Ecological risk assessment of soil cadmium in China’s coastal economic development zone: a meta-analysis

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ABSTRACT

The coastal area of China has faced major strategic planning and environmental pollution, including heavy metals pollution. This study aimed to provide a comprehensive evaluation of the effects of Cd pollution on the ecology in coastal areas of China. A soil Cd pollution database of 300 counties or districts in coastal areas was screened from academic dissertations and academic journal papers. Based on the database, the ecological risk was evaluated using entropy methods and probabilistic ecological risk assessment (PERA), and the advantages and disadvantages of these methods were analyzed. In China’s coastal areas, the soil Cd content in 10.33% of the counties was higher than the minimum of risk control value (1.5 mg/kg), and in 4.00% of the counties was higher than the maximum of risk control value (4.0 mg/kg). The ecological risks were highly compatible with national strategic planning areas. Guangxi Province, Zhejiang Province, and Guangdong Province ranked among the top three coastal areas for soil Cd contamination, and the ecological risks were 18.80%, 17.89%, and 15.77% at the maximum no-effect concentration/lowest effect concentration (NOEC/LOEC) level. This study can provide insights to policymakers regarding the protection of ecosystems threatened by heavy metals in the process of regional strategic planning.

INTRODUCTION

In the past few decades, combined with the rapid economic development in China, environmental quality has faced significant challenges. Heavy metals, which are a typical type of pollutant, have attracted widespread attention (Marrugo-Negrete, Pinedo-Hernandez, and Diez 2017; Yang et al. 2018). Heavy metal contamination and accumulation in soil are a serious problem worldwide owing to the toxicity, abundant sources, non-biodegradable properties, and accumulative behaviors of these metals (Hu et al. 2017). Heavy metals originate from natural sources and anthropogenic activities. The main anthropogenic activities include mineral resources exploration, metal smelting and processing, factory emissions, fertilizer and pesticide input, and sewage irrigation (Chen et al., 2014; Ma et al. 2016; Reboredo et al. 2019). Coastal areas, which are rapidly developing economic zones in China, have been increasingly disturbed by human activities, thereby resulting in severe heavy metals pollution. The most widely studied metals include Pb, Cd, Cr, Hg, and As (Shi et al. 2018). However, the contamination levels of Cd and As are higher than those of the other metals (Wei and Yang 2010), and Cd pollution is the most serious soil pollution in farmland in China (Chen et al. 2016). Therefore, Cd pollution is of greatest concern to the government and the public in China, and a pilot project has been launched to remediate cropland contaminated by Cd in Hunan Province (PGHU 2014-2016; Xu et al. 2019). Heavy metals pollution in coastal areas is a global problem, and it affects countries such as Vietnam, Turkey, and America (Baltas et al. 2017; Costa-Boeddeker et al. 2017; Polidoro et al. 2017).

Many previous studies tended to reveal the heavy metals pollution conditions and evaluate their ecological risks in selected study areas, especially in coastal areas since they threaten the security of terrestrial and marine ecosystems (Harikrishnan et al. 2017). The heavy metals pollution in the Beijing-Tianjin-Hebei region, Yangtze River Delta region, and Pearl River Delta region, which are the three regions at the forefront of China’s economic development, has received extensive attention from researchers (Yang et al. 2018). Shi et al. (2018) distinguished the spatial distribution of the ecological risks from multiple heavy metals within the region around the Bohai Sea and the Yellow Sea. Some studies have focused on the Yangtze River Delta...
region and the Pearl River Delta region in China (Li et al., 2015a; Gao and Wang 2018; Lu and Wang 2018), as well as agricultural areas in Guangxi Province (Liu et al. 2018). According to the national communique of soil pollution survey, the heavy metals concentration in sampling sites exceeded the standard (Grade II environmental quality standard for soils in China (GB15618-1995)) by an average of 16.1%, which showed that the soil in cultivated land has been heavily contaminated in some regions (MEP of China 2014). The overall macro-evaluation of soil heavy metals pollution at the national scale has been conducted in a previous study (Yang et al. 2018). However, the overall macro-evaluation focused on health risks, but ecological risks were omitted. With the development of national strategies in the Xiong’an New Area (XANA) and Guangdong-Hong Kong-Macao Greater Bay Area, the importance of coastal areas in China is increasing and many large regional plans are being drawn up or implemented (Xiao and Zhao 2017; Hui et al. 2018). An overall macro-evaluation of ecological risks in coastal areas is urgently needed, which will facilitate the systematic transformation of cities and regions to fulfill sustainable development goals (Lu, Cao, and Wang. 2019a; Lu et al. 2019b).

The ecological risk assessment (ERA) is an effective tool to evaluate the impact of chemical contaminants on ecosystems (Shi et al. 2018). The selection of an ERA method is the key to evaluation. According to the evolution of ERA methods, three methods, namely the hazard quotient (HQ), species sensitivity distribution (SSD), and probabilistic ecological risk assessment (PERA), are commonly used. The HQ method, which mainly consists of the single factor index, Hakanson potential ecological risk index, and Nemerow integrated pollution index, is the most widely used method for evaluating ecological risk (Ke et al. 2017; Wu et al. 2018). The use of the SSD method has increased in scientific and administrative activities since the 1990s. Although the SSD method has been used in some studies, compared with the HQ method, the large and precise toxicity data demands in the SSD model hinder the more intensive promotion of the method (Del Signore et al. 2016; Zhang et al. 2017; Gao et al. 2019). The HQ and SSD methods belong to the group of entropy methods. PERA, which consists of the SSD model and joint probability curve (JPC), is more frequently used to quantitatively evaluate the ecological risk of pollutants (Xu et al. 2015; Shi et al. 2016; Zeng et al. 2016). The advantages and disadvantages of different methods have been briefly discussed in previous studies, but only qualitative, non-comprehensive descriptions have been provided (Yang et al. 2007; Xu et al. 2019). A quantitative comparative analysis of these methods is urgently needed. In particular, the identification of the most suitable method for evaluating ecological risk for policymaking in coastal areas of China was one of the main purposes of this study.

This study intended to assess the soil Cd pollution levels and ecological risks in coastal regions in China on a macro-regional scale. The study area included all the mainland coastal provinces and municipalities directly controlled by the central government. The concentration of Cd exposure in soil was screened from peer-reviewed papers and dissertations published from 2013 to 2018. The objectives of this study were as follows. First, it aimed to evaluate the pollution level and ecological risk of Cd in China’s coastal economic development zone; second, it attempted to comparatively analyze the advantages and disadvantages of different ERA methods using a qualitative approach; and finally, it aimed to identify the hot spots and geographical features of pollution and ecological risks in order to provide references from an environmental perspective for regional development planning in China.

**Data sources and research methods**

**Study area**

Coastal administrative areas of China consist of 11 provinces (or municipalities directly controlled by the central government). Because Beijing surrounded by Hebei Province is the capital city of China and the core of the Beijing-Tianjin-Hebei region, it was necessary to include Beijing in the study area. In this study, the coastal areas of China exceed the limits of the coastal administrative areas, including 11 coastal provinces (municipalities) and Beijing. As shown in **Figure 1**, a total of 12 provincial-level regions were selected as research areas along the coast of China. The study area covered the Beijing-Tianjin-Hebei region, Yangtze River Delta region, Pearl River Delta region, and Guangdong-Hong Kong-Macao Greater Bay Area, which are fast-growing areas of the Chinese economy and have a high degree of urbanization. However, while their economy is developed, these regions also face significant environmental challenges, including heavy metals contamination in soil.

**Data collection**

Cd was the priority heavy metal in this study. The time span of the dataset was from 2013 to 2018. The data were screened from academic dissertations and academic journals from the Web of Science (WOS) and China National Knowledge Infrastructure (CNKI) databases. From the WOS database, 229 literatures were screened using the keywords “heavy metal,” “soil” and “China.” In addition, 521 literatures were screened using the keywords “heavy metal” and “soil” from the
The potential ecological hazard index, which was developed by Hakanson (1980), is a method for evaluating the heavy metals contamination in soil or sediments from the perspective of sedimentology; it is based on the characteristics of heavy metals and their environmental behaviors (Hakanson 1980). The formula is as follows:

\[ E_i = T_i \times C_i \]  

(2)

\[ C_i = \frac{C_i}{C_{ir}} \]  

(3)

where \( E_i \) is the potential ecological risk index of a single heavy metal, \( T_i \) is the toxicity response parameter for a single heavy metal, \( C_i \) is the pollution index of heavy metal \( i \), \( C_i \) is the concentration of pollutant \( i \) in the soil (mg/kg), and \( C_{ir} \) is the reference value of heavy metal \( i \) where the background value of the heavy metal in soil is generally used as the reference value (Table S2). The specific classification criteria of \( E_i \) for a single pollutant are shown in Table 1.

Regarding the setting of the toxicity response parameters, the toxicity response coefficient of heavy metals was set by referring to the calculation results of Hakanson (1980), and the corresponding toxicity coefficient of Cd was 30.

Species sensitivity distribution method

In general, the SSD for a chemical can be derived by the following steps: (1) toxicity data collection, (2) data processing, (3) curve fitting, and (4) calculation of the 5% hazard concentration (HC5). The risk quotient can be identified according to the following steps: (1) exposure assessment, (2) calculation of the predicted no-effect concentration (PNEC), and (3) calculation of the risk quotient (Wang et al. 2017; Shi et al. 2018; Xu et al. 2019).

Toxicity data on the toxic responses of native species in China to Cd were screened from the USEPA ECO-TOX database, WOS database, and CNKI database. The data were screened for two levels of standards, including the first level for the half lethal effect concentration (LC50), half-maximal effective concentration (EC50), and median inhibitory concentration (IC50), and the second level for the maximum no-effect concentration (NOEC) and lowest effect concentration (LOEC). The rules for the processing of toxicity data were consistent with the

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\begin{array}{c|c}
\text{Table 1. Classification criteria of the potential ecological risk index (} E_i \text{).} \\
\hline
E_i & \text{Degree of ecological risk of a single pollutant} \\
\hline
< 40 & \text{Low} \\
40 \leq E_i < 80 & \text{Moderate} \\
80 \leq E_i < 160 & \text{High} \\
160 \leq E_i < 320 & \text{Slightly heavy} \\
E_i \geq 320 & \text{Heavy} \\
\hline
\end{array}
\]

Methodology for ecological risk assessment

Hazard quotient method

The single factor pollution index and potential ecological hazard index were calculated to represent the ecological risk of soil Cd pollution using the HQ method.

The single factor pollution index is widely used for evaluating the ecological risk of single pollutants. It is calculated as the following computational formula:

\[ P_i = \frac{C_i}{S_i} \]  

(1)

where \( P_i \) is the environmental quality index of pollutant \( i \) in the soil, \( C_i \) is the concentration of pollutant \( i \) in the soil (mg/kg), and \( S_i \) is the evaluation standard of pollutant \( i \) (mg/kg). The classification standard of the environmental quality index is as follows: \( P_i \leq 1 \): non-contamination; \( 1 < P_i \leq 2 \): slight contamination; \( 2 < P_i \leq 3 \): medium contamination; \( P_i > 3 \): heavy contamination.

The location of the study area.
methods described in previous studies (Shi et al. 2016, 2018; Xu et al. 2019). In total, 20 effective LC/EC/IC_{50} toxicity data and 16 NOEC/LOEC toxicity data on toxic effect for Cd were collected for native species in China. In this study, ETX 2.0 software was used to construct the SSD model and calculate the HC_{5}, which means that all species affected by the toxic effects of Cd do not exceed the threshold of the acute/chronic concentration of Cd with 5% of the total number of species affected. In this study, HC_{5} at the NOEC/LOEC level was used as the PNEC value, which had high credibility (Wang et al. 2015).

The quotient method was deployed to calculate the ecological risk of Cd in the SSD method. The standard value was replaced by the PNEC in the single factor index formula to calculate the risk value of Cd (Hu et al. 2012), which could be expressed according to the following formula:

\[ Q_R = \frac{C_i}{C_{PNE}} \]  

where \( Q_R \) is the ecological risk, \( C_i \) is the pollutant exposure concentration, and \( C_{PNE} \) is the PNEC. Generally, HC_{5} at the NOEC/LOEC level was used as the PNEC value. In order to evaluate the ecological risk more scientifically, the ecological risk at the LC/EC/IC_{50} level was also evaluated. The HC_{5} at the LC/EC/IC_{50} level was used as the dividend instead of the \( C_{PNE} \) in formula (4). When \( Q_R < 0.1 \), it means that Cd poses a low risk to the environment (low risk). When 0.1 < \( Q_R < 1.0 \), it means that Cd poses a certain risk to the environment (medium risk) and the associated risk sources need to be tracked. When \( Q_R > 1.0 \), it indicates that the chemicals pose a serious risk (high risk) to the environment and corresponding risk reduction measures need to be taken.

Probabilistic ecological risk assessment

PERA consists of the SSD and JPC. The SSD curve was consistent with that in Section 2.3.2 and the HC_{5} was also needed for evaluation. The main difference between this method and the abovementioned method is the method of risk characterization. PERA can represent the quantitative relationship between the concentration of Cd and the proportion of affected species, which has been applied frequently in previous studies (Shi et al. 2018; Xu et al. 2019). The risk probability is presented as the integral area of the region of the JPC curve and the horizontal and vertical axes, namely the expected total risk.

Data analysis

All the statistics were processed by Microsoft Office 2016, and parts of the figures were created using ArcGIS 10.0. ETX 2.0 software was used to simulate the results of the SSD and PERA (RIVM, 2001).

Results and discussion

Distribution characteristics of soil Cd in coastal areas of China

Spatial distribution of Cd

The distribution of Cd in the surface soil of coastal areas in China is illustrated in Figure 2. The classification was based on the environmental quality standard for soils (GB15618-2018). The standard value depends on the soil pH level. The minimum and maximum of risk screening values are 0.3 and 0.8 mg/kg at different pH levels, while the minimum and maximum of risk control values are 1.5 and 4 mg/kg at different pH levels, respectively. The concentrations of Cd in the study area ranged from 0.01 mg/kg to 90.30 mg/kg (average concentration of 1.21 mg/kg), and the maximum value of 90.30 mg/kg was found in Zhuji County, Zhejiang Province. In China’s coastal areas, the soil Cd content in 61.33% of the counties was lower than the minimum of risk screening value (0.3 mg/kg), and in 10.33% of the counties was higher than the minimum of risk control value (1.5 mg/kg), that in 4.00% of the counties was higher than the maximum of risk control value (4.0 mg/kg). Compared with other provinces, the Cd content in the Yangtze River Delta area was relatively high, especially in the northern part of Zhejiang Province. In addition, the northwest region of Guangxi Province and the northern region of Guangdong Province and the Pearl River Delta area also had high Cd concentrations. Meanwhile, in Hainan Province, the
concentration of Cd was evenly distributed, most of which was lower than the maximum of risk screening value (0.8 mg/kg).

Statistical analysis of Cd concentrations in different provinces along coastal areas in China is shown in Table 2. The highest arithmetic mean concentration of soil Cd appeared in Zhejiang province and the lowest in Hainan province. The top three provinces with the highest levels of soil Cd contamination were Zhejiang > Guangxi > Guangdong. The variable coefficient of each province was between 0.64 and 4.79, which indicated that the soil Cd content in different counties and districts in each province was significantly different.

Characteristics of Cd contamination distribution
Fertilization, atmospheric deposition, industrial emissions, and soil parent materials are the major sources of heavy metals in soil (Luo et al. 2015; Ke et al. 2017). The geological background values of heavy metals in soil parent material determine the concentration of heavy metals in soil to some extent. However, it was demonstrated that anthropogenic activities had a significantly greater contribution than that of natural sources for heavy metals pollution in surface soil (Hu et al. 2018). A previous study showed that heavy metals pollution and its associated risks in southeast China were more severe than those in northwest China (Yang et al. 2018). In addition, most developed and populous areas have been subjected to heavy metals pollution (Duan et al. 2016). The results showed the soil Cd content in the Beijing-Tianjin-Hebei region, Yangtze River Delta region, Pearl River Delta region, and Guangxi province was much higher than other regions. Considering the heavy metals contamination caused by economic development, some studies revealed that developed cities and industrializing cities have higher contamination levels of heavy metals, such as the Beijing-Tianjin-Hebei region and Yangtze River Delta (Wei and Yang 2010), which is consistent with our analysis. However, the results of correlation analysis showed that the relationship between Cd concentration and the economic development at city level represented by GDP was not significant (p >0.05).

As illustrated in Figure 3(a), the soil Cd content in the Beijing-Tianjin-Hebei region was 0.67 mg/kg, but distributed unevenly, and formed a triangular spatial distribution pattern. The Yangtze River Delta region is one of the three regions at the forefront of China’s economic development. The Yangtze River Delta region has Shanghai at its core and Nanjing and Hangzhou at its sides. The soil Cd arithmetic mean content was 1.75 mg/kg in the Yangtze River Delta region. It can be clearly seen from Figure 3(b) that the soil Cd concentration in Shanghai, Nanjing, and Hangzhou was relatively high. Similar findings have been reported in previous studies (Mao et al. 2017; Wang et al. 2018; Chen et al. 2019). In addition, the soil Cd concentrations in Shaoxing and Xuzhou, which have rich mineral resources and intensive mining industries, were also high. As a power-based city in East China, Xuzhou has abundant coal resources, which may be one of the reasons for the high Cd content in the soil (Fang, Dong, and An 2019). Similarly, Shaoxing also has a large number of metal mining areas, thereby resulting in the accumulation of Cd in the soil.

In addition, the Pearl River Delta is another region at the forefront of China’s economic development. In particular, the Guangdong-Hong Kong-Macao Greater Bay Area has become a new national strategic development area. Guangdong Province had a serious soil heavy metals pollution problem (1.11 mg/kg (Figure 3(c)), which may have been caused by the development of the electronics industry and metal mines, such as the Meizhou Pb-Zn mine (Chen et al. 2016). The development strategy and construction planning of the Guangdong-Hong Kong-Macao Greater Bay Area should follow the principles of rational planning and prevention, realizing cleaner production, and high-standard industry development. Guangxi Province also showed high Cd contamination (1.59 mg/kg), shown in Figure 3(d). Similarly, the heavy metals contamination in farmland soil in southeastern provinces in China was relatively high, especially in Guangxi Province (Chen et al. 2016). According to the data sources screened in this study, the high Cd pollution in Guangxi Province mainly occurred around mining areas, such as near Hechi and Guilin. The exploitation of mineral resources will inevitably lead to heavy metals contamination in soil.

Table 2. Statistical analysis of Cd concentration in coastal economic development zone of China.

| Provinces | Number of districts or counties | Maximum value (mg/kg) | Minimum value (mg/kg) | Median value (mg/kg) | Arithmetic mean (mg/kg) | Geometric mean (mg/kg) | Variable coefficient |
|-----------|--------------------------------|-----------------------|-----------------------|----------------------|-------------------------|-----------------------|---------------------|
| Liaoning  | 20                             | 4.22                  | 0.11                  | 0.23                 | 0.66                    | 0.34                  | 1.64                |
| Beijing   | 11                             | 2.59                  | 0.14                  | 0.25                 | 0.98                    | 0.52                  | 0.97                |
| Tianjin   | 7                              | 1.41                  | 0.27                  | 0.43                 | 0.66                    | 0.55                  | 0.64                |
| Hebei     | 26                             | 2.54                  | 0.07                  | 0.18                 | 0.36                    | 0.23                  | 1.44                |
| Shandong  | 43                             | 3.10                  | 0.04                  | 0.13                 | 0.31                    | 0.17                  | 1.74                |
| Jiangsu   | 47                             | 35.75                 | 0.01                  | 0.19                 | 1.08                    | 0.21                  | 4.79                |
| Zhejiang  | 50                             | 90.30                 | 0.01                  | 0.32                 | 3.89                    | 0.41                  | 3.62                |
| Shanghai  | 10                             | 0.71                  | 0.11                  | 0.20                 | 0.27                    | 0.23                  | 0.64                |
| Fujian    | 29                             | 2.84                  | 0.01                  | 0.20                 | 0.34                    | 0.21                  | 1.48                |
| Guangdong | 21                             | 2.96                  | 0.02                  | 0.86                 | 1.11                    | 0.61                  | 0.85                |
| Guangxi   | 17                             | 4.86                  | 0.06                  | 0.63                 | 1.59                    | 0.75                  | 1.08                |
| Hainan    | 19                             | 0.71                  | 0.02                  | 0.09                 | 0.20                    | 0.10                  | 1.10                |
Ecological risk assessment of soil Cd in coastal areas of China

Ecological risk assessment of Cd using the hazard quotient method

The ecological risk evaluation results of the single factor index and Hakanson potential ecological risk are shown in Figure 4. Both ecological risk evaluation methods showed that the risks of Cd in the Beijing-Tianjin-Hebei economic circle, Yangtze River Delta, Guangxi Province, and Guangdong Province were relatively high. The maximum risk values of the single factor index and Hakanson potential ecological risk were 150.5 and 38 700.0, respectively, which were both located in Zhuji, Zhejiang Province.

Figure 3. Distribution of Cd in the soil of key areas.
Ecological risk assessment of Cd using the species sensitivity distribution method

ETX 2.0 software was used to calculate the fitting results of the SSD model at two toxicity levels. Based on the fitting results, the PNEC value of the toxicity of Cd species in soil was evaluated. The results showed that the estimated median HC$_{50}$ value was 1.15 mg/kg at the LC/EC/IC$_{50}$ level, and the confidence interval was 0.24–3.33 mg/kg. The estimated PNEC median value was 0.21 mg/kg at the NOEC/LOEC level, and the confidence interval was 0.03–0.70 mg/kg. The ERA results of Cd at the levels of LC/EC/IC$_{50}$ and NOEC/LOEC are shown in Figure 5. In general, the ecological risk of Cd in coastal areas was relatively low at the LC/EC/IC$_{50}$ level but was high at the NOEC/LOEC level.

The probabilistic ecological risk assessment results of soil Cd

According to the fitting results of the SSD model and the exposure concentration of Cd in the soil of the study area, the results of PERA at the LC/EC/IC$_{50}$ level were calculated, which are illustrated in Figure 6. The risk probability values of Cd in China’s coastal provinces were ranked in the order of Zhejiang > Guangxi > Guangdong > Beijing > Tianjin > Liaoning > Jiangsu > Fujian > Hebei > Shandong > Shanghai > Hainan. The ecological risk had different orders between the two evaluation levels. Guangxi Province and Zhejiang Province had higher risks of Cd with a probability of 18.80% and 17.89%, respectively, which meant that there was a probability of 18.80% and 17.89% that 5% of species would be affected by the toxic effect at the NOEC/LOEC level, respectively.

Meanwhile, Figures 6 and 7 show that Beijing and Tianjin were in the top five in terms of ecological risk probability at the LC/EC/IC$_{50}$ level and NOEC/LOEC level. Beijing has historically had heavy industry, such as the Capital Iron and Steel Company, and the development of heavy industry might have led to the accumulation of Cd in the soil. Some articles have shown that Cd pollution in the surface soil of Beijing is a very serious issue (Chen et al. 2010; Xia et al. 2011). The results also showed that Baoding in Hebei Province and Tianjin had a higher Cd ecological risk. Baoding and Tianjin are industry-oriented cities, which might have led to the enrichment of Cd in the soil and the persistent trend of intensification (Xue et al. 2012; Han et al. 2018). The Xiongan New Area (XANA) was in the center of the triangle. From the perspective of the integrated analysis in this study, it was revealed that the construction of the XANA faced higher ecological risk, which was verified by many studies (Zhang et al. 2018; Xue et al. 2019). It also showed that Zhejiang Province had very high ecological risk probabilities at both the LC/EC/IC$_{50}$ and NOEC/LOEC levels, as it ranked within the top two, while the Pearl River Basin had higher Cd-induced ecological risk than other areas. Similar results at the Pearl River Basin were also found by previous studies (Li et al., 2015b; Zhang et al. 2015). As shown in Figures 6 and 7, Guangxi Province and

Figure 4. The ecological risk of Cd pollution under the methods of the single factor index and potential ecological risk index ($E_i^r$).
Guangdong Province had high ecological risk probabilities at the LC/EC/IC\textsubscript{50} and NOEC/LOEC levels, as they ranked within the top three.

Comparison analysis of ecological risk assessment results

Taking Hainan Province as an example, compared with the single factor index, the potential ecological risks of Anding County, Tunchang County, and Wuzhishan in central Hainan Province were lower, while those of Wenchang, Qionghai, and Qiongzhong were higher. The single factor pollution index was calculated by dividing the concentration by the evaluation standard of the pollutant, while the potential ecological risk index was calculated by dividing the concentration by the local background value and multiplying the toxicity response parameter. The evaluation results were different owing to the different dividends and different evaluation grades. Based on the single factor pollution index, the SSD evaluation result was obtained by replacing the evaluation standard of the pollutant with the HC\textsubscript{5} or PNEC. Since the evaluation standard was 0.60 mg/kg, HC\textsubscript{5} was 1.15 mg/kg, and PNEC was 0.21 mg/kg, it was clear that the result was stricter for the PNEC, followed by those of the single factor pollution index and HC\textsubscript{5}. According to the

![Figure 5. Distribution of ecological risk under the species sensitivity distribution (SSD) method.](image)

![Figure 6. Probabilistic ecological risk at the LC/EC/IC\textsubscript{50} level.](image)
results of PERA, Hainan Province had a Cd risk probability of 3.84%, which meant that there was a probability of 3.84% that 5% of species would be affected by the toxic effect at the NOEC/LOEC level. Owing to the restriction of the screened data, the PERA results were only presented at the provincial level, but the results were quantitative. Taking other provinces into comparison, the conclusion was robust and the finding was consistent with the above comparison analysis.

By comparing various entropy methods and the probability method, it was found that each has advantages and disadvantages. The single factor pollution index and the potential ecological hazard index are both simple in calculation and have low demands for data and technology. The two methods are similar in that the ecological risk can be evaluated qualitatively, and the applied standard values partly determine the degree of risk. The toxicity response parameter for heavy metals is integrated into the potential ecological hazard index method, which can better reveal the toxicity of heavy metals and the harm of heavy metals pollution to the environment. However, the weighting of the toxicity coefficient was not consistent in the current study. Similarly, the SSD is also based on the entropy method. The biggest difference between the methods is that the soil Cd background value of each province is applied as the denominator in Hakanson potential ecological risk method, while the PNEC is used as the denominator in the SSD method. PNEC inferred from the dose-effect evaluation is introduced in the SSD model, which makes the results more precise and makes the risk assessment over a whole region possible. Meanwhile, for the SSD, the evaluation result is also qualitative because it is still a type of entropy method, and it fails to express the harm to specific species in the ecosystem chain. In contrast, PERA takes the form of probability as a quantitative approach, and the evaluation result is more objective. However, compared with other methods, it has high data demands and the methodology is complicated, which makes it difficult to popularize in practical applications. In conclusion, entropy methods were widely used for its handleability, but its incomplete quantization limited the accuracy of this method in ecological risk assessment. With the establishment of basic database and the development of computer technology, the probability method will play a greater role in the quantitative assessment of ecological risk in multi-evaluation area.

**Conclusion**

The heavy metal contamination problem in China’s coastal areas cannot be ignored, especially Cd contamination. Based on the environmental exposure and ERA results, the soil in coastal areas was seriously contaminated by Cd, and the contamination was more serious in economically developed or highly industrialized regions, such as the Beijing-Tianjin-Hebei region, Yangtze River Delta region, and Pearl River Delta. In China’s coastal areas, the soil Cd content in 10.33% of the counties was higher than the minimum of risk control value (1.5 mg/kg), and in 4.00% of the counties was higher than the maximum of risk control value (4.0 mg/kg). Zhuji which is a county under the jurisdiction of Zhejiang Province has the highest ecological risk. According to the probabilistic risk assessment results, Guangxi Province, Zhejiang Province, and Guangdong Province ranked among the top three coastal areas for soil Cd contamination, and the
ecological risks were 18.80%, 17.89%, and 15.77% at the NOEC/LOEC level, respectively.

In this study, the ecological risk was assessed by applying four methods, namely the single factor pollution index, potential ecological hazard index, SSD method, and PERA. By comparing and analyzing the advantages and disadvantages of different methods, it was determined that PERA was the best way to represent the ecological risk using a quantitative approach, and the qualitative results of the other methods are subject to the selection of environmental criteria. In general, this study provided a quantitative contrasting analysis for the methods of ERA, while the identification of the ecological risks of Cd in the soil of coastal areas of China can help policymakers in regional strategic planning from the perspective of ecosystem protection.

Disclosure statement
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