Spatiotemporal variation in the blood lead levels of Chinese children with the environmental Kuznets curve trend

Yang Lii,a,1, Chengdong Xub,c,1, Feiyian Liue, Fengbei Shenb,c, Boya Zhangf, Jingyi Zhanga, Gexin Xiafo, Ning Wanga, Ni Lina, Shaoqi Zhoug, Huijun Wanga,**, Qingfeng Duah,*

a The Seventh Affiliated Hospital, Southern Medical University, Foshan 528200, China
b Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China
c University of Chinese Academy of Sciences, Beijing 100049, China
d China National Center for Food Safety Risk Assessment, Beijing 100022, China
e CityDO Group, Hangzhou 310000, China
f National Institute of Hospital Administration, Beijing 100044, China
g College of Resources and Environmental Engineering, Guizhou University, Guiyang 550025, China
h School of Traditional Chinese Medicine, Southern Medical University, Guangzhou 510515, China

ARTICLE INFO

Keywords:
Blood lead levels
Spatial variation
Environmental Kuznets curve
Regional sustainable development
China

ABSTRACT

The environmental Kuznets curve (EKC) is often used to analyze the relationship between environmental pollution health indicators and economic development level in different regions. In developed countries, the blood lead levels (BLLs) of children have been declining fitting the EKC since the 1970s. However, such figures in China have remained at relatively high levels, without any obvious decline, since 2010. We explored spatial variations and graded countermeasures using reported data on BLLs including the lead poisoning rates (LPRs) of children. We found that there were prefectures where either the mean BLLs of the children had reached 100.00 μg/L or the LPRs of more than 40% of the children had reached 100 μg/L. When we reduced the average BLLs to 50 μg/L or lowered the proportion of children with a lead poisoning rate (LPR) above 100 μg/L to 10.00%, the EKC trend decreased, and the linear slope after 2010 became -0.202. If the areas where children’s BLLs exceeded 50.00 μg/L or the proportion of children with an LPR above 100 μg/L was more than 10.00% will be controlled, the linear slope of the EKC decrease trend after 2010 will became -0.989, and the national average of children’s BLLs would decline by 22.17%. The study concluded that children’s BLLs in different regions of China are situated at different EKC stages, and urgent prevention and control strategies must be put in place for undeveloped areas.

1. Introduction

Lead exposure has caused irreversible health damage to children (Landrigan et al., 2018; O’Connor et al., 2020), especially in underdeveloped countries (Tong et al., 2000; Attina and Trasande, 2013; Landrigan et al., 2018; Ericson et al., 2021). China has over 100 million children aged 0–6 years, accounting for 12.17% of the world’s children (Trading Economics, 2020). The health conditions of such a vast, vulnerable, and susceptible population warrant more attention. Numerous studies have indicated that there is no safe threshold for exposure to lead and that all countries should thus reduce their average blood lead level (BLL) to zero (U.S. Centers for Disease Control and Prevention, 2012; World Health Organization, 2016). Fortunately, childhood lead poisoning is preventable, and the cost-effectiveness of prevention strategies is no less than that of vaccines (U.S., President’s Task Force on Environmental Health Risks and Safety Risks to Children, 2018).

Many studies have confirmed that the relationship between environmental health and development levels in different countries and regions is in line with EKC rules (Destek and Sarkodie, 2019; Chen and Taylor, 2019). EKC is a hypothesized relationship between environmental quality and economic level. According to the theory, while environmental quality degradation is expected to occur in the early period of economic development, it is expected to improve at high
economic levels. An inverted U-shaped function is usually presented to illustrate the relationship between environmental quality and economic development. As pollution and economic development are both empirical phenomena, EKC has been widely used to model the relationship between ambient pollution concentration and economic development.

Previous studies have found that children's BLLs and economic development in developed countries are in line with the EKC theory, and that different countries are at different stages of EKC development. Among developed countries, children's BLLs have been declining for 40 years, consistent with the EKC hypothesis in the right parts of the curves, which have a downturn (Figure 1). In the US, the median BLLs of children aged 1–5 years decreased by 95% in 30 years, from 150 μg/L (1976–1980) to 7 μg/L (2013–2014). (U.S., President's Task Force on Environmental Health Risks and Safety Risks to Children, 2018). Canada's average BLL in children declined rapidly to about 5 μg/L in the past 40 years (Government of Canada, 2013; Health Canada, 2021). France's average BLL in children decreased to 14.9 μg/L in 2009 (Etchevers et al., 2014). UK and Germany presented similar decline trends in children's BLLs (Singal et al., 1988; Davies et al., 1990; Chandramouli et al., 2009; Wilhelm et al., 2007; Schulz et al., 2009).

The difference between children's BLLs and economic development in China is also in line with the EKC law, but there are unique aspects that distinguish it from that in developed countries. In the US and China, the variation trends of children's BLLs are consistent with the typical EKC. However, as China's average BLL in children reached a plateau (Figure 1) at about 50 μg/L in 2010, the right tail of the EKC, failed to continue dropping (Han et al., 2018; Zhang et al., 2020). In contrast, the right tail of the EKC in the US has continued to decline, falling to below 7 μg/L. How to make the BLLs of Chinese children continue to decline has become an important concern. The relevant departments are currently taking related measures, but the measures must not be one-size-fits-all for the different regions; more precise measures must be taken. To determine the measures that must be taken for the different regions, further research must be conducted. The key step, however, is to determine which areas in China are high-risk areas for lead poisoning so that targeted interventions can be implemented in them.

The incomplete BLL data for children in the prefecture-level regions across China make it difficult to understand the distribution of children's BLLs nationwide and impossible to provide precise scientific guidance for prevention and treatment. Obtaining complete data on children's BLLs in the prefecture-level regions nationwide through large-scale sampling is costly and time-consuming. However, studies have shown that the lead industry is associated with regional children's BLLs and LPRs (Liu et al., 2022). In China, the BLLs of children in areas with lead industries are significantly higher than those in lead-free areas, so it is important to identify the high-risk areas and obtain complete data on children's BLLs in these areas.

There is significant regional heterogeneity in children's BLLs in China. Recent research has mainly focused on the spatial distribution of children's BLLs at the provincial level or in individual provinces and cities across the country (Han et al., 2018; Li et al., 2020; Zhang et al., 2020; Wang et al., 2021). The prefecture-level variation in children's BLLs has important implications for efforts to comprehensively analyze and guide national prevention and control measures for children's BLLs throughout the country.

To analysis the spatiotemporal variation in the BLLs of Chinese children with the EKC trend, we extracted environmental and socio-economic data from some prefecture-level regions with lead industries across the country. Based on the collected spatial data, we calculated the children's BLLs in these regions, and estimated their distribution. We identified areas with a high risk of excessive children's BLLs to provide a scientific basis for prevention and control strategies to reduce children's BLLs in China and the disparity in them among different areas. Policymaking agents allocating healthcare resources to underdeveloped areas can use these data to address regional inequality in children's BLLs.
2. Data and methods

2.1. Data collection

Previous studies have shown that children's BLLs are associated with various factors, including gross domestic product (GDP), GDP per capita, secondary sector GDP, tertiary sector GDP, lead industry density, and the number of lead battery companies, lead mines, and lead smelting companies (Liu et al., 2022). In addition, it has been shown that the sources of lead absorption include diet, air, soil, and water, and the contributions of these four exposure sources to the BLLs of children aged 0–6 years in China are 86.76%, 7.79%, 5.23%, and 0.22%, respectively (Han et al., 2020). Diet has thus been shown to be the principal source. In the present study, we used residents’ dietary lead intake as a surrogate variable of children’s dietary lead intake. We also chose the following related variables: GDP per capita in prefecture-level regions, national GDP per capita, the density of the lead industry, dietary lead intake of residents, number of lead battery companies, number of lead mines, number of lead smelting companies, children’s BLLs, standard deviation (SD), and LPRs. Since 2010, children’s BLLs have been static, with only slight variations of around 50 μg/L (Han et al., 2018; Zhang et al., 2020). Therefore, we used the children's BLL data for the 2010 and 2020 period. The data included BLLs and LPRs of the Chinese children in the prefecture-level regions, and the following socioeconomic data of the leaded regions: population, GDP, areas, and numbers of the three major industries in the leaded areas (the lead mining, lead smelting and chemicals, and lead-acid battery industries) (Li et al., 2014; Zhang et al., 2020; Liu et al., 2021).

2.1.1. Children’s blood lead level data

Children’s BLL data were collected from literature sources. We used the keywords “City name AND Blood lead level AND Children” and “City name AND Trace element AND Children” to systematically search survey

Figure 2. Search strategy and selection criteria for the blood lead levels of children in China.

\[ N_{Ref}=254 \]

Exclusion criteria

A. Published before January 2010;
B. Failure to adhere to strict quality control measures;
C. Children were sampled with bias from prominent lead-contaminated areas;
D. Duplicated publications;
E. The age of survey subjects or survey area was not apparent;
F. Data were incomplete or had precision errors;
G. Sample size was less than 50.

\[ N_{Ref}=192 \]

Actual selected literature for data entry:

---

Y. Liu et al. Heliyon 8 (2022) e11609
data about children’s BLLs on PubMed, China National Knowledge Infrastructure, and the Wanfang Data Knowledge Service Platform published within the period from 2010 to 2020. We derived relevant data from primary studies on children’s BLLs rather than from literature reviews. We also adopted a rigorous data collection strategy to ensure data quality. After the initial screening, two reviewers retrieved the full texts of the selected studies to assess the studies’ eligibility against the inclusion and exclusion criteria and identify potentially relevant studies (Figure 2).

Finally, we obtained 192 regional data on children’s blood lead from the literature. The 13 regions with missing data on children’s BLLs were marked with circles and the 22 regions with missing data on children’s LPRs were marked with triangles (Figure 3).

2.1.2. Regional economic development data

We collected the following economic data from leaded regions corresponding to the year in which children’s blood lead were sampled: year, GDP, resident population, area, and GDP per capita in 2020. The data were from the regional statistical bulletin on the national economic and social development of the China Statistical Information Network (http://www.tjcn.org/tjgb/).

2.1.3. Regional lead industry data

Except for Tibet, the lead industry in mainland China was found to be focused on lead-related companies in the secondary industry, including lead mines, primary lead and secondary lead smelting companies, chemical companies, and lead-acid battery companies. The list of lead companies was obtained from several representative databases (Liu et al., 2022). We then obtained the required information including the company name, address, registered capital, industry type through the public database online.

2.1.4. Residents’ dietary lead intake data

The dietary lead intake data were from the fifth China Total Diet Study, which was conducted from 2009 to 2013, covered 20 provinces, and represented nearly 70% of the total population. The samples included the adult males aged 18–45 years old (Wu et al., 2018). 13 groups food samples, representing the dietary patterns in various geographical regions of China, were collected from 200 kinds of food. Because children cannot drink alcohol, we used the data on adults’ lead intake from only 12 food groups, excluding alcohol.

2.2. Data analysis

All the blood lead data were tested by a government-licensed medical institution in compliance with the national regulations. The characteristics of children’s blood lead data were analyzed as shown in Table 1. Previous studies have shown that different types of lead industries have various effects on the BLLs in the same region. Given the lead industry types and the sample size, we stratified the sample into three parts (Van der Kuijp, 2013; Liu et al., 2017; Ericson et al., 2021): (i) regions with only lead-acid battery companies; (ii) regions with only lead mines or a combination of lead mines and lead-acid battery companies; and (iii) regions with only primary and secondary lead smelting and chemical companies or a combination of primary and secondary lead smelting and chemical companies, lead mines, and lead-acid battery companies.

There are two main types of interpolation methods in the environmental and health fields: co-regression-based and geostatistical-based methods. Linear regression is more suitable when some co-variables have a significant statistical association with the study’s objective. Geostatistical analysis is more appropriate when the population data presented have statistically significant spatial autocorrelations. Furthermore, regression kriging (RK) can be used if the residual of the regression demonstrates spatial autocorrelation. We used the linear regression model and geostatistical methods to perform spatial interpolation for cities without lead sample data.

2.2.1. Linear regression model

For mapping BLLs in stratified regions, we used a multiple linear regression model (MLR), which could be expressed as follows:

\[ y = \beta_0 + \sum_{i=1}^{p} \beta_i x_i + \epsilon \]  

where \( y \) represents the explained variable (i.e., BLL); \( x_i \), the explanatory variables; \( p \), the number of explanatory variables; \( \beta_i \), the regression coefficients estimated using ordinary least squares (OLS); \( \beta_0 \), the model
Table 1. Descriptive characteristics of children’s blood lead data.

| Variables                                      | Descriptive characteristics |
|------------------------------------------------|----------------------------|
| Number of regions with children’s blood lead data | 192                        |
| Number of regions with BLLs                    | 178                        |
| Number of regions with LPRs                    | 181                        |
| Number of provinces with children’s blood lead data | 29                        |
| Ratio of reporting between boys and girls      | 1.28:1                     |
| Ratio of capillary blood testing to venous blood testing | 35:26                      |
| Number of regions used atomic absorption spectroscopy | 118                       |
| Number of children evaluated                  | 585,772                    |
| Average sample size in each region             | 3,051                      |

The estimation of unknown points can be represented as weighted averages of the sampled data in the neighborhood:

\[
\hat{Z}(x_i) = \sum_{n=1}^{N(h)} \omega_i Z(x_i)
\]  

where \(N(h)\) represents the number of data pairs for a specific lag \(h\). Then, the estimation of unknown points can be represented as weighted averages of the sampled data in the neighborhood:

\[
Z(x_0) = \sum_{i=1}^{n} \lambda_i Z(x_i)
\]  

where \(Z(x_0)\) represents the value of random variable \(Z(x)\) at unknown point \(x_0\); \(Z(x_i)\), the observed value at sampled point \(x_i\); \(n\), the number of sampled data close to location \(x_0\); and \(\lambda_i\), the weight assigned to the sampled point.

Regression Kriging (RK) is a combined of linear regression (LR) and OK, where LR is used to model a trend and OK is used to model the spatial correlations between regression residuals that can be explained by a spatial variogram. In theory, RK performs better than LR, and OK is used independently; however, there is no need to model the residual if LR nearly completely explains the variability of the observed variables and if the residuals have no spatial structure.

2.2.2. Geostatistical methods

Ordinary Kriging (OK) is the most commonly used kriging method. It first calculates an experimental variogram that describes the spatial data continuity and fits a variogram model. The variogram \(\gamma(h)\) is a function of lag \(h\), which calculates the variability between pairs of points \([Z(x_0) - Z(x_0 + h)]\) at different distances:

\[
\gamma(h) = \frac{1}{2N(h)} \sum_{n=1}^{N(h)} [Z(x_n) - Z(x_n + h)]^2
\]  

3. Results

3.1. Overall spatial distribution of children’s BLLs

We identified 179 prefecture-level regions with data on children’s BLLs available in the literature. We also identified 184 prefecture-level regions with lead industries, of which 114 had available data on children’s BLLs; for the remaining 70 regions, the children’s BLL data could be estimated via spatial interpolation (Table 2, Table 3). Therefore, there were 249 regions in all with data on children’s BLLs. The BLLs in the grid cells of the children in these 249 prefecture-level regions indicate the regional distribution of children’s BLLs in China. The areas with high levels of children’s BLLs are widely distributed throughout the country. The spatial distribution of these areas is shown in Figure 4.

Results for BLLs showed that the linear regression model performed best, with the lowest errors (ME = 1.7 × 10^-15; MAE = 0.24; RMSE = 0.31). With the same covariates, RK was less accurate than the linear regression model; its ME was 2.66 × 10^-4, much greater than that in the linear regression model, and the MAE and RMSE were 0.25 and 0.32, respectively. OK was not suitable for BLL estimation because it had the highest errors (ME = -3.18 × 10^-4; MAE = 0.30; RMSE = 0.37). The LPR results matched the BLL results, with the linear regression model also showing the highest accuracy in the former, while RK and OK had larger errors in all the indices (ME, MAE, and RMSE). It seemed that the linear regression model had already explained the variations in the BLLs and LPRs, and there was little spatial autocorrelation left in the linear regression residuals.

In both Figures 4a and b, the areas with serious pollution are on the right side of the Hu Line. The difference was that after the interpolation, the northern, central, and southern areas were shown to have serious children’s BLLs, as opposed to before interpolation.

The BLLs on the two sides of the Hu Line had significant regional heterogeneity: the areas with high children’s BLLs were mainly distributed on the right side of the Hu Line, especially in the eastern and southern regions. After the estimation, excluding Tibet, the areas in mainland China with the highest incidence of BLLs were found to be mainly located in Yunnan-Guangxi-Guizhou in the south, Guangdong-Fujian-Zhejiang-Jiangsu-Shandong in the east, southern Hebei-Shanxi in the north, Henan-Anhui-Jiangxi-Hunan in the center, and Shaanxi in the west, representing a semi-circular high-value area composed of northeastern Inner Mongolia and parts of Liaoning. The low-value areas were mainly distributed in Sichuan-Chongqing-Hubei, Hainan, Beijing, Shanghai, and Xinjiang. There was no apparent aggregation of children’s BLLs in the Yangtze and Yellow River areas.

3.2. Overall spatial distribution of children’s LPRs

The LPRs of children shown in the grid cells in the 249 prefecture-level regions also indicate the regional distribution of blood lead in children in China. Children’s LPRs had the most expansive distribution areas, with significant regional heterogeneity. Among the 184 prefecture-level re-

Table 2. The estimated BLLs errors of selected interpolation methods.

| Methods           | Variables                                      | ME     | MAE    | RMSE   |
|-------------------|------------------------------------------------|--------|--------|--------|
| Linear regression | GDP, GDP per capita, lead company density, residents’ dietary lead intake | 1.70 × 10^-15 | 0.24  | 0.31   |
| Regression Kriging| GDP, GDP per capita, lead company density, residents’ dietary lead intake | 2.66 × 10^-4 | 0.25  | 0.32   |
| Ordinary Kriging  | —                                              | -3.18 × 10^-4 | 0.30  | 0.37   |
regions with lead industries, children's LPRs were estimated via spatial interpolation in 79 regions. Among the 249 prefecture-level regions, the children's LPRs in 65 lead-free industrial areas were collected from published literature. The spatial distribution of these areas is shown in Figure 5.

In both figures 5a and b, most of the large areas with serious pollution are on the right side of the Hu Line, and the difference is that, after

| Methods               | Variables | ME    | MAE   | RMSE  |
|-----------------------|-----------|-------|-------|-------|
| Linear regression     | BLLs      | $5.63 \times 10^{-7}$ | 0.30  | 0.41  |
| Regression Kriging    | BLLs      | $4.14 \times 10^{-3}$ | 0.32  | 0.43  |
| Ordinary Kriging      | —         | $9.58 \times 10^{-3}$ | 0.49  | 0.62  |

Figure 4. Estimated distribution map for prefecture-level regions with children's blood lead level data. (a) shows the spatial distribution of children's BLLs and Standard Deviation of BLLs in prefecture-level cities in China before interpolation. (b) shows the spatial distribution of children's BLLs and Standard Deviation of BLLs in prefecture-level cities in China after interpolation.
interpolation, areas with serious children's BLLs are prominent in the southern part, as opposed to before interpolation.

The areas with high children's LPRs are mainly distributed on the right side of the Hu Line, especially in the eastern and southern regions. The areas with high children's BLLs in mainland China were found to be Yunnan-Guangxi-Guizhou in the south, Fujian-Zhejiang-Shandong in the east, Shanxi in the north, Henan-Anhui-Jiangxi-Hunan in the center, and Shaanxi in the west, representing a semi-circular high-value area and a line of Hebei-Liaoning, a beaded thread composed of Gansu and parts of Ningxia. The low-value areas were mainly distributed in Sichuan-Chongqing-Hubei, Hainan, Beijing, Tianjin, Shanghai, and Xinjiang. There was no apparent aggregation in China's Yangtze and Yellow River regions.

Figure 5. Estimated distribution of children's LPRs in prefecture-level regions in China. (a) shows the spatial distribution of children's BLLs and LPRs in prefecture-level cities in China before interpolation. (b) shows the spatial distribution of children's BLLs and LPRs in prefecture-level cities in China after interpolation.
3.3. Regional risk assessment and graded prevention and control of children’s BLLs

For a deeper understanding of the presented data, we drew on the World Bank's classifications and used different colors to indicate the current economic development levels (2020 GDP per capita). The areas with a GDP per capita of USD0–3,000 or USD3,000–5,000 were classified as underdeveloped. Those with a GDP per capita of USD5,000–10,000 were listed as intermediate developing areas, reflecting a limited ability to improve children’s BLLs. Those with a GDP per capita higher than USD10,000 were defined as developed areas, demonstrating the ability to minimize children’s BLLs. Figure 6 shows that most economically developed areas with a GDP per capita above USD10,000 are located in zones with lower children’s BLLs.

By contrast, areas with lower economic development were associated with higher children’s BLLs. From the perspective of hierarchical prevention and control of children's lead toxicity, the most critical task is to reduce children’s BLLs in the nine highest-risk areas. Among these nine areas, only Kunming (KM) has a GDP per capita above USD10,000, reflecting the ability to lower children’s BLLs: the eight other areas (Suqian [SQ], Baoding [BD], Yuncheng [YC], Linfen [LF], Honghe [HHZ], Hechi [HC], Samenxia [SMX], and Chenzhou [CHZ]) may need financial subsidies and investments from the central government.

The critical areas for governance are those revealing BLLs above 50 μg/L and LPRs above 10%. For the areas with a GDP per capita of more than USD10,000, the national government only issued lead prevention standards for guidance. Twenty-six regions with a GDP per capita of USD5,000–10,000 (such as Xinxiang [XX], Qujing [QJ], Yunfu [YF], Jinzhou [JZ], Zhoukou [ZK], Liaocheng [LC], Huainan [HN], Chifeng [CF], Ganzhou [GZ], Dali [DL], Wuzhong [WZ], Hanzhong [HZ], Yiyang [YY], Loudi [LD], Anyang [AY], Puyang [PY], Qiannan [QN], Anqing [AQ], Chuxiong [CX], Huaihei [HB], Dezhou [DZ], Xining [XN], Baoji [BJ], Yuelang [YUY], and Langfang [LF]) need to be given at least partial financial support. Finally, funds and other resources should be invested in the 12 regions with a GDP per capita of USD0–5,000 that cannot otherwise lower the children's BLLs (Baiyin [BY], Fuyang [FY], Shaoxing [SY], Huludao [HLD], Qiandongnan [QDN], Meizhou [MZ], Kizilsu Kirgiz [KK], Tongren [TR], Zaotong [ZT], Haidong [HD], Nuijiang [NJ] and Lu'an [LA]). These areas are becoming China’s key investment areas, which can significantly improve the efficiency of national lead pollution prevention and control measures.

4. Discussion

4.1. Analysis of areas with high BLL

The regions with a high risk of lead toxicity are mainly distributed east of the famous Hu Line, especially in the eastern and southern regions. Stratification heterogeneity is primarily associated with socio-economic and environmental factors. The Hu Line also represents the regional heterogeneity of aerosol spray, a transmission medium for lead. Aerosol pollution is more likely related to the human activities east of the Hu Line, but natural processes dominate in the areas west of the line (Zheng, 2012; Zhang and Pan, 2020). Lead and its compounds are widely used in industrialization, including metallurgy, storage batteries, printing, paintings, glazes, solders, and so forth. Compared with the western regions, China’s eastern and central regions are more industrialized, with more lead industries. Thus, the distribution of lead industries partly explains why the high-BLL areas are concentrated on the east side of the Hu Line. There is no systemic risk of high BLLs among the Chinese children living in the Yangtze and Yellow River regions, which confirms that the environmental pollution caused by China's lead industry is concentrated in the areas with lead industries.

The high-risk spots are mainly Honghe, Hechi, Chenzhou, and Kunming. These areas are rich in mineral resources, such as lead and zinc, and have a high distribution of smelting enterprises (Hou et al., 2012; Zhang and Pan, 2020).
2011; Chen et al., 2019). Yuncheng and Linfen are major mining cities, and the large number of coal-based, electronics, and pharmaceutical factories in them causes atmospheric lead pollution (Jin, 2015). Baoding, Suqian, and Sanmenxia have many small mining companies and long histories of smelting and lead recycling. Small smelting companies often discharge waste into the environment, causing degradation (Zhao, 2014). The residents of these areas may need to be encouraged to migrate to areas with low environmental lead pollution to reduce the impact of the lead industry on children's BLLs. The effects of environmental strategies and policies are always seen after a long period of time. The migration of children living in high-lead-pollution areas is the fastest way to reduce children's BLLs. Local governments should develop strategies and policies to support the migration of children away from these areas.

4.2. Regional hierarchical prevention and control

Apparent regional heterogeneity is reflected in the distribution of children's BLLs in China. Currently, the total resources for preventing and controlling children's BLLs are currently limited to the national level. The unfocused investment plan lacks cost-effectiveness due to the regional differences in development stage and availability of financial resources. For instance, well-developed areas with sufficient financial resources are more likely to improve their environments, aligning with the EKC. According to recent research, children living in economically developed areas have lower BLLs than children living in underdeveloped areas. The Chinese government has recently invested considerable resources in improving the environment and controlling pollution (Landrigan et al., 2018), many policies have also been effective in controlling BLLs in adults (Li et al., 2021). However, in underdeveloped areas, the investment has not achieved evident results. According to previous research, graded prevention and control of children's BLLs will distribute resources and make the use of interventions more efficient (Dwyer-Lindgren et al., 2019). Compared with the EKC of the US, China's EKC has entered the platform period and is not likely to decline. For it to decline steadily, measures must be taken, and the subregional classification measures are more efficient. Investment at the national level should focus on strengthening continuous monitoring, and the first increments of financial aid should be concentrated on those nine areas with the highest children's BLLs. If, through policy and governance funds, the focus over the course of the decade will be on the 9 areas with severe BLLs in children, children's BLLs in those areas could be reduced to under 50.00 μg/L, and their LPRs could decline to 10.00%. This will lead to a significant drop in the national averages of BLLs and LPRs (4.43% and 20.15%, respectively). The EKC trend will decrease, and the linear slope after 2010 will be -0.202 (children's BLLs nationwide will drop from 55.267 μg/L to 53.248 μg/L, so the slope of the decline will be (53.248–55.267)/10 = -0.202). The graded prevention and control plan, when resources permit, must also cover the 12 areas with a GDP per capita of USD0–5,000 and the 26 areas with a GDP per capita of USD5,000–10,000. This will cause a significant drop in the national averages of BLLs and LPRs (by 22.17% and 60.99%, respectively). The EKC trend will also decrease, and the linear slope after 2010 will be -0.989 (children’s BLLs nationwide will drop from 55.267 μg/L to 53.248 μg/L, so the slope of the decline will be (53.248–55.267)/10 = -0.989) (see Figure 7). Therefore, regional hierarchical prevention and control are conducive to reducing children's BLLs in China. Such measures are also applicable in preventing and controlling other heavy metal pollution and related health issues.

The spatial interpolation method can estimate and identify most areas with high children's BLLs to compensate for the shortage of data. Further research may find a few missed hot spots with the continuous accumulation of data. This will be a valuable step toward completing the map of the distribution of Chinese children's BLLs. It will also provide a new perspective and methodology for controlling the overall risk posed by other heavy metal and environmental pollution problems. It was found in the present study that the spatial interpolation of public data is a low-cost way to identify key risk areas.

5. Conclusions and limitations

The present study was the first to map the prefecture-level regions with lead industries in China in comparison with the EKC. We found that
the children’s BLLs present significant regional heterogeneity at the prefecture level. The regions with a high risk of lead toxicity are mainly those with lead industries found east of the famous Hu Line, especially in the eastern and southern regions. In contrast to the developed countries, the EKCs of these regions have shown no obvious decline in children’s BLLs after 2010. The results of present study indicate that urgent prevention and control strategies need to be put in place by the central and local governments to control the situations, especially for the underdeveloped areas, where specific financial investments are desperately required for monitoring or even for the migration of the local people.

Although the relationship between environmental pollution health indicators and economic development level in different regions is line with the EKC, and the Chinese children’s BLLs and China’s economic development level are also in line with the EKC laws, the shape and inflection point of EKC at different stages of development in different regions in China will vary due to the specific parameters of such regions. In the time series analysis, it was found that the children’s BLLs in the 50 μg/L platform period after 2010 could decline with a good prevention and control policy, and that the children’s BLLs in the areas with a high GDP per capita that were found in the spatial distribution were often in the low-LPB and low-BLL quadrants (Figure 6.). This confirms that children’s BLLs must be classified and graded for prevention and control, and provides a policy basis for hierarchical and subregional prevention and control. However, region-specific EKC studies must be conducted with greater depth and using more local data.

Although the temporal dimension explains the changing trend of BLLs in children at different stages of development; from the spatial dimension, the BLLs of children in different regions were also analyzed. The results of analysis confirm that children’s BLLs must be classified and graded for prevention and control in different regions, and provide a policy basis for hierarchical and subregional prevention and control. The present study had some limitations that should be addressed. First, city-scale data were collected: the environmental and industrial conditions in each city could present spatial heterogeneity, which could introduce uncertainty because of spatial confounding. Second, although data on some factors were collected to explain the spatial variation of children’s BLLs, it was difficult to find data on such factors, which could have introduced uncertainties in the study’s results.

Declarations

Author contribution statement

Qingfeng Du: Conceived and designed the experiments, Contributed reagents, materials, analysis tools or data, Wrote the paper.
Huijun Wang: Conceived and designed the experiments, Wrote the paper.
Yang Liu: Conceived and designed the experiments, Performed the experiments, Contributed reagents, materials, analysis tools or data, Wrote the paper.
Chengdong Xu: Conceived and designed the experiments, Analyzed and interpreted the data, Contributed reagents, materials, analysis tools or data, Wrote the paper.
Feyian Liu, Fengbei Shen: Analyzed and interpreted the data, Wrote the paper.
Boya Zhang, Jingyi Zhang: Contributed reagents, materials, analysis tools or data.
Gexin Xiao, Ning Wang, Ni Lin, Shaoqi Zhou: Performed the experiments, Contributed reagents, materials, analysis tools or data.

Funding statement

Professor Qingfeng Du was supported by National Key R&D Program of China (2020YFC2006400), and Science Foundation of Guangdong and Foshan, China (2020001005585, 2018A0303130346, F50A-KJ819-4901-0257), and Professor Shaoqi Zhou was supported by the Department of Science & Technology of Guizhou Province ([2022]213 and [2023]60).

Data availability statement

Data will be made available on request.

Declaration of interests statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

References

Attina, T.M., Tranandre, L., 2013. Economic costs of childhood lead exposure in low-and middle-income countries. Environ. Health Perspect. 9, 1097–1102.
Chandramouli, K., Steer, C., Ellis, M., Emond, A., 2009. Effects of early childhood lead exposure on academic performance and behaviour of school age children. Arch. Dis. Child. 94, 844–848.
Chen, Q., Taylor, D., 2019. Economic development and pollution emissions in Singapore: evidence in support of the Environmental Kuznets Curve hypothesis and its implications for regional sustainability. J. Clean. Prod. 243, 118637.
Chen, W.P., Yang, Y.T., Jiang, H.Y., 2019. Serum lead level and its impact on development and thyroid function among preschool children from mining area. Guangxi Med. J. 41, 1142–1145.
Davies, D.J., Thornton, L., Watt, J.M., Culbard, E.B., Harvey, P.G., Delves, H.T., Sherlock, J.C., Smart, G.A., Thomas, J.F.A., Quinn, M.J., 1990. Lead intake and blood lead in 2-year-old U.K. urban children. Sci. Total Environ. 90, 13–29.
Destek, M.A., Sarkodie, S.A., 2019. Investigation of environmental Kuznets curve for ecological footprint: the role of energy and financial development. Sci. Total Environ. 650, 2483–2489.
Dwyer-Lindgren, L., Cork, M.A., Sligar, A., Steuben, K.M., Wilson, K.F., Provost, N.R., Mayala, B.K., VanderHeide, J.D., Collison, M.L., Hall, J.B., Bleib, M.H., Carter, A., Frank, A.T., Donnern-Schultz, D., Breuer, R., Casey, D.C., Deshpande, A., Earl, L., Behera, C.E., Farag, T.H., Henry, N.J., Kinyoki, D., Mareczak, L., Nixon, M.R., Ogugbue, B., Figgot, D., Reiner Jr., R.C., Ross, J.M., Shaefler, L.E., Smith, D.L., Weaver, N.D., Wierse, K.E., Eaton, J.W., Justman, J.E., Opio, A., Sartorius, B., Tanner, F., Wahiri, N., Piot, P., Murray, C., Hay, S.I., 2019. Mapping HIV prevalence in sub-Saharan Africa between 2000 and 2017. Nature 570 (7760), 189–193.
Ericson, B., Hu, H., Nath, E., Ferrato, G., Sinitsky, J., Taylor, M.F., 2021. Blood lead levels in low-income and middle-income countries: a systematic review. Lancet Planet. Health 5, e145–e153.
Etchevers, A., Biret, P., Lecoffre, C., Bidondo, M.L., Le Strat, Y., Glorrenec, P., Le Terrire, A., 2014. Blood lead levels and risk factors in young children in France, 2008–2009. Int. J. Hyg. Environ. Health 217, 528–537.
Government of Canada, 2013. Risk Management Strategy for Lead https://www.canada.ca/en/health-canada/services/environmental-workplace-health/reports-publications/environmental-contaminants/risk-management-strategy-lead.html.
Han, Z., Guo, X., Zhang, B., Liao, J., Nie, L., 2018. Blood lead levels of children in urban and suburban areas in China (1997–2015): temporal and spatial variations and influencing factors. Sci. Total Environ. 625, 1659–1666.
Health Canada, 2021. Lead in Canadians, https://www.canada.ca/en/health-canada/services/environmental-workplace-health/reports-publications/environmental-contaminants/human-biomonitoring-resources/lead-canadians.html.
Hou, B.L., Wang, A.F., Shi, W.Y., Che, L., Xiao, D.M., 2011. Investigation of blood lead levels and related factors in children aged 0.16 years in Chengzhou City. China Mater. Child Heal Care. 26 (13), 1994–1995.
Jin, N., 2015. About the detection and analysis of 1000 children’s blood lead in Shaxi Province. Modern Chin. Medi. Appl. 7, 275–276.
Landrigan, P.J., Fuller, R., Acosta, N.J., Adayi, O., Arnold, R., Basu, N., Balde, A.B., Bertollini, R., Bose-O'Reilly, S., Boufford, J.I., Breynie, P.N., Chiles, T., Mahdiol, C., Coll-Seck, A.M., Cropper, M.L., Fohli, J., Fuster, V., Greenstone, M., Haines, A., Hamran, D., Hunter, D., Kharra, M., Krugman, A., Lapeyre, B., Lohani, R., Martin, K., Mathiasan, V.K., McEman, A., Murray, C.J.L., Naliamanjarja, J.D., Perera, P., Potoczny, J., Preker, A.S., Ramesh, J., Rockström, J., Salinas, C., Samson, L.D., Sandiliy, K., Stoy, P.D., Smith, R.K., Stein, A., Stewart, R.B., Suk, A.W., Schayy, O., Yadama, G.N., Yumkella, K., Zhong, M., 2018. The Lancet Commission on pollution and health. Lancet 391, 462–512.
Li, M.M., Cao, J., Xu, J., Cai, S.Z., Shen, X.M., Yan, C.H., 2014. The national trend of blood lead levels among Chinese children aged 0–18 years old, 1990–2012. Environ. Int. 71, 109–117.
Li, M.M., Gao, Z.Y., Dong, C.Y., Wu, M.Q., Yan, J., Cao, J., Ma, W.J., Wang, J., Gong, Y.L., Xu, J., Cai, S.Z., Chen, Y., Xu, S.Q., Song, S., Tang, D., Zhang, J., Yan, C.H., 2020. Contemporary blood lead levels of children aged 0.84 months in China: a national cross-sectional study. Environ. Int. 134, 105280.
Li, Y.N., Chen, J., Bu, S.H., Wang, S., Geng, X., Guan, G., Zhao, Q.W., Ao, L., Qu, W.D.,
Zheng, Y.X., Jin, Y., Tang, J., 2021. Blood lead levels and their associated risk factors in
Chinese adults from 1980 to 2018. Ecotoxicol. Environ. Saf. 218, 112294.
Liu, Y., Liu, F., Dong, K.F., Wu, Y., Yang, X., Yang, J., Tan, H., Niu, X., Zhao, X., Xiao, G., Zhou, S.,
2021. Regional characteristics of children’s blood lead levels in China: a systematic
synthesis of national and subnational population data. Sci. Total Environ. 769, 144649.
Liu, W., Tian, J., Chen, L., Guo, Y., 2017. Temporal and spatial characteristics of lead
emissions from the lead-acid battery manufacturing industry in China. Environ.
Pollut. 220, 696–703.
O’Connor, D., Hou, D., Ok, Y.S., Lanphear, B.P., 2020. The effects of inequitable lead
exposure on health. Nat. Sustain. 2, 77–79.
Schulz, C., Angerer, J., Ewers, U., Heudorf, U., Wilhelm, M., 2009. Revised and new
reference values for environmental pollutants in urine or blood of children in
Germany derived from the German environmental survey on children 2003-2006
(GerES IV). Int. J. Hyg Environ. Health 212 (6), 637–647.
Singal, G.M., Gatrad, A.R., Howse, P.M., Johnson, K.W., Ganley, M., Thomas, A.,
Braithwaite, R.A., Brown, S.S., 1988. Blood lead, ethnic origin, and lead exposure.
Arch. Dis. Child. 63 (8), 973–975.
Tong, S., Schiendling, Y.E., Prapamontol, T., 2000. Environmental lead exposure: a public
health problem of global dimensions. Bull. World Health Organ. 78, 1068–1077.
Trading Economics, 2020. Statistical Table of the Total Number and Proportion of
Chinese Children (Aged 14 and under) from 2010 to 2018
http://data.chinaobao.com/hphj/2020/0494X10H020.html.
U.S., President’s task Force on environmental health risks and safety risks to children,
2018. The Federal Action Plan to Reduce Childhood Lead Exposures and Associated
Health Impacts. https://www.epa.gov/sites/production/files/2018-12/documents/
redactionplan_lead_final.pdf.
U.S. Centers for Disease Control and Prevention, 2012. Recommendations of the Advisory
Committee for Childhood Lead Poisoning Prevention
https://www.cdc.gov/ncbddd/lead/acclpp/Final_Document_030712.pdf.
Van der Kuip, T.J., Huang, L., Cherry, C.R., 2013. Health hazards of China’s lead-acid
battery industry: a review of its market drivers, production processes, and health
impacts. Environ. Health 1, 1–10.
Wang, S., Jin, Y., Chen, J., Lu, I., Li, Y.N., Zhao, Q.W., Bu, S.H., Geng, X., Guan, G.,
Qu, W.D., Zheng, Y.X., Tang, J.L., 2021. Blood lead levels of Chinese children
from 1991 to 2020: based on Monte Carlo simulation. Environ. Pollut. 278, 116823.
Wilhelm, M., Ewers, U., Wittsiepe, J., Fürst, P., Hölzer, J., Eberwein, G., Angerer, J.,
Marczynski, B., Ranh, U., 2007. Human biomonitoring studies in north rhine-
Westphalia, Germany. Int. J. Hyg Environ. Health 210 (3), 307–318.
World Health Organization, 2016. Lead Poisoning and Health
http://www.who.int/mediacentre/factsheets/fs379/en/.
Wu, Y.N., Zhao, Y.F., Li, J.G., 2018. The Fifth China Total Diet Study. Science Press,
Zhang, L.L., Pan, J.H., 2020. Spatial-temporal pattern of population exposure risk to PM2.5
in China. China Environ. Sci. 40 (1), 1–12.
Zhang, Y., O’Connor, D., Xu, W., Hou, D., 2020. Blood lead levels among Chinese children:
the shifting influence of industry, traffic, and e-waste over three decades. Environ.
Int. 135, 105379.
Zhao, Q., 2014. Analysis of blood lead levels of 6000 children in Baoding city, Hebei
province. Shanxi Medi. J 12, 1368–1369.