi* (r>a1)	0.2745* (1.79)	0.3083** (2.11)	ln*udi* (a1<r≤a2)	0.3289** (2.23)
			ln*udi* (r>a2)	0.3540** (2.40)
N	290	290	N	290
trend	U-shaped	Staged increase	trend	Staged increase
R^2 (overall)	0.7972	0.8373	R^2(overall)	0.8411
F-statistics	47.61	53.52	F-statistics	47.59
P-value	0.0000	0.0000	P-value	0.0000

Note: *, **, and *** indicate the significance level is 10%, 5%, and 1%, respectively, the number in () is the value of T statistic.

population density is taken as the threshold variable, the number of non-governmental organizations has a significant negative impact on domestic waste production – the more the non-governmental originations, the less the domestic waste production.

Based on this, it is suggested that (1) cities with population density below 272 person/km^2 such as Ha'erbin, Yinchuan, Lanzhou, Xining, Kunming and Hohhot, do not have the pressure of domestic waste production at present, but they should be prepared for the situation when the population density exceeds the threshold by enhancing the residents' awareness of green consumption and recycling, or proper urban planning to avoid rapid population agglomeration; (2) the share of tertiary industry should be reasonably regulated to improve the development quality of the tertiary industry; the impact of per capita GDP has smallest impact on domestic waste production when the share of tertiary industry is between 61% and 71%, so it is necessary to properly adjust the share of tertiary industry and maintain it within a reasonable range. Additionally, the quality of service and catering industry should be improved by reducing the provision and use of disposable articles; (3) the use of new energy ought to be further promoted. The popularity of natural gas makes residents use less coal, which can reduce the generation of coal ash, and further reduce the domestic waste. In recent years, China has been vigorously promoting the policy of changing fuel from coal to natural gas, however, the problem of short supply of natural gas has gradually become prominent, and the promotion of new energy such as wind energy and solar energy is becoming a pressing issue; (4) the express packaging of recyclable materials should be used, and the express packaging recycling system established; (5) the construction of social network needs strengthening, as well as making rational use of the communication function of non-governmental organizations, and effectively promoting the concept of domestic waste reduction and waste sorting.

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