

Original Research

Pollution Characteristics and Risk Assessments of Mercury in the Soil of the Main Urban Regions in a Typical Chinese Industrial City: Changchun

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Abstract

As a typical industrial city in northeastern China, the environmental conditions of the soil in Changchun City face high ecological risks. In the present study, in order to more fully understand the characteristics of the soil mercury content and its related health risks in the main urban areas of Changchun City, the pollution degrees were evaluated using the data of land accumulation indexes (I_{geo}), potential ecological risk indexes (Er), and health risk assessment methods. The mercury content (TSM) levels in the urban soil, along with the atmospheric mercury content (TGM) levels, were analyzed. The results showed that the mean value of the mercury content in the soil in Changchun City was 0.0569 ± 0.103 mg/kg, and the concentration range was between 0.0052 and 1.3240 mg/kg. It was found that the mercury content levels in nearly 70% of the soil samples exceeded the background value of soil (0.040 mg/kg). In addition, the atmospheric mercury concentration at 0 cm was determined to be directly related to soil mercury content ($P = 0.000532$). In addition, the atmospheric mercury content of 0 cm was observed to be positively correlated with the distribution of the atmospheric mercury content at 100 cm ($P = 0.000524$). The mercury content levels in the soil were found to vary from different directions, with the mercury content found to be the highest in the southeastern section of the city. However, there were no significant differences in the mercury content of any direction. The I_{geo} showed that 25.0% of the sample points were polluted. The unsanitary areas were mainly concentrated in the southwestern and southeastern sections of the city. The mercury content levels in the soil of Changchun City ranged from pollution-free to moderate pollution levels overall. The Er indicated that the potential ecological risk level was high in the northwestern and southeastern sections of Changchun City. However, the soil mercury levels in Changchun City presented a low level of ecological risk overall.

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The average values of the non-carcinogenic risks (HQ) and the total non-carcinogenic risk assessment indexes (HI) in all directions within Changchun City were determined to be far less than 1. Therefore, it was concluded that the soil mercury levels were not potentially harmful to human health.

Keywords: mercury (Hg), urban soil, pollution characteristics, risk assessments, Changchun City

Introduction

The soil pollution caused by heavy metals, along with their associated harmful ecological and health effects, are currently of growing concern. During the last century, the residents of Japan's Kumamoto Minamata Village experienced "Minamata Disease", which was the world's first mercury pollution incident caused by an environmental pollution event. As a result, mercury pollution has aroused widespread concerns throughout the world [1]. Heavy metal mercury is a highly toxic non-essential element and is considered to be one of the most toxic substances affecting the health of organisms. In the environment, mercury tends to accumulate in organisms, sometimes resulting in fatal damage to those organisms [2]. At the same time, mercury pollution can migrate with water and the atmosphere, and remain in the environment for long periods of time. Therefore, mercury pollution has a wide range of influence [3-4]. As a result, mercury pollution has been listed as a global pollutant by the United Nations Environment Program [5-8]. Environmental soil can form reservoirs for mercury and mercury pollution in the soil is known to have latent, persistent, acutely toxic, and irreversible characteristics [9]. In addition, mercury may become widely distributed and accumulated in various ecosystems [10]. Soil mercury pollution is now considered to be an important part of the global mercury pollution situation.

With the increasing number and density of urban populations, the accumulation of mercury in the soil of urban areas has one of the main ways in which dense urban populations have become exposed to mercury pollution. Urban soil environments are subjected to heavy metal input from atmospheric deposition, irrigation water, industrial activities, and natural sources. This is particularly true for heavy metal mercury [11-14]. Due to the fact that mercury can affect the health of the urban residents, it has become necessary to understand the status of city soil environments with regard to mercury accumulation levels. At the present time, the problems related to mercury pollution in urban soil environments have one of the main focuses of studies regarding urban environmental issues, and a great deal of work has been completed in that area [15-21]. According to the previous study results, the mercury pollution in soil is considered to mainly originate from the following urban sources [7, 22]:

1) Burning of fossil fuels: Coal-fired power plants and heating plants are the single largest source of atmospheric mercury emissions. Mercury is eventually

returned to the soil through atmospheric subsidence, and the production of energy from fossil fuels, such as oil refining. In addition, vehicle emissions also result in increased pollution indexes.

2) Smelting of non-ferrous metals: The raw materials used in nonferrous metal smelting contain mercury, and the mercury element used in nonferrous metal smelting processes will appear in the form of elemental or compounds with the discharge of smelting smoke, causing mercury pollution to air, water, and soil.

3) Production of items containing mercury: Some medical instruments used in daily life, as well as such daily articles as blood pressure meters, thermometers, fluorescent lamps, electrical switches, pressure sensors, and so on. Cement products also contain mercury.

4) Emissions caused by waste treatment and incineration processes: Various waste treatments in landfills also produce mercury pollution.

Although a great deal of attention has been given to the risks of heavy metal pollution in agricultural soil and industrial land, less is currently known regarding metal pollution in Chinese urban soil [23-24]. This information is identified as being critical, considering the continuous exposure to urban residents, and especially children, to the accumulated metals in urban soil [25-29]. Such exposure may take the forms of oral ingestion, inhalation, or dermal contact. At the present time, Chinese researchers have investigated the mercury content levels in the soil of Hulun Buir [30], Zhongshan [31], Guilin [32], and Tianjin [33], as well as some of the counties in Shanxi Province [34] and other cities in China. On an international scale, the status of soil mercury accumulation in Palermo (Sicily) [19], Glasgow [18], Khabarovsk [20], and Avero [21] have been examined. However, while the previous studies have largely focused on a single type of urban soil, comprehensive risk assessments of metals in the major types of urban soil in China continue to be lacking [35]. Therefore, in the present study, the key research focus was placed on the current content levels of heavy metal mercury in urban soil and risk assessments of the negative health impacts of mercury on urban residents, including adults and children.

The main objective of this study was to assess the risks of heavy metal mercury pollution in the soil of Changchun, which is a typical industrial city in northeastern China. Previously, researchers have conducted studies on the sources of Changchun's surface soil mercury. The results revealed that the Hg mainly originates from coal burning and industrial activities [36]. Therefore, Changchun is also considered to be one of the representative cities affected by

industrial processes. It is believed that the adjustments of energy structures that have been applied to the formation of mercury pollution will still exist for a long period of time, and that they may have certain impacts on human living environments. Therefore, this study chose to discuss the situation of such impacts. Surface soil samples were collected in Changchun and their concentrations of heavy metal mercury and atmospheric mercury were analyzed. The ecological risks of the heavy metal Hg in the soil were assessed by calculating the geo-accumulation indexes [37-38] and the potential ecological risk indexes [39]. The associated health risks were then assessed by determining the levels of metal exposure through oral ingestion, inhalation, and dermal contact, and then calculating the hazard quotient (HQ), and hazard index (HI). The results of this study will contribute to a more comprehensive understanding of the risks arising from human exposure to heavy metal mercury in Chinese cities.

Materials and Methods

Study Area

The study area of Changchun is located in northeastern China, and is the capital of Jilin Province. Changchun City is the provincial capital of Jilin Province, with the geographic coordinates to E125°44'06"-125°28'53", N43°47'35"-44°00'38" [36]. Changchun is located in the middle of a northeastern plain, and characterized by a continental monsoon climate. The duration of the hottest period is five months, with an annual average temperature of 4.6°C; average wind speed of 4.2 m/s; and annual rainfall

of 567 mm (70% of which occurs during the summer months) [40]. Changchun is an important base for China's automobile industry, agricultural product processing industry, science, education, culture, and trade. Its industries are mainly transportation equipment manufacturing, and its energy is derived mainly from the burning of coal [41]. By consulting Changchun City's master plan (2011 to 2020), this study selected designated urban areas as the research objects. Changchun's urban planning area (391.1 km²) included the Nanguan District; Chaoyang District; Kuancheng District; Erdao District; Luyuan District; economic and technological development zones; high-tech development zones; automobile net economic development zones; and economic and technological development zones, for a total of nine administrative regions. This study chose the People's Square as the center point, and then divided the main urban areas of Changchun into the following four directions: northwest, northeast, southwest, and southeast. The main urban area was selected as the research scope since it included both built-up areas and suburban areas. These were composed of the early development zones and new urban areas of Changchun City, which comprehensively reflected the basic characteristics of the urban spaces of the typical urban core area and peripheral expansion areas [42], as detailed in Fig. 1.

Sampling and Analysis Processes

In the current research investigation, the sample collection areas of the main urban areas and the urban-rural junctions of Changchun City were evenly distributed on a grid, which was then divided into a total of 80 sampling cells (1 km × 1 km). However,

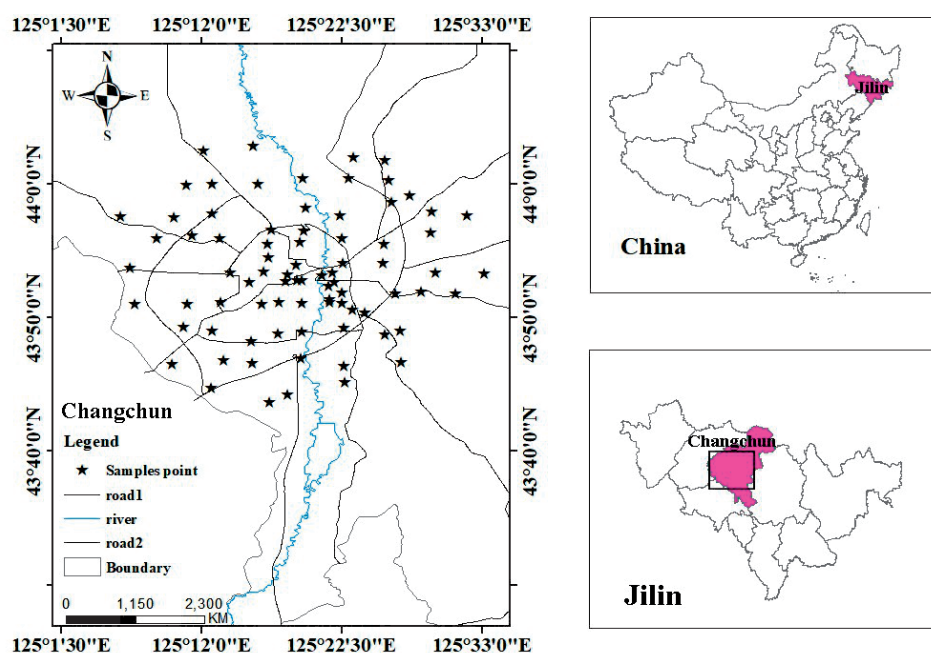


Fig. 1. Study area and sampling points.

with consideration given to the actual sampling process, some points were deleted and adjusted within a small range. Finally, a location map of the sampling points was drawn according to the longitude and latitude of each sampling point, as shown in Fig. 1. Each sample was collected using a plug arrangement procedure. Five equal volume samples were collected in the range of 5 m × 5 m, and uniformly mixed into one sample. In addition, all of the samples were collected from the 0 to 10 cm surface soil layers, and any plants, dead branches, fallen leaves, rocks, sand grains, and so on were removed. The samples were sealed and stored in polyethylene bags, with each sample weighing approximately 500 g. For the soil samples obtained in areas without hardened sampling points, the dust removed within a certain area around the sampling points were taken as the test samples. Following the completion of the sample collection process, the samples were stored in a cool place until the analysis was completed.

In this study, a Zeeman LUMEX RA915⁺ was used for the determination of the mercury content levels in the air. It was found that when fit with UMA modules, it had the ability to realize both solid and liquid detections. All of the different types of sampling points were divided into two layers in the vertical direction in the air according to a range of 0 cm and 100 cm, and an in-vehicle mercury meter (Zeeman LUMEX RA915⁺) was used for the monitoring process according to the sample point sequence number. The atmospheric detection limit was 2 ng/m³. Each point was followed for six minutes. That is to say, each layer within each point was continuously monitored for 30 seconds, with one datum per 10 seconds, 6 cycles, and 18 parallel data per layer within each point, respectively.

The collected soil samples were dried under dark conditions, and then ground and passed through 80 mesh nylon sieves. The various soil samples were then bagged for the subsequent analysis process. The soil detection limit of the instrument adopted in this study was 0.005 mg/kg. Then, using the national standard soil sample guidelines, the standard curves were obtained. Soil samples of 50 mg to 200 mg were weighed and placed into the soil sample detection port of the Zeeman LUMEX RA915⁺ via a quartz tank. The mercury content levels of the soil samples were measured, and parallel samples were obtained five times.

Ecological Risk Assessment Processes

Geo-Accumulation Index (I_{geo})

The geo-accumulation index (I_{geo}) is used to assess contamination levels of a specific metal in soil by evaluating the metal enrichment above the baseline or background values. In this study, the geo-accumulation index was calculated according to Eq. (1) [43-44] as follows:

$$I_{geo} = \log_2[C_n/(K \times B_n)] \quad (1)$$

...where I_{geo} represents the ground accumulation index; C_n is the measured concentration of mercury (mg/kg); K indicates the modified index (which is generally 1.5) in order to take into account the changes in the background values which may have been caused by the differences in the rock characteristics in different locations; and B_n denotes the municipal soil background value (0.040 mg/kg) [45].

Potential Ecological Risk Index (Er)

The assessments of potential ecological risks are considered to be one of the conventional methods for the ecological risk assessment index [46]. A quantitative method was previously developed, which includes a toxic reaction factor (Tr) [39]. The toxicity of each heavy metal can be quantitatively calculated using the aforementioned method. In this study, the potential ecological hazard coefficient Er of the mercury in the study area was calculated according to Eq. (2):

$$Er = Tr \times Cf = Tr \times (C_n/C_o) \quad (2)$$

...where Er is the potential ecological harm coefficient of the mercury; Tr represents the toxicity coefficient of the mercury, which was set at 40 [47]; Cf corresponds to the toxic reaction of a particular metal by dividing the measured concentration of the actual heavy metal with its background level [48].

Health Risk Assessments

Exposure Assessments

ADI indicators are generally used to assess the health risks of heavy metal pollution to humans, in which humans are exposed to heavy metals in soil via three main ways, namely ingestion, inhalation, and skin contact [49]. However, previous research results have shown that mercury can also be ingested as vapor [50]. In China, ingestion of soil particles has been found to be an important way in which urban populations come into contact with heavy metals [51-53]. During health risk assessment processes, the determination of the exposure factors and other related parameters is essential to accurately calculating the health risks. In addition to consulting the American Standards, this study was supplemented and modified according to the national conditions and regional characteristics of the study area [54]. Among those factors, the exposure frequency was modified to 350 days according to the national conditions of China [50]. The daily ADI of metals in urban soil was computed according to Formulae (3) to (6) as follows:

The direct contact route of human skin:

$$ADI_{Skin\ intake} = \frac{C \times SA \times AF \times ABS \times EF \times ED}{BW \times AT} \times 10^{-6} \quad (3)$$

The direct oral ingestion route:

$$ADI_{\text{Oral intake}} = \frac{C \times IFP \times EF \times ED}{BW \times AT} \times 10^{-6} \quad (4)$$

The respiratory intake route:

$$ADI_{\text{Breathing intake}} = \frac{C \times IR \times EF \times ED}{BW \times AT \times PEF} \quad (5)$$

The mercury vapor intake route:

$$ADI_{\text{Steam intake}} = \frac{C \times IR \times EF \times ED}{BW \times AT \times VF} \quad (6)$$

...where ADI represents the chronic daily exposure (mg/(kg·d)); C is the measured concentration (mg/kg); SA denotes the skin area (cm²/d) which may come in contact with soil, and the reference value is 5,000 cm²/d [55]; AF indicates the adsorption coefficient of skin on soil (mg/cm²), and the reference value is 1 mg/cm² [56]; ABS is the skin respiration rate, and the reference value is 0.001 [55]; EF indicates the exposure frequency (d/a), and the reference value is 350 d/a [56]; ED denotes the exposure duration (a), and the reference value is 25 a [54]; BW indicates the body weight (kg), and the reference value is 55.9 kg [55]; AT represents the exposure cycle (d), and the reference value is $365 \times ED$ (d) [55]; IFP is the soil intake (mg/d), and the reference value is 114 mg/d [56]; IR refers to the air intake (m³/d), and the reference value is 20 m³/d [56]; PEF represents the production factor of the soil dust particles, and the reference value is 1.32×10^{-9} m³/kg [57]; and VF is the evaporation coefficient (m³/kg), and the reference value is 32657.6 m³/kg [50].

Non-Carcinogenic Risk Assessments

Health risk assessments are generally divided into carcinogenic risk assessments and non-carcinogenic risk assessments. Non-carcinogenic risk assessments are generally carried out by mercury. In the present study, in order to assess the potential health risks associated with the non-carcinogenic effects of heavy metals in soil, the methodology provided by the United States Environmental Protection Agency was utilized. In terms of the hazard quotient HQ [58], the risk factor (HQ) was calculated as the ratio of the ADI of a given metal to the reference dosage (RfD), as per Formula (7):

$$HQ = \frac{ADLi}{RfDi} \quad (7)$$

...where $ADLi$ is the chronic daily exposure (mg/(kg·d)); RfD represents the reference dosage of heavy metal mercury (mg/(kg·d)), which is the maximum allowable

content of a metal which has no harmful effects on human health [59].

HI is often used to evaluate the non-carcinogenic effects of heavy metals. Therefore, the total non-carcinogenic risk values of mercury in different pathways can be expressed as HI , as per Formula (8):

$$HI = \sum_i^n HQ \quad (8)$$

When HI or $HQ > 1$, it is generally considered that there are potential non-carcinogenic risks. Meanwhile, when HI or $HQ < 1$, it is generally considered that the risks are small and can be potentially ignored.

Results and Discussion

Metal Concentrations in the Soil

The intuitive reflections of the mercury concentrations in soil within the main urban areas of Changchun City are shown in Table 1.

It was determined in this study that the mean mercury content in soil samples was (0.0569±0.103) mg/kg, and the concentrations ranged between 0.0052 and 1.3240 mg/kg. The variations in the soil mercury content levels among the main urban areas of Changchun City were observed to be large. The background value [45] of the mercury in the soil in Changchun City was 0.040 mg/kg. It was found that in nearly 70% of the 80 sample sites, the mercury levels had exceeded the soil background value, with the highest reaching levels nearly 8 times higher than the background value. The soil in the main urban areas of Changchun City had been preliminarily affected by exogenous mercury, and the soil layers in the different regions were contaminated with mercury to varying degrees. It was observed that when compared with other Chinese cities (Table 2), it can be seen that the urban soil in Guangzhou (a first-tier city) was the most seriously polluted by exogenous mercury. Therefore, it will be necessary to strictly control the artificial introduction of mercury in that area in order to avoid the destruction of the soil ecological environments as a result of mercury accumulation. Secondly, Chongqing, Xuzhou, Beijing, and Taiyuan were all found to be more seriously polluted by exogenous mercury than Urumqi, Changchun, Nanjing, and Tibet. Overall, Changchun City was determined to be less polluted by exogenous mercury when compared with other cities. However, vigilance will still be required in order to control the artificial introduction of mercury elements.

Table 1. Description of the mercury content levels in the soil of Changchun City (n = 400, mg/Kg).

Entire distance	Maximum	Minimum	Average	95% UCL	Max/Min	Background
1.3188	1.3240	0.0052	0.0569	10.1797	254.6154	0.0400

Table 2. Mercury content levels in the soil of other urban areas in China.

City	Range	Average	Background	Reference
Chongqing	0.060 to 3.881	0.319	0.040	(Li et al., 2006) [60]
Beijing	0.010 to 0.966	0.278	0.058	(Han et al., 2015) [61]
Guangzhou	0.013 to 12.231	0.614	0.157	(Yin et al., 2009) [9]
Taiyuan	0.040 to 0.297	0.105	0.098	(Guo et al., 1996) [62]
Xuzhou	0.020 to 1.300	0.290	-	(Wang et al., 2005) [40]
Tibet	Unknown to 0.056	0.026	0.021	(Zhu et al., 2014; Zhang., 1994) [63-64]
Urumqi	0.012 to 0.176	0.062	0.055	(Xia et al., 1985; Hu et al., 2003) [65]
Nanjing	0.041 to 8.090	0.043	0.025	(Huang et al., 2007) [66]

It was found that the Hg in Changchun City had mainly originated from coal burning and industrial activities [67]. In addition, previous related studies have found that a large number of mercury lamps, fluorescent lamps, and other gas discharging lamps are extensively used throughout the region, which are known to greatly increase the mercury content in surface soil layers. There are more than 64,000 streetlamps in Changchun, and nearly 6,500 lamps are replaced every year [68], thus creating a source of exogenous mercury. Moreover, such lighting devices are extensively used within the Changchun Industrial Park, logistic parks, thermal power plants, and cement factories, which has directly led to increases in exogenous mercury pollution [69].

Relationship between the Soil Mercury Concentrations and the Atmospheric Mercury Concentrations

In this study's comparison of the atmospheric mercury concentration levels at 100 cm with that at 0 cm (Fig. 2), it was found that 72% of the sampling sites had concentrations of atmospheric mercury at 100 cm which were higher than those at 0 cm. This was mainly attributed to the rapid construction and development of Changchun City in recent years, which has to the strengthening of urban heat island effects and stronger vertical convection of air [70-71]. It was determined that although the urban heat island circulation tends to be a weak mesosphere circulation, it often causes high weather impacts. For example, as one of the important types of circulation in urban boundary layers, it often affects the spread and diffusion of various pollutants. As a result, the pollutants in the atmosphere are not easily diffused and tend to settle on the surface areas [72]. In addition, such effects may also be caused by secondary dust. Since the majority of the sampling points in this study were located on roads with high traffic flow, the secondary dust phenomena was relatively serious, resulting in the atmospheric mercury content levels at 100 cm being higher than those observed at ground level. The results also indicated that road traffic is a primary source of heavy metal pollution

in urban areas. It was confirmed through this study's analyses of the sampling points that the atmospheric mercury concentrations at 0 cm were directly related to the soil mercury content ($P = 0.000532$). In addition, it was verified that the higher the mercury concentration in the atmosphere was, the higher the mercury content in the soil would be. Moreover, the results obtained in related research have shown that atmospheric mercury concentrations are significantly positively correlated with the soil mercury content levels, with a correlation coefficient of 0.741 ($n = 52$) [73]. Also, it was found that the atmospheric mercury pollution had a major influence on the mercury accumulation levels in the surface soil layers.

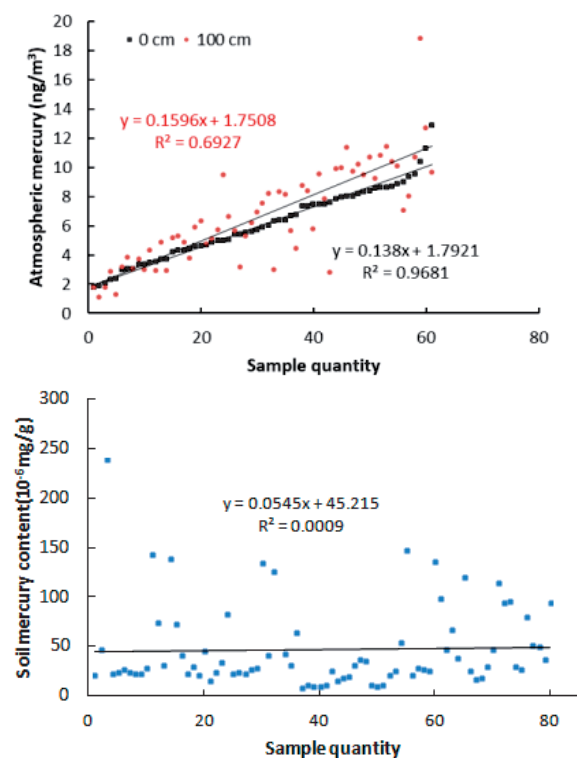


Fig. 2. Atmospheric mercury content and soil mercury content levels in the study area.

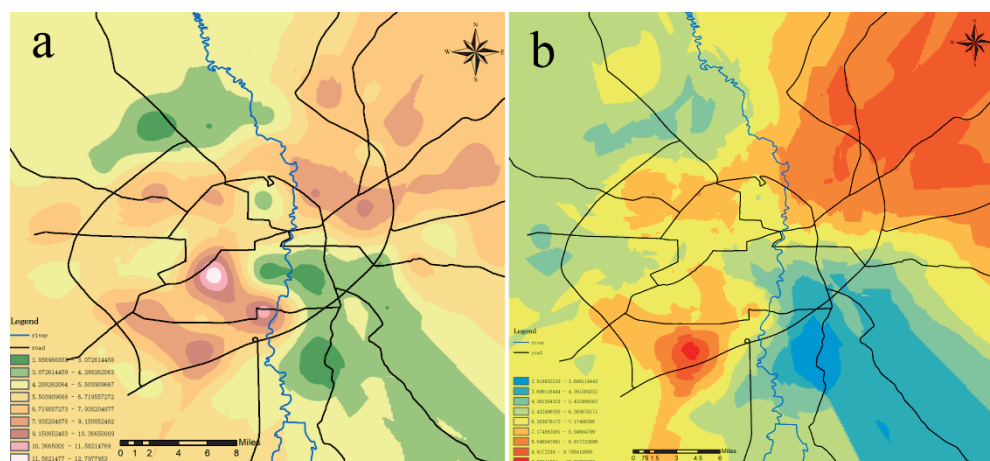


Fig. 3. Distribution map of the atmospheric mercury content at: a) 0 cm; and b) 100 cm.

In the current research investigation, a comparison was made of the distributions of mercury content in the atmosphere at 0 cm and 100 cm, respectively (Fig. 3). It was found that there was a good correlation between the distributions ($P = 0.000524$), with the mercury content at 100 cm higher than that observed at 0 cm. Those findings indicated that atmospheric mercury deposition was the main source of the soil mercury content. Also, according to the mercury pollution index in Changchun City (thermal plants, medical apparatus, instrument factories, and so on), the distribution of the mercury content at 0 cm had mainly originated from heating companies, industrial and logistics parks, and transport and industrial parks in which the production processes involved the burning of coal. The waste gases and waste residue of such industrial areas generally contain different types of heavy metals, and those pollutants can be transferred to urban soil through dry or wet subsidence methods, such as deposition and enrichment in the soil nearby as the result of excessive amounts of heavy metal accumulation [74]. The areas with high mercury content at 100 cm were found to be mainly concentrated in the vicinity of the logistic parks and residential areas. This was mainly due to the large traffic flow in the logistic parks, with the mercury content of the atmosphere found to be related to the relatively dense traffic flow. The high mercury content levels near residential areas were generally affected by coal-burning heating and household garbage processes [75].

Relationship between the Concentration Levels of Mercury in the Soil and the Wind Directions

In order to study the influences of the different wind directions on the mercury content levels of soil in the main urban areas of Changchun City, a box chart and a variance analysis method were adopted to analyze the mercury content levels in the following four directions: northwest, northeast, southwest, and southeast. As shown in Fig. 4, there were differences

observed in the soil mercury content levels among the four directions, with the highest mercury content found to be in the southeast direction. The results of this study's one-way ANOVA showed that the mercury content in the northeastern direction was greater than in the southwestern direction. However, there were no significant differences observed between the two ($P = 0.37 > 0.05$). In addition, there were no significant differences observed in soil mercury content levels between the northeastern and northwestern directions ($P = 0.83 > 0.05$), and no significant differences between the northeastern and southeastern directions ($P = 0.60 > 0.05$). One-way ANOVA was performed in the northwest and southeast directions, with no significant differences found in the soil mercury content between those two directions ($P = 0.45 > 0.05$). Furthermore, there were no significant differences observed between southwest and northwest ($P = 0.48 > 0.05$) and southeast directions ($P = 0.15 > 0.05$).

However, according to the data shown in Figs 3 and 4, the soil mercury content levels in the southeast direction of Changchun City were relatively high.

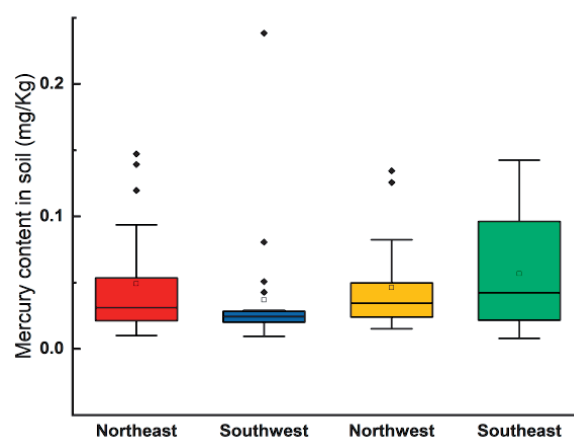


Fig. 4. Box chart of the mercury content levels in the different wind directions.

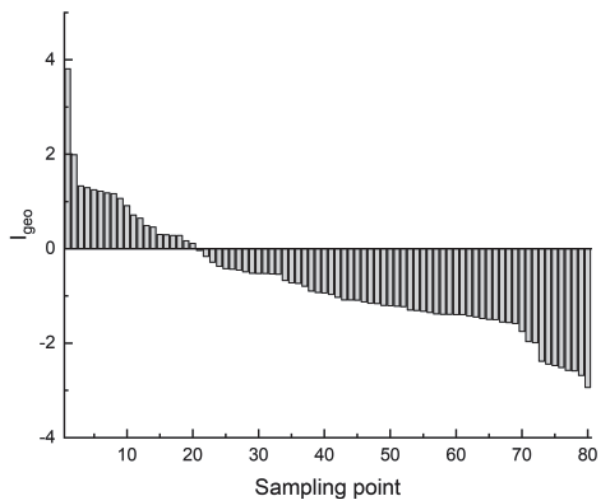


Fig. 5. Descending chart of the ground accumulation index.

According to the urban layout of Changchun City, its thermal power group is mainly located in the southeastern section of the main urban area. The pollutants generated by winter heating mainly occur in that area, and the prevailing northwest winds during the winter seasons also cause the mercury pollutants to migrate from the northwest to the southeast. In addition, according to the dominant wind directions in Changchun City, the mercury pollution levels in the soil are direct results of the wind directions. This study's sampling time was in early April, when Changchun City was experiencing prevailing southwesterly winds. Those winds caused the atmospheric mercury pollution to be transported through rain and snow into the corresponding regional soil. Then, under the effects of rain and snow water leaching, the accumulation levels of the soil water-soluble Hg^{2+} had increased with the surface runoff erosion, or had seeped more deeply into

the soil layers [76]. Therefore, the southwestern wind direction on the surface soil had resulted in the mercury concentrations becoming significantly higher than those under the other wind conditions. Consequently, the mercury content in the surface soil layers was observed to gradually increase from the southwest to the northeast in the study area. However, it was determined in this study that the mercury content in the soil of the region was not only influenced by the meteorological conditions (dominant wind directions), but also by the surrounding topography [76]; physical and chemical properties of soil [77]; and human activities and other factors.

Evaluation of the Soil Mercury Pollution Levels in Changchun City

Ecological Risk Assessments of the Soil Mercury Pollution

In the present research investigation, the descending order table and distribution diagram of the ground accumulation index (Fig. 5 and Fig. 6) were obtained using a ground accumulation pollution index method.

According to the results obtained in this research study, 25.0% of the sample points in Changchun City were polluted ($\text{index} > 0$). Among those points, only one point was found to be strongly polluted; 10.0% of the sampling points were moderately polluted; 13.8% of the sampling points were non-polluted to moderately polluted; and the remainder of the sample points were considered to be not polluted. As detailed in Fig. 6, the polluted areas were mainly concentrated in the southwestern and southeastern regions of Changchun City. Also, there was some pollution detected in the northeastern region, which was consistent with the analysis results of the wind directions. Due to the existence of an industrial park, thermal plant, and

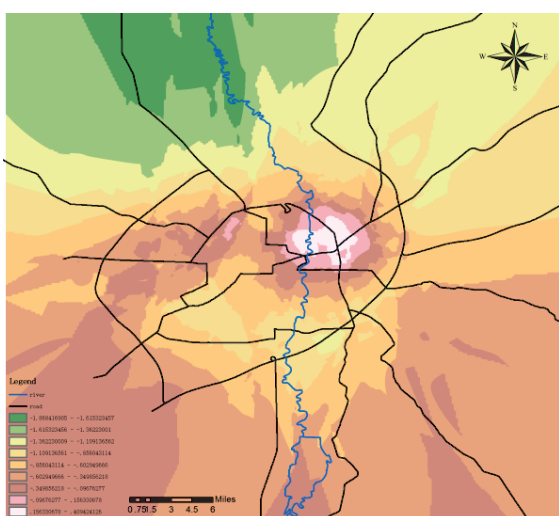


Fig. 6. Distribution of the soil mercury accumulation pollution index (I_{geo}) in Changchun City.

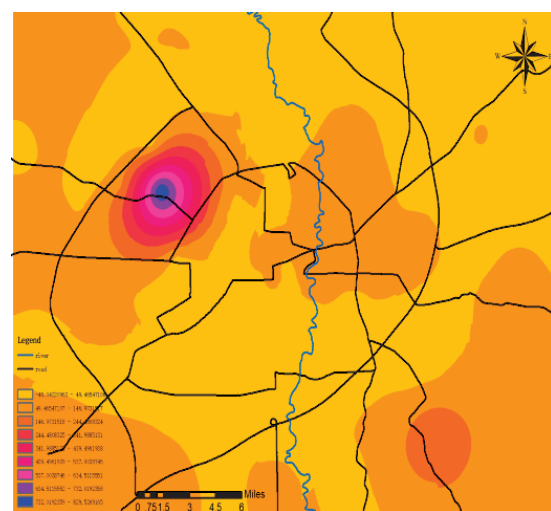


Fig. 7. Distribution of the soil mercury potential ecological risk assessment index (E_r) in Changchun City.

medical machinery plant, the content levels of mercury in the soil of the aforementioned areas were relatively high. It was also observed that industrial park, thermal plant, and medical machinery plant were in fact the main sources of the mercury pollution. In addition, due to the influences of the dominant wind direction (southwest), there was also some pollution detected in the northeastern section of the study area. Due to the large number of logistic parks distributed in the northeastern section, their cumulative index was much higher than that of the other locations in the study area, which indicated that logistic traffic had significantly contributed to the urban soil mercury pollution. Overall, the ground accumulation index of the mercury content levels in the soil of Changchun City revealed no pollution to moderate pollution levels, which indicated that the overall mercury pollution degree was not high, and mainly concentrated in some specific areas. However, if no control measures are taken, then the safety of the ecological environment will potentially be threatened.

According to the evaluation standard of the potential ecological risk index method (Fig. 7), the potential ecological risk levels of the northwestern and southeastern sections of Changchun City were higher than those of the other two directions, with 41.3% of the sampling points found to have moderate or above potential ecological risk levels (index > 40). Two of the potential ecological risk indexes were as high as 840.8 and 238.4, respectively, which represented relatively extreme potential ecological risks and were rated as serious. The reason for these high index results may have been that those two points were located near an industrial park, and the industrial waste residue and other pollutants may have polluted the soil at those locations, resulting in abnormal mercury content levels. It was also revealed that 15.0% of the samples had high levels of potential ecological risk; 23.8% of the sampling sites had medium levels of potential ecological risk; and the remainder were observed to have low levels of potential ecological risk, accounting for 57.5%. Therefore, generally speaking, this study found that that

the soil mercury contamination levels in Changchun City presented low ecological risk potential.

Assessment of the Potential Health Risks of Soil Mercury Contamination

As can be seen in Fig. 8, the order of the daily exposure and non-carcinogenic risk coefficient under the different exposure pathways was as follows: Intake of steam > oral intake > skin contact > respiratory pathways. In addition, the intake of mercury vapor was determined to be the main factor affecting the health risks of heavy metal mercury exposure. Also, the spatial distribution order of the two was northwest > southeast > northeast > southwest, with the non-carcinogenic risks determined to be far less than 1.

In the present study, the *HI* was calculated by the *ADI* and *HQ*, and its distribution is detailed in Fig. 9. As can be seen in the figure, the spatial distribution of the total non-carcinogenic risk assessment index (*HI*) was northwest > southeast > southwest > northeast. It was revealed that, depending on the analysis results, the southwestern section of the study area was mainly industrial, and the total health risk value was low, since the southwestern section was located in the upwind direction. However, in the northeastern section, logistic parks were concentrated and located in the downwind direction, resulting in the total health risk values being slightly lower. The study area's thermal power companies were mainly located in the southeastern section. Another factor was that coal burning processes were more common than that in the southwestern and northeastern section, and with coal burning being one of the important sources of exogenous mercury, the total health risk values were higher in the northeastern section. Moreover, there were cement factories, medical equipment factories, and logistic parks located in the northwest, and the absolute health risk value was slightly higher. Generally speaking, the average value in each direction was determined to be much less than 1. Therefore, it was considered that the soil mercury accumulation had not

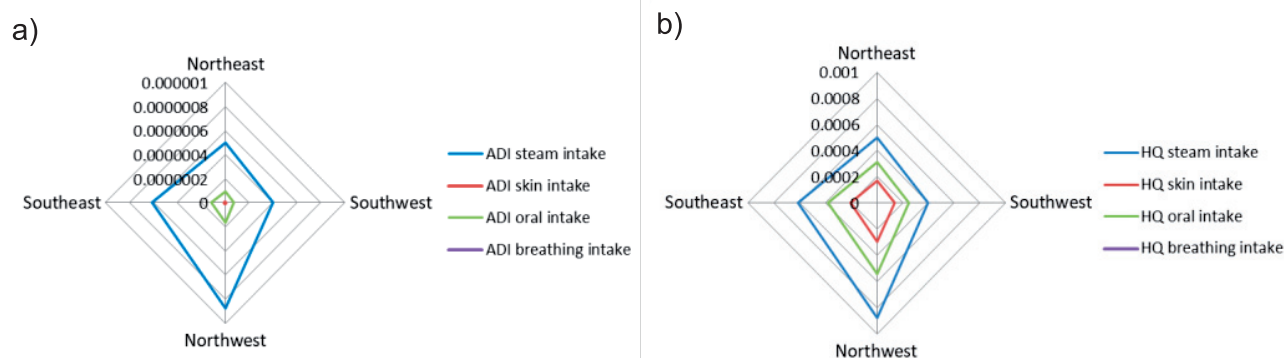


Fig. 8. a) Daily exposure amounts (*ADI*); and b) non-carcinogenic risk coefficient (*HQ*) of the mercury content in the soil in Changchun City under different exposure routes.

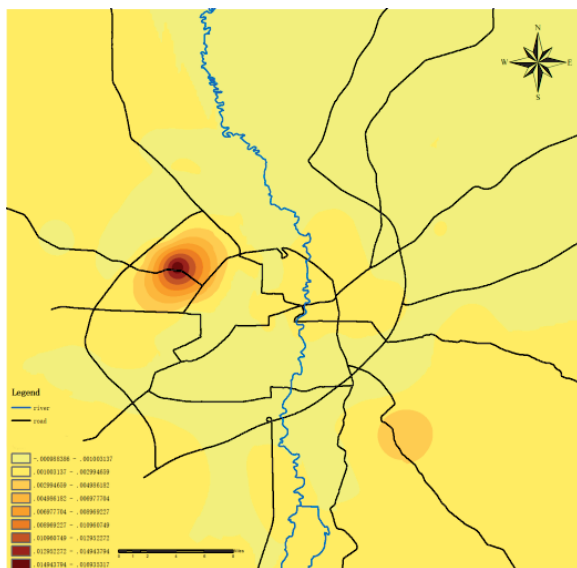


Fig. 9. Distribution of the total non-carcinogenic risk assessment index (*HI*) of the soil mercury content in Changchun City.

yet reached levels which were harmful the health of the resident adults.

As can be seen in Figs 8 and 9, the health risks and total health risk values of all the approaches were far less than 1, which indicated that the soil mercury contamination in the study area was not harmful to the health of the local adults. However, the northwestern section of the study area had displayed certain potential risks due to its higher observed values.

Conclusions

The average mercury content of the soil in the main urban areas of Changchun City was (0.0569 ± 0.103) mg/kg, and the concentration range was determined to be between 0.0052 and 1.3240 mg/kg. This study found that the mercury content levels in nearly 70% of the examined soil samples had exceeded the background value of the soil. There was observed to be a direct correlation between the atmospheric mercury concentrations at 0 cm and the soil mercury content levels ($P = 0.000532$). In addition, extremely significant correlations were observed between the atmospheric mercury content distributions at 0 cm and 100 cm ($P = 0.000524$).

It was found that according to the evaluation results obtained using a local cumulative pollution index method, 25% of the sample points in Changchun City were considered to be polluted, and the unsanitary areas were mainly concentrated in the southwestern and southeastern regions of Changchun City. Overall, the soil mercury accumulation index indicated a range of pollution-free to moderate pollution in Changchun City. Also, the evaluations conducted using a potential ecological risk index method revealed that the

potential ecological risk levels in the northwestern and southeastern sections of Changchun City were greater than those in the other two directions. Generally speaking, the soil mercury contamination levels in Changchun City were found to currently present low ecological risks. In addition, through this study's calculations of the next day exposure levels of the different exposure pathways, it was determined that the intake of mercury vapor was the principal factor of the health hazards related to heavy metal mercury. The average values of the non-carcinogenic risks (*HQ*) and the total non-carcinogenic risk assessment index (*HI*) in the four examined directions in Changchun City were found to be far less than 1. Therefore, it was concluded that the soil mercury contamination levels were not currently at the levels which could be considered to be harmful to the health of the resident adults. However, it should be noted that the northwestern section of the study area had displayed certain potential cancer risks due to its high risk values.

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Conflict of Interest

The authors declare no conflict of interest.

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