https://doi.org/10.17221/361/2023-PSE

Differences in the removal efficiency of heavy metals in soils with different vegetation backgrounds along the China-Russia crude oil pipeline

Shiyi Chen[1,2], *Cunyong Ju*[1,2]*, *Yang Du*[3,4], *Tianqi Mu*[1,2], *Tijiu Cai*[1,2]

[1]*School of Forestry, Northeast Forestry University, Harbin, P.R. China*
[2]*Key Laboratory of Sustainable Forest Ecosystem Management-Ministry of Education, Northeast Forestry University, Harbin, P.R. China*
[3]*Harbin Research Institute of Forestry Machinery, National Forestry and Grassland Administration, Harbin, P.R. China*
[4]*Research Center of Cold Temperate Forestry, Chinese Academy of Forestry, Harbin, P.R. China*
**Corresponding author: qucy09@nefu.edu.cn*

Citation: Chen S.Y., Ju C.Y., Du Y., Mu T.Q., Cai T.J. (2023): Differences in the removal efficiency of heavy metals in soils with different vegetation backgrounds along the China-Russia crude oil pipeline. Plant Soil Environ., 69: 628–639.

Abstract: This work discusses the differences in the removal efficiency of heavy metals in soils along the China-Russia crude oil pipeline in different vegetation backgrounds. In this paper, two representative forest types, birch forest and larch forest, were selected for replicated sampling and experimental study in the soil of disturbed and undisturbed areas along the pipeline, respectively. The results showed that after ten years of vegetation restoration, the amount of heavy metals in the soil of birch and larch forests decreased, the Cu content in the soil under the background of the birch forest was higher than that of the larch forest, while the Zn, Mn and Pb contents were lower than that of the larch forest. The order of decreasing magnitude was Mn, Pb, Zn and Cu, and the overall decreasing rate of heavy metal content in larch forest soil was more obvious. The above conclusions indicate that vegetation restoration is an effective measure to alleviate soil heavy metal pollution.

Keywords: pipeline laying; petroleum; toxic element; contamination; ecosystem

Petroleum plays a crucial strategic role in the nation's growth and is closely related to national strategy, international politics, and the global power structure (Tsui 2011). Since the energy problem has become severe in recent years, petroleum has steadily taken on a vital role in restricting the steady growth of the national economy (Hughes and Rudolph 2011, Martínez-Palou et al. 2011, Xiao et al. 2022). Countries and regions that are not rich in oil resources inevitably need to solve the problem of oil procurement and transportation. The long-distance oil pipeline serves as a pipeline system for the movement of crude oil and petroleum products, making it the most important piece of transportation equipment in the oil storage and transportation sector (Tsoskounoglou et al. 2008). After all, pipeline oil transportation provides advantages over railroad and highway oil transportation (Martínez-Palou et al. 2011), including large volume, good tightness, low cost, and high safety factors (Hasan et al. 2010, Martínez-Palou et al. 2011, Ilman and Kusmono 2014). The completion of the China-Russia crude oil pipeline is an important step in accelerating the development of China's strategic energy channel, optimising oil supply and transportation patterns, ensuring the security of the country's energy supply, strengthening China-Russia

Supported by the National Key R&D Program of China, Project No. 2018YFC0507302.

https://doi.org/10.17221/361/2023-PSE

strategic cooperation, and promoting economic and social development (Azevedo 2007).

However, the construction of the China-Russia crude oil pipeline inevitably caused a certain degree of damage to the topsoil and vegetation around the pipeline (Nuttall 2010). In particular, due to the artificial excavation of the soil to a depth of more than 2 m during the construction (Xu et al. 2020), the soil was severely disturbed, and this disturbance significantly changed the concentration of heavy metal components in the topsoil. After all, industrial and human activities, including oil pipeline installation, are primary sources of soil heavy metal pollution, especially for most zinc and copper (Morton-Bermea et al. 2009). Compared with other soil pollutants, soil heavy metal pollution is easy to accumulate and has a high and persistent pollution level (Dong et al. 2019, Jiao 2022). If soil heavy metal pollution is not addressed in time, it will have a negative impact on ecosystem health (Remon et al. 2005, Chai et al. 2007, Zhang 2020) and even human survival (Shifaw 2018, Li et al. 2019, Atanasov et al. 2023). For example, Ko and Day (2004) examined the multifaceted ecological effects of oil and gas exploration on the coastal ecosystems of the Mississippi Delta. They determined that both the toxicity of oil spills and the indirect consequences of petroleum-related activities increased the likelihood of plant stress and mortality (Ko and Day 2004). Experts have suggested a variety of treatments for soil heavy metal problems, including physical treatments such as leaching, improved soil importation from other places, adsorption and immobilisation, and chemical treatments like bioreduction and complex leaching. However, compared with these techniques, vegetation restoration presents a more significant avenue for research due to its ability to tolerate, absorb, and translocate heavy metal elements in the soil (Bech et al. 2016, Marrugo-Negrete et al. 2016, Nero 2021). This method requires less capital investment, is simple to implement, and, most importantly, does not generate secondary pollution while providing high economic and ecological benefits (Tan et al. 2020). Xu et al. (2021) emphasised that vegetation restoration serves as an effective ecological strategy to alleviate heavy metal pollution in open pit mine areas, and the duration of the restoration process was also positively related to the degree of mitigation of soil heavy metal contamination. Bhattacharya et al. (2015) also found that the duration of wetland restoration significantly influenced the concentration and distribution of heavy metals in wetland soils. Hu et al. (2021) indicated that soil properties and the heavy metal distribution varied considerably depending on the type of vegetation restoration employed. Although a large body of research has been conducted on the effects of industrial activities or vegetation restoration on soil heavy metal content, there is still a gap in comprehensive studies examining their combined effects on soil heavy metal content or contamination.

The project management implemented vegetation restoration procedures by sowing bluegrass and alfalfa seeds in areas disturbed by the pipeline when it started operation approximately ten years ago (Yu et al. 2010). However, these introduced plant species disappeared over the following decade and were replaced by native species (Figure 1). The impact of vegetation restoration on soil heavy metal content over the past decade remains uncertain. It is also unclear if this change is correlated with the pre-project background vegetation. To address these questions, two representative forest types crossed by the pipeline, larch forest and birch forest, were selected for investigation of soil heavy metal levels in this study. Four heavy metal elements, copper (Cu), zinc (Zn), manganese (Mn) and plumbum

Figure 1. Changes of vegetation cover in disturbed areas by the China-Russia crude oil pipeline, 2013 (left) and 2016 (right)

https://doi.org/10.17221/361/2023-PSE

(Pb), were focused on due to their common occurrence and representation in soils and to allow for accurate comparison with early data from engineering construction. By comparing survey and measurement data from the year the project was completed, the influence of vegetation restoration on soil heavy metals over the previous decade was determined. This study emphasises the natural variability of heavy metal contents due to the implementation of vegetation restoration measures over a decade. It also explores how the effects vary between different forest types to provide a reference basis for developing vegetation restoration techniques following the completion of other large linear projects in the Greater Khingan Region or across China (Liu and Wang 2020).

MATERIAL AND METHODS

Study site. This study mainly focused on the low mountain hilly area of the Greater Khingan Mountains (50°10'–53°33''N, 121°12'–27°00'E). The average altitude of the region is 300–700 m a.s.l. The climate is cold and dry in winter and hot and rainy in summer. There is a large diurnal temperature difference, with an annual average temperature of –3.5 °C and a minimum temperature of –52.5 °C. The frost-free period is 80–110 days, and the average annual precipitation is 438–530 mm. The area belongs to a cold-temperate continental monsoon climate. The typical vegetation type in the region is boreal forest, and domain species are *Larix gmelinii*, (Rupr.) Kuzen., *Pinus sylvestriis* L. var. *mongoloca* Litv., *Betula platyphylla* Suk, *Populus davidiana* Dode and so on; there are also meadows and swamps distributed in the low flat valley which are composed of mesophytic herbaceous plants. The primary types of native soils are brown coniferous forest soils, accompanied by black soils, meadow soils, swampy soils and new accumulation soils. Most of the samples selected for this study were derived from brown coniferous forest soils. These soils are typically light and rough in texture, containing high quantities of sand and gravel and substantial clay content. They also have high humus content, but effective fertility is low. Due to the construction of the crude oil pipeline, topsoil pH increased from 4.8–5.6 to 5.4–6.6 in the disturbed area. During the initial phase of pipeline installation, there was a notable decrease in the organic matter content of the 0–10 cm and 10–20 cm soil layers. Specifically, the 0–10 cm layer experienced a reduction of 32.74%, while the 10–20 cm layer witnessed a decrease of 26.31% (Teng et al. 2015). With the gradual vegetation restoration, the soil organic matter content in the disturbed areas gradually increased (Hu and Guo 2012). In addition, in the study site, the carbon mineralisation rate of forest soils showed a decreasing and then stabilising trend with time (Dong et al. 2019)

Sample collection and processing. The recent vegetation survey and soil sampling were conducted in July 2022. Sample plots (10 m × 10 m) of each forest type were established in both the disturbed zone (above the pipeline) and the undisturbed zone (50–100 m away from the disturbed area), with three replicates for each forest type. Vegetation cover surveys were performed on selected sample plots, and the fraction of vegetation cover reached more than 60% in all sample plots, with most having 100% coverage. In 2013, the fraction of vegetation cover was less than 50%; in some quadrats, it was less than 20% (Duan 2015). Soil samples were collected at 0–10 cm and 10–20 cm soil levels (each sample weighed approximately 1 kg) (Tan et al. 2020). The soil samples collected were returned to the labora-

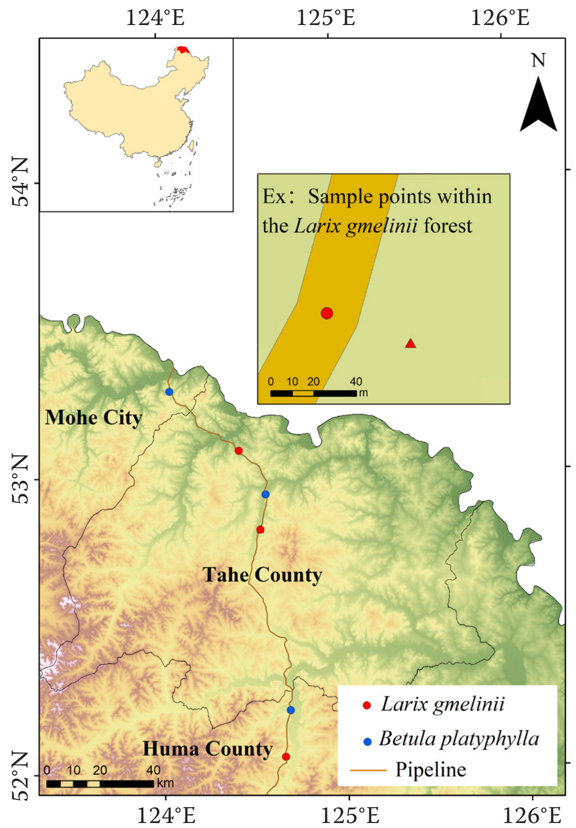

Figure 2. The map of the study area and sampling points in both disturbed areas (circle) and undisturbed areas (triangle)

https://doi.org/10.17221/361/2023-PSE

tory and air-dried in a well-ventilated chamber. After air-drying, the samples were crushed with a wooden hammer head, ground and sieved through a 2 mm mesh (Liu et al. 2013), and placed in a desiccator for indicator determination (Li et al. 2019).

Sample measurement method. Heavy metals Cu, Zn, Mn, and Pb were determined after three acid digestions of soil samples (Audu et al. 2020). The following are the specific steps: Air-dried soil samples were accurately weighed and passed through a 100-mesh sieve 0.2 g (accurate to 0.001 g) into a clean oven-dried 50-mL Teflon crucible, with a little deionised water added to wet the soil samples. Then, 5 mL HF (hydrogen fluoride), 3 mL HNO_3 (nitric acid), and 3 mL $HCLO_4$ (perchloric acid) were added in turn, and the crucible was gently shaken to allow the acid to react with the bubbles fully (Shen et al. 2019). Place the crucible in the fume hood on the hot plate, and after one hour of cooking at a low temperature of 130 degrees, gradually increase the temperature to 250 degrees for cooking. Remove the lid of the crucible when white smoke begins to form while wearing safety gloves, and then give the crucible a gentle shake to allow the liquid and soil to react fully. Continue heating the sample until it is dry after the perchloric acid has stopped emitting white smoke and the sample has turned paste-like. If the residue is grey, digestion is not complete. Add 1 mL $HCLO_4$ and 3 mL HF, and heat until digestion is complete. The residue should be colourless, transparent, or bright yellow. After digestion, remove the crucible and allow it to cool to room temperature before adding 5 mL of nitric acid solution (10 + 90), heating it to dissolve the residue, and then wholly transferring it into a 50-mL volumetric flask. Next, wash the crucible with deionised water before adding the scale and deionised water, shaking vigorously before standing for testing (Rrong et al. 2016)

Evaluation method. The single-factor index and Nemerow multi-factor index were used to evaluate the degree of heavy metal pollution. The formula for single factor index (Chen et al. 2005, Wei and Yang 2010):

$$P_i = C_i/S_i$$

where: P_i – pollution index of soil pollutants and was utilised to calculate the enrichment of heavy metals relative to soil background in polluted soils (Hakanson 1980); C_i – content of heavy metal in polluted soils; S_i – background concentration of heavy metal i in unpolluted natural soils, values of the P_i are interpreted as follows: $P_i < 1$, low contamination of the soil with examined substance; $1 \leq P_i < 3$, moderate contamination; $3 \leq P_i < 6$, considerable contamination, and $P_i \geq 6$, very high contamination (Loska et al. 1997).

The Nemerow multi-factor index illustrates the impact of high-concentration pollutants on soil environmental quality while also reflecting each pollutant's impact on soil. It separates the levels of pollution, according to the Nemerow multi-factor index (Wang et al. 2011). The formula for the Nemerow multi-factor index:

$$PI = \{[(C_i/S_i)_{max}{}^2 + (C_i/S_i)_{ave}{}^2]/2\}^{1/2}$$

where: PI – Nemerow multi-factor index; $(C_i/S_i)_{max}$ – maximum value of single factor index; $(C_i/S_i)_{ave}$ – average of single factor index. The Nemerow multi-factor index is divided into 5 levels to indicate the pollution degree from none to heavy pollution. If $PI \leq 0.7$ is safety; $0.7 < PI \leq 1$ is precaution; $1 < PI \leq 2$ is slight pollution; $2 < PI \leq 3$ is moderate pollution; $PI > 3$ is heavy pollution (Yari et al. 2021).

Data processing. The data were analysed by *t*-test paired analysis using SPSS 26.0 software (SPSS, Chicago, USA) (Xu et al. 2021). The differences in the contents of the four heavy elements in the soils of the disturbed and undisturbed zones were analysed by the paired *t*-test for different forest types. The changes in heavy metal contents after ten years of vegetation restoration were also analysed using the same method (Rrong et al. 2016). If the result obtained was $P > 0.05$, the difference was not significant; if $0.05 > P > 0.01$, it showed a significant difference; if $P < 0.01$, the difference was highly significant (Butera et al. 2020). The impact of vegetation restoration on heavy metal enrichment and degradation on the soil of the China-Russia crude oil pipeline was evaluated and analysed in comparison with soil heavy metal content data obtained when the project was put into operation ten years ago in order to provide basic data support for vegetation restoration measures of large-scale linear projects (Zeng et al. 2016).

RESULTS

Differences in heavy metal contents with different vegetation backgrounds. In both vegetation backgrounds, the order of soil heavy metal content was disturbed > undisturbed areas. In addition, except for Pb and Zn in the larch background and the disturbed area of the birch forest, all followed the pattern of higher heavy metal contents in the surface soil than in the sub-surface soil.

https://doi.org/10.17221/361/2023-PSE

According to Figure 3, the Cu content in the soil of birch forest was higher than that of larch forest in both disturbed and undisturbed areas, with the soil in the disturbed area having a Cu content that was 8.21% higher than that of the larch forest, whereas the soil in the undisturbed area had a Cu content that was 17.39% higher than that of the larch forest. However, there was no proof of statistical significance for this difference ($P > 0.05$).

Various vegetation backgrounds had various Zn contents in the soil. Overall, it appears that larch soil has more Zn than birch forest. In the disturbed areas of the two forest types, there was a very significant difference in the sub-surface soil's Zn content ($P < 0.01$), with the Zn content in larch forest soil being 48.59% higher than that of birch forest.

Larch forest soil had a higher Mn content in both disturbed and undisturbed areas than birch forest soil, but there was little variation between the two different forest types ($P > 0.05$). While the Mn content of larch forest soil was 8.84% higher in the undisturbed area than that of white birch forest, it was 16.80% higher in the disturbed area.

Sub-surface soil > surface soil was the vertical pattern of change in Pb content in both forest types, which was significant ($0.05 > P > 0.01$). The Pb content in the birch forest's soil was higher than that of the larch forest, with the undisturbed area's Pb content being 60.25% more than that of the larch forest and the disturbed area's being 21.98% higher. In the undisturbed area, the difference in Pb content between the two forest types was statistically significant ($P < 0.01$).

Differences in the removal efficiency of heavy metals. Observation of Figure 4 shows that the Cu concentration in the soil of the study region dramatically dropped after ten years of vegetation development at a natural rate, and the change from ten years earlier was significant ($0.05 > P > 0.01$). Compared with the initial period of pipeline laying, the soil's Cu content declined by 35.54% in the disturbed area of birch forest and by 27.21% in the undisturbed area; similarly, the Cu content decreased by 34.36% in the disturbed area of larch forest and by 23.54% in the undisturbed area. The decrease in Cu content in the sub-surface soil was larger in both forest types than in the surface soil. Overall, the decreasing trend of soil Cu content in birch forests was more obvious.

Except for the undisturbed area of birch forest, where the change in Zn content in the sub-surface

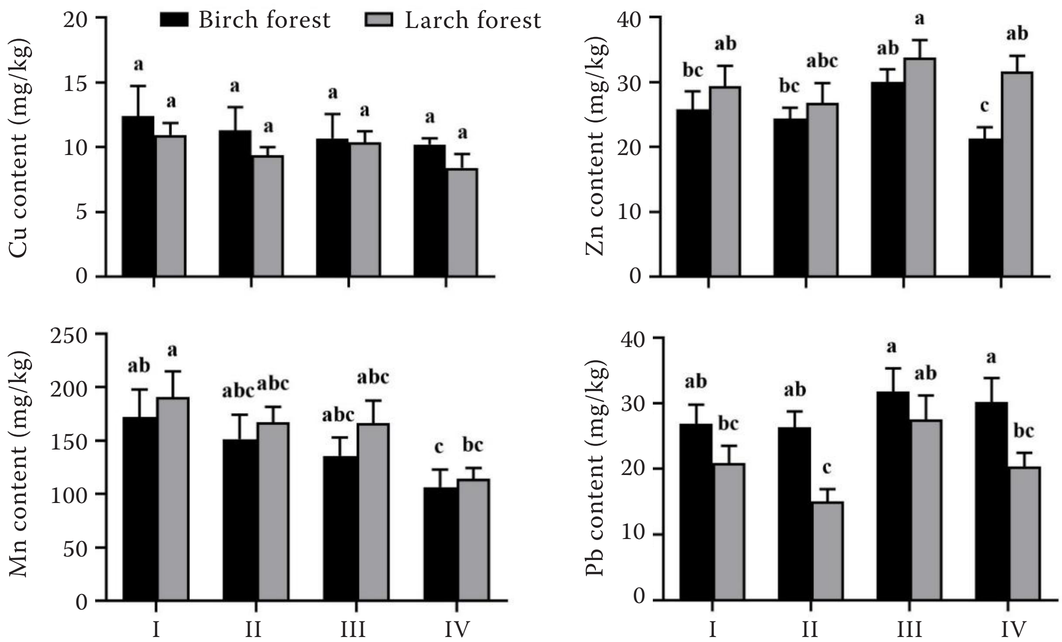

Figure 3. Content of heavy metals in soils of different vegetation backgrounds along the China-Russia crude oil pipeline ($n = 24$). Data are mean ± standard error. Variations are minimum to maximum values. Lowercase letters indicate that the data meet the chi-square test, and the two-way comparison is based on the Bonferroni method. Different letters in the same column indicate significant differences ($P < 0.05$). I – disturbed area 0–10 cm; II – undisturbed area 0–10 cm; III – disturbed area 10–20 cm; IV – undisturbed area 10–20 cm

https://doi.org/10.17221/361/2023-PSE

soil was minor throughout the decade, the Zn content of other soil varied significantly over the decade, as indicated in the figure. With a decrease of 81.22% in the disturbed area and a fall of 62.68% in the undisturbed area, the overall decrease in Zn content in the larch soil was 71.95%, above the 57.46% decrease in the birch forest. In the disturbed area of the birch forest, the soil Zn content declined by 81.63%, whereas in the undisturbed area, it decreased by 33.28%. In contrast to Cu, the Zn content of the study area's sub-surface it decreased less than that of the surface soil. In conclusion, the difference in soil Zn content in the study area was highly significant compared to ten years ago (P < 0.01).

The Mn content in the soil of the study area clearly showed a large decline, with highly significant differences (P < 0.01). Both forest types had a general drop, with larch forests experiencing an 83.55% decline in soil Mn content and birch forests experiencing an 82.36% decline. The Mn content decreased by 84.84% in the larch-disturbed area and 82.25% in the undisturbed area, while soil Mn content decreased by 90.86% in the disturbed area of the birch forest and 74.86% in the undisturbed area.

The Pb content in the study area varied considerably before and after the decade. In the disturbed area of the birch forest, the Pb content decreased by 61.13%, in the undisturbed area by 54.94%, and overall by 58.04% in the birch forest, whereas in the disturbed area of the larch forest, the Pb content decreased by 72.38%, in the undisturbed area fell by 76.65%, and the larch forest decreased overall by 74.96%, which was a significant decrease in comparison to that of birch forest. Compared to 10 years before, the Pb content in the research area reduced by 65.80%, which was highly significant (P < 0.01).

Evaluation of heavy metal pollution in soil. As an important indicator of soil chemical properties, soil heavy metal content can effectively reflect soil fertility and quality. Table 1 summarises the different heavy metal content in disturbed and undisturbed areas of birch and larch forests. After ten years of natural growth in birch forests and larch forests, the accumulation of Mn in the soil is the highest, while the content of Pb is the least, which is consistent with ten years ago.

The Nemero multi-factor index can fully reflect the degree of pollution of each pollutant to the soil, and at the same time, it can highlight the influence of high concentrations of heavy metals on the soil's environmental quality. The Nemerow index method explicitly considers the largest factor's impact on evaluation results (Wei et al. 2023). In addition, the Nemerow evaluation method also considers the contribution of mean value and its evaluation results for environmental factors, which makes the method more comprehensive and objective (Yaylalı-Abanuz 2019). Therefore, the multi-factor index is used to assess and classify soil quality levels. Table 2 is based on the measured values of heavy metals in Table 1 and the single factor index formula, single factor index (P_i) and pollution degree of the two forest types. Background values of Cu, Zn, Mn and Pb in brown coniferous forest soil were 13.8, 89.4, 1 790 and 20.2 mg/kg (Teng et al. 2015). The largest single factor index was Pb (1.45) in birch forest soil. It can be seen from the single factor index that Pb is an important metal element causing soil pollution in the region. Among them, the disturbed and undisturbed areas of the birch forest were slightly polluted, the larch forest work area was slightly polluted, and the remaining areas were not polluted. The P_i value of the lightly polluted area is about 1.3, which contributes less to soil pollution.

The two forest types' comprehensive pollution index (PI) was calculated using the single factor index and Nemero multi-factor index formula, as shown in Table 2. The PI of the birch forest disturbed area was the largest, indicating that the area was slightly contaminated and the soil began to be polluted. The birch forest undisturbed area and the larch forest undisturbed area are precautions that should be attention to prevent soil heavy metal pollution; the larch forest undisturbed area is an unpolluted area.

Table 1. Heavy metal content in disturbed and undisturbed areas

Forest type	Investigation place	Cu	Zn	Mn	Pb
		(mg/kg)			
Birch forest	disturbed area	11.55 ± 2.11	27.9 ± 4.14	154.06 ± 36.52	29.36 ± 3.07
	undisturbed area	10.43 ± 1.75	22.87 ± 2.43	129.02 ± 44.53	28.06 ± 2.17
Larch forest	disturbed area	10.67 ± 1.59	31.63 ± 6.66	178.86 ± 51.64	24.25 ± 5.11
	undisturbed area	8.91 ± 0.87	29.26 ± 6.18	140.8 ± 37.47	17.75 ± 3.38

https://doi.org/10.17221/361/2023-PSE

Table 2. Single factor index and Nemero multi-factor index of soil in disturbed area and undisturbed area

Forest type	Investigation place	Single factor index (P_i)				Nemerow multi-factor index (PI)
		Cu	Zn	Mn	Pb	
Birch forest	disturbed area	0.84	0.31	0.09	1.45	1.03
	undisturbed area	0.76	0.26	0.07	1.39	0.98
Larch forest	disturbed area	0.77	0.35	0.1	1.2	0.85
	undisturbed area	0.65	0.33	0.08	0.88	0.62

DISCUSSION

Vegetation restoration is one of the best solutions to address soil heavy metal pollution caused by pipeline installation in terms of balancing between ecological and economic benefits (Raiesi 2017, Altaf et al. 2021). Different vegetation backgrounds have different effects on the prevention and control of heavy metal pollution (Huang and Zhang 2021). This study provided quantitative solid support for these conclusions. After 10 years of vegetation restoration, it was found that the heavy metal content in the study area had significantly decreased.

The variations in the concentrations of four heavy metals in the soil differ across forest backgrounds. Within the context of birch, both Cu and Pb concentrations exceeded those in larch. Compared to data from a decade ago, the decrease in Cu concentration was more significant in birch backgrounds than in larch backgrounds, while Pb reduction was more pronounced in larch backgrounds. Zn and Mn concentrations were higher under larch backgrounds than in birch forests and decreased more significantly under larch backgrounds. This indicates that the characteristics of changes in different heavy metals within soils vary based on the type of forest background. Vegetation

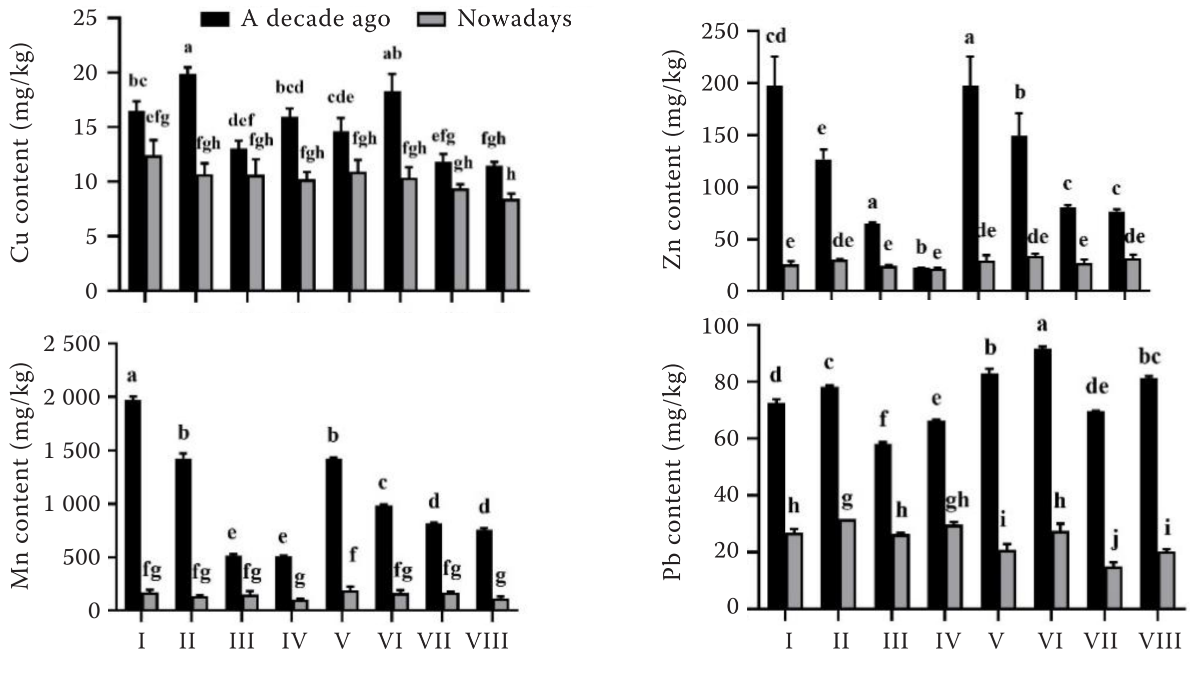

Figure 4. Differences in heavy metal contents in soils of different vegetation backgrounds along the China-Russia crude oil pipeline between nowadays and a decade ago (n = 48). Data are mean ± standard error. Variations are minimum to maximum values. Lowercase letters indicate that the data meet the chi-square test, and the two-way comparison is based on the Bonferroni method. Different letters in the same column indicate significant differences (P < 0.05). I – birch forest disturbed area 0–10 cm; II – birch forest disturbed area 10–20 cm; III – birch forest undisturbed area 0–10 cm; IV – birch forest undisturbed area 10–20 cm; V – larch forest disturbed area 0–10 cm; VI – larch forest disturbed area 10–20 cm; VII – larch forest undisturbed area 0–10 cm; VIII – larch forest undisturbed area 10–20 cm

https://doi.org/10.17221/361/2023-PSE

cover has a synergistic effect on soils contaminated by heavy metals through migration (Zhang 2021). The capacity of different plant types to absorb heavy metals varies greatly, leading to significant differences in heavy metal removal from across different vegetation backgrounds (Huang and Zhang 2021). Birch, a pioneer species of second-growth forest with persistent life, is in the middle and early stages of community succession (Ji 2016). It may enhance soil quality, interact well with soil, and effectively absorb heavy metals from soil without having stringent requirements for growing soil (Zhu and Tan 2008). Larch, another fast-growing tree species known for producing high-quality wood, alters the soil's physicochemical properties over an extended period of growth, changing it from acidic to alkaline (Yang et al. 2013). More importantly, the ability of larch to absorb heavy metals increases over time (Meng 2019). Birch and larch forests, which are dominant woody plants, have been found to be effective at removing heavy metals from soil (Gu 2015). In addition, a decrease in soil heavy metal content may also be attributed to the migration of such metals due to the vertical or horizontal movement of aqueous solutions within the soil. Soil erosion is a significant conduit for the horizontal migration of soil heavy metals (Qiao et al. 2014). The preceding lack of vegetation cover in the disturbed area, prior to implementing vegetation restoration measures, might have contributed to exacerbated soil erosion. However, with the present substantial increase in vegetation cover, the issue of soil erosion is essentially resolved, thereby reducing the horizontal migration of heavy metals in soil. Moreover, the experimental data indicating that most heavy metals accumulate in the surface layer of the soil negates any possibility that this accumulation could be attributed to the vertical direction movement of the aqueous solutions within the soil. As such, this study disregards any potential reasons for reducing heavy metal content due to vertical or horizontal migration of soil aqueous solutions and focuses solely on the impact of vegetation restoration measures on soil heavy metal content.

The Cu and Mn content in both forest types decreased with increasing soil depth. Most heavy metals accumulate in the surface layer of the soil (Manapanda et al. 2005). This is due to the continuous loss of water from the surface layer of the soil by evaporation and the top-down transport of soil water to the surface layer of the soil, where some of the heavy metals also move. The surface soil is in direct contact with the surrounding environment and is the first to be affected by heavy metal contamination, so it has a high level of contamination. With further influence from the surrounding environment, heavy metals slowly leach down, and the underlying soil becomes contaminated. Heavy metals are included in soil minerals and bound to different phases of soil particles by various mechanisms, mainly absorption, ion exchange, coprecipitation, and complexation (Ashraf et al. 2012). In addition, soil properties such as organic matter content, carbonates, and oxides, as well as soil structure and profile development, influence heavy metal mobility (Kabata-Pendias 2000). Because heavy metals are difficult to dissolve and move around, they are more easily fixed in surface soil because of their long retention times, poor mobility (Wang et al. 2018), and difficulty being broken down by other microorganisms. The reason for the different Cu and Mn contents in soils at different depths may be due to the low mobility of these heavy metals, which aggregate in the surface soil. A contributing factor is also the strong adsorption power of soil (Yu et al. 2018). Compared with sub-surface soil, surface soil has relatively active microbial activity, and microorganisms absorb and immobilise heavy metal ions (Wu et al. 2016), resulting in a higher heavy metal content in surface soil. Soil pH is also increased by pipe laying, and in general, as soil pH increases, the amount of dissolved heavy metals in the soil decreases (Zhang et al. 2022). Generally, as pH increases, the adsorption process of heavy metals is enhanced, and more heavy metals enter the solid phase, reducing their migration. The climate also contributes to this phenomenon. The study area is in a temperate continental climate with low precipitation and uneven seasonal distribution. Heavy metals enriched in the soil's surface layer have less opportunity to migrate downward with water resources. The infiltrated water flow in the area is weak, and when influenced by the surface humus layer or other materials, heavy metals are retained in large quantities in the surface layer (Kakareka and Salivonchik 2017). The above factors will affect most heavy metals and accumulate on the soil surface (Chandrasekaran et al. 2015, Obiora et al. 2016, Khudur et al. 2018). The research proved that the vertical pattern of heavy metal Cu and Mn content in the soil was consistent with the description that the surface soil was higher than the sub-surface soil.

The vertical distribution of heavy metals in the soils occasionally deviates from the pattern mentioned above. In some cases, an increase in soil depth results in a higher concentration of these heavy metals. This

https://doi.org/10.17221/361/2023-PSE

deviation from the usual trend may be attributed to anthropogenic activities such as stampede and reclamation. These activities can cause heavy metal Zn in the soil to bind with various inorganic or organic ligands (Shi et al. 2014). The coordination of heavy metals with hydroxyl and chlorine can make insoluble heavy metal complexes more soluble and reduce the adsorption by soil colloids, influencing the movement and transformation of heavy metals within the soil. Changes in organic matter content due to the pipelaying may also contribute. The quantity of organic matter in soil influences the transport and transformation of heavy metals (Tan et al. 2011). Soils rich in organic matter tend to dissolve, producing more soluble organic carbon (DOC). This DOC reacts with certain heavy metals to form chelates that enhance the transport of that particular heavy metal. As a result, the soil sub-surface layer contains higher concentrations of heavy metals than the surface layer (Sherene 2009). Vertical variation of Zn content in larch and birch forests showed that soil Zn content increased with increasing soil depth in disturbed areas of both forest types and in undisturbed areas of larch forests. At the same time, it decreased with the soil layer deepening in the undisturbed areas of birch forests. This theory helps explain why, generally, surface layer soil contains slightly less Zn than sub-surface layers.

The migration capacity of various heavy metals also differs. The mobility of Pb is influenced by soil organic matter, and the migration capacity of Pb is weakened in soils with a higher content of organic matter. The content of surface soil organic matter is positively correlated with the content of heavy metal Pb. Affected by the pipeline laying, the content of the surface soil organic matter in the study area may have been reducing, which leads to the enhanced migration capacity of Pb and the infiltration of heavy metals, and the content of Pb in the sub-surface soil is then higher than that in the surface soil (Quenea et al. 2009). In addition, soil parent material and human pollution are considered to be the causes of heavy metal Pb's concentration in the sub-surface of the soil. As a result, it was found that sub-surface soil had a higher Pb content than surface soil.

According to the single factor index and Nemero multi-factor index, Pb is the main pollutant in the study area, and the birch forest disturbed area has the highest Pb pollution levels. Current PI shows a significant downward trend compared with the Nemero multi-factor index for the area ten years ago, indicating that soil pollution has decreased and supporting the idea that vegetation restoration can reduce soil heavy metal pollution. It is recommended that measures be taken to prevent human activities from polluting the environment and improve the soil environment in the area, according to the main causes of heavy metal contamination.

This study further supports researchers' widespread belief that vegetation restoration efficiently addresses soil pollution caused by heavy metals. The two forest types in the study exhibited different pollution avoidance effects for different heavy metal pollution (Gao et al. 2018). The birch background was more effective than the larch background in controlling the Cu contamination, while the larch background was more effective in mitigating the Zn, Mn and Pb contamination. In the future, when considering managing heavy metal pollution following pipeline laying, researchers can be explicit about which vegetation restoration strategies to use to address different types of heavy metal pollution. In conclusion, after 10 years of project operation, there was a notable trend towards reducing all four heavy metals in the soils. However, the soil from the disturbed area exhibited higher heavy mental content than the undisturbed area. The type of background vegetation and the heavy metals influenced the reduction rate, with the latter determining the pattern of variation in the vertical direction. The impact of different vegetation backgrounds on the removal of various heavy metals also varied. The removal of Cu in the soil was more pronounced in the birch background, while the remaining three heavy metals, Zn, Mn and Pb, were more effectively removed in the larch background. Overall, vegetation restoration measures appear to be beneficial for reducing soil contamination from heavy metals in the pipeline laying areas, enhancing local ecological environments, and improving living conditions for people. These findings also hold significant reference value for developing large-scale linear projects in the Greater Khingan Region and potentially across the nation.

Acknowledgement. We thank the reviewer for the positive and constructive comments regarding our manuscript. We also thank the Natural Science Foundation of Heilongjiang Province of China, Project No. LH2020C032.

REFERENCES

Altaf R., Altaf S., Hussain M., Shah R.U., Ullah R., Ullah M.I., Rauf A., Ansari M.J., Alharbi S.A., Alfarraj S., Datta R. (2021): Heavy

https://doi.org/10.17221/361/2023-PSE

metal accumulation by roadside vegetation and implications for pollution control. PloS One, 16: e0249147.

Ashraf M.A., Maah M.J., Yusoff I. (2012): Chemical speciation and potential mobility of heavy metals in the soil of former tin mining catchment. The Scientific World Journal, 2012: 125608.

Atanasov A.Z., Hristakov I.S., Kuncheva G.S., Koszel M., Dochev V.Y. (2023): Assessment of heavy metals in soil, oilseed rape (*Brassica napus* L.) and honey. Plant, Soil and Environment, 69: 400–407.

Audu K.E., Adeniji S.E., Obidah J.S. (2020): Bioremediation of toxic metals in mining site of Zamfara metropolis using resident bacteria (*Pantoea agglomerans*): a optimization approach. Heliyon, 6: e04704.

Azevedo C.R. (2007): Failure analysis of a crude oil pipeline. Engineering Failure Analysis, 14: 978–994.

Bech J., Roca N., Tume P., Ramos-Miras J., Gil C., Boluda R. (2016): Screening for new accumulator plants in potential hazards elements polluted soil surrounding Peruvian mine tailings. Catena, 136: 66–73.

Bhattacharya B.D., Nayak D.C., Sarkar S.K., Biswas S.N., Rakshit D., Ahmed M.K. (2015): Distribution of dissolved trace metals in coastal regions of Indian Sundarban mangrove wetland: a multivariate approach. Journal of Cleaner Production, 96: 233–243.

Butera A., Gallo S., Maiorani C., Molino D., Chiesa A., Preda C., Esposito F., Scribante A. (2020): Probiotic alternative to chlorhexidine in periodontal therapy: evaluation of clinical and microbiological parameters. Microorganisms, 9: 69.

Chai X.L., Shimaoka T., Cao X.Y., Guo Q., Zhao Y.C. (2007): Characteristics and mobility of heavy metals in an MSW landfill: implications in risk assessment and reclamation. Journal of Hazardous Materials, 144: 485–491.

Chandrasekaran A., Ravisankar R., Harikrishnan N., Satapathy K.K., Prasad M.V.R., Kanagasabapathy K.V. (2015): Multivariate statistical analysis of heavy metal concentration in soils of Yelagiri Hills, Tamilnadu, India – spectroscopical approach. Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy, 137: 589–600.

Chen T.B., Zheng Y.M., Lei M., Huang Z.C., Wu H.T., Chen H., Fan K.K., Yu K., Wu X., Tian Q.Z. (2005): Assessment of heavy metal pollution in surface soils of urban parks in Beijing, China. Chemosphere, 60: 542–551.

Dong X., Chen C., Zang S., Zhao G., Liu C., Wu X. (2019): Effects of temperature and moisture on soil organic carbon mineralization of predominantly permafrost forest in the Great Hing'an Mountains, Northeastern China. Acta Scientiae Circumstantiae, 39: 4269–4275.

Duan T. (2015): Effects of China-Russia oil pipeline on speciation of heavy metal in soil of different forest types passed by the project. Heilongjiang, Northeast Forestry University.

Gao L., Zou G., Du L., Li S., Liu J., Duan H. (2018): Effect of different cultivation practices on soil physical and chemical properties for greenhouse vegetables under long-term continuous cropping. Asian Agricultural Research, 10: 74–81.

Gu J. (2015): Research on soil heavy metal pollution and ecological restoration in representative abandoned mining land of Da Xing'anling. Heilongjiang, Northeast Forestry University.

Hakanson L. (1980): An ecological risk index for aquatic pollution control. A sedimentological approach. Water Research, 14: 975–1001.

Hasan S.W., Ghannam M.T., Esmail N. (2010): Heavy crude oil viscosity reduction and rheology for pipeline transportation. Fuel, 89: 1095–1100.

Hu B., Guo P.Y., Su H.T., Deng J., Zheng M.Y., Wang J.Y., Wu Y.Q., Jin Y.F. (2021): Fraction distribution and bioavailability of soil heavy metals under different planting patterns in mangrove restoration wetlands in Jinjiang, Fujian, China. Ecological Engineering, 166: 106242.

Hu C., Guo L. (2012): Advances in the research of ecological effects of vegetation restoration. Ecology and Environmental Sciences, 21: 1640–1646.

Huang H., Zhang L. (2021): Effects of vegetation restoration patterns on soil heavy metals in industrially polluted areas: a case study of maba forest park. Forestry and Environmental Science, 37: 52–60.

Hughes L., Rudolph J. (2011): Future world oil production: growth, plateau, or peak? Current Opinion in Environmental Sustainability, 3: 225–234.

Ilman M.N., Kusmono (2014): Analysis of internal corrosion in subsea oil pipeline. Case Studies in Engineering Failure Analysis, 2: 1–8.

Ji T. (2016): Influence of artificial forest gap on soil bacterial community diversity in the *Pinus massoniana* plantation. Sichuan, Sichuan Agricultural University.

Jiao Z. (2022): Pollution characteristics and risk assement of heavy metals in farmland soil around a lead-zinc mine in Liaoning province. Shenyang, Shenyang University.

Kabata-Pendias A. (2000): Trace Elements in Soils and Plants. Boca Raton, CRC Press. ISBN: 9780429192036

Kakareka S., Salivonchik S. (2017): Forecasting heavy metal pollution of soils in an administrative district of Belarus. Geography and Natural Resources, 38: 295–302.

Khudur L.S., Gleeson D.B., Ryan M.H., Shahsavari E., Haleyur N., Nugegoda D., Ball A.S. (2018): Implications of co-contamination with aged heavy metals and total petroleum hydrocarbons on natural attenuation and ecotoxicity in Australian soils. Environmental Pollution, 243: 94–102.

Ko J.-Y., Day J.W. (2004): A review of ecological impacts of oil and gas development on coastal ecosystems in the Mississippi Delta. Ocean and Coastal Management, 47: 597–623.

Li J.W., Zhang X.C., Wang M.R., Bi W.L., Faisal M., Teixeira da Silva J.A., Volk G.M., Wang Q.C. (2019): Development, progress and future prospects in cryobiotechnology of *Lilium* spp. Plant Methods, 15: 125.

Liu C., Cui J., Jiang G., Chen X., Wang L., Fang C. (2013): Soil heavy metal pollution assessment near the largest landfill of China.

https://doi.org/10.17221/361/2023-PSE

Soil and Sediment Contamination: An International Journal, 22: 390–403.

Liu R., Wang D. (2020): Soil C, N, P and K stoichiometry affected by vegetation restoration patterns in the alpine region of the Loess Plateau, Northwest China. Plos One, 15: e0241859.

Loska K., Cebula J., Pelczar J., Wiechuła D., Kwapuliński J. (1997): Use of enrichment, and contamination factors together with geoaccumulation indexes to evaluate the content of Cd, Cu, and Ni in the Rybnik water reservoir in Poland. Water, Air, and Soil Pollution, 93: 347–365.

Manapanda F., Mangwayana E.N., Nyamangara J., Giller K.E. (2005): The effect of long-term irrigation using wastewater on heavy metal contents of soils under vegetables in Harare, Zimbabwe. Agriculture, Ecosystems and Environment, 107: 151–165.

Marrugo-Negrete J., Marrugo-Madrid S., Pinedo-Hernández J., Durango-Hernández J., Díez S. (2016): Screening of native plant species for phytoremediation potential at a Hg-contaminated mining site. Science of The Total Environment, 542: 809–816.

Martínez-Palou R., de Lourdes Mosqueira M., Zapata-Rendón B., Mar-Juárez E., Bernal-Huicochea C., de la Cruz Clavel-López J., Aburto J. (2011): Transportation of heavy and extra-heavy crude oil by pipeline: a review. Journal of Petroleum Science and Engineering, 75: 274–282.

Meng K. (2019): Enrichment study on forest soil heavy metal elements content and characteristics of dominant plants in tangwanghe catchment. Heilongjiang, Northeast Forestry Unieversity.

Morton-Bermea O., Hernández-Álvarez E., González-Hernández G., Romero F., Lozano R., Beramendi-Orosco L.E. (2009): Assessment of heavy metal pollution in urban topsoils from the metropolitan area of Mexico City. Journal of Geochemical Exploration, 101: 218–224.

Nero B.F. (2021): Structure, composition and diversity of restored forest ecosystems on mine-spoils in South-Western Ghana. Plos One, 16: e0252371.

Nuttall M. (2010): Pipeline Dreams: People, Environment, and the Arctic Energy Frontier. Copenhagen, International Work Group for Indigenous Affairs.

Obiora S.C., Chukwu A., Toteu S.F., Davies T.C. (2016): Assessment of heavy metal contamination in soils around lead (Pb)-zinc (Zn) mining areas in Enyigba, southeastern Nigeria. Journal of the Geological Society of India, 87: 453–462.

Qiao P., Zhou X., Yang J., Chen T., Lei M. (2014): The comparison of simulation methods for soil heavy metal movement in the ore concentration area. Geological Bulletin of China, 33: 1121–1131.

Quenea K., Lamy I., Winterton P., Bermond A., Dumat C. (2009): Interactions between metals and soil organic matter in various particle size fractions of soil contaminated with waste water. Geoderma, 149: 217–223.

Raiesi F. (2017): A minimum data set and soil quality index to quantify the effect of land use conversion on soil quality and degradation in native rangelands of upland arid and semiarid regions. Ecological Indicators, 75: 307–320.

Remon E., Bouchardon J.-L., Cornier B., Guy B., Leclerc J.-C., Faure O. (2005): Soil characteristics, heavy metal availability and vegetation recovery at a former metallurgical landfill: implications in risk assessment and site restoration. Environmental Pollution, 137: 316–323.

Rrong W., Aiping T., Ashraf M.A. (2016): The effects of applying sewage sludge into Jiangxi red soil on the growth of vegetables and the migration and enrichment of Cu and Zn. Saudi Journal of Biological Sciences, 23: 660–666.

Shen F., Mao L., Sun R., Du J., Tan Z., Ding M. (2019): Contamination evaluation and source identification of heavy metals in the sediments from the Lishui River Watershed, Southern China. International Journal of Environmental Research and Public Health, 16: 336.

Sherene T. (2009): Effect of dissolved organic carbon (DOC) on heavy metal mobility in soils. Nature Environment and Pollution Technology, 8: 817–821.

Shi P., Xiao J., Wang Y., Chen L. (2014): Assessment of ecological and human health risks of heavy metal contamination in agriculture soils disturbed by pipeline construction. International Journal of Environmental Research and Public Health, 11: 2504–2520.

Shifaw E. (2018): Review of heavy metals pollution in China in agricultural and urban soils. Journal of Health and Pollution, 8: 180607.

Tan C., Huang D., Wan D., Liu L., Yang Y., Yu X. (2011): Effects of soil organic matter on the accumulation, availability and chemical speciation of heavy metal. Journal of Hunan University Natural Sciences, 34: 82–87.

Tan X., Huang Y., Xiong D., Lv K., Chen F. (2020): The effect of *Elymus nutans* sowing density on soil reinforcement and slope stabilization properties of vegetation-concrete structures. Scientific Reports, 10: 20462.

Teng T., Cai T., Liu J., Ju C., Wang T., Duan T. (2015a): Impacts of the Sino-Russia crude oil pipeline on nutrients and heavy metals in the soil of different *Larix gmelinii* forests. Journal of Soil and Water Conservation, 29: 94–99.

Teng T., Cai T., Liu J., Ju C., Wang T., Duan T. (2015b): Impacts of the Sino-Russia crude oil pipeline on nutrients and heavy metals in the soil of different *Larix gmelinii* forests. Journal of Soil and Water Conservation, 29: 94–99.

Tsoskounoglou M., Ayerides G., Tritopoulou E. (2008): The end of cheap oil: current status and prospects. Energy Policy, 36: 3797–3806.

Tsui K.K. (2011): More oil, less democracy: evidence from worldwide crude oil discoveries. The Economic Journal, 121: 89–115.

Wang L.F., Bai Y.X., Gai S.N. (2011): Single-factor and nemerow multi-factor index to assess heavy metals contamination in soils on railway side of Harbin-Suifenhe Railway in Northeastern China. Applied Mechanics and Materials, 71: 3033–3036.

https://doi.org/10.17221/361/2023-PSE

Wang X., Wang W., Gao Q., Wang X., Lei C., Zhu F. (2018): *Chrysomya megacephala* larvae feeding favourably influences manure microbiome, heavy metal stability and greenhouse gas emissions. Microbial Biotechnology, 11: 498–509.

Wang Q.R., Dong Y., Cui Y., Liu X. (2001): Instances of soil and crop heavy metal contamination in China. Soil and Sediment Contamination: An International Journal, 10: 497–510.

Wei B., Yang L. (2010): A review of heavy metal contaminations in urban soils, urban road dusts and agricultural soils from China. Microchemical Journal, 94: 99–107.

Wei J., Zheng X., Liu J. (2023): Modeling analysis of heavy metal evaluation in complex geological soil based on Nemerow index method. Metals, 13: 439.

Wu H., Wu Q., Wu G., Gu Q., Wei L. (2016): Cd-resistant strains of *B. cereus* S5 with endurance capacity and their capacities for cadmium removal from cadmium-polluted water. Plos One, 11: e0151479.

Xiao S., Zhou Q., Qu S., Guo J., Xu D. (2022): Overview of research on environmental impact of petroleum development. Liaoning Chemical Industry, 51: 1450–1452.

Xu S.S., Zhao Q.H., Qin C.Z., Qin M.Z., Lee J., Li C.Y., Li Y.Y., Yang J.X. (2021): Effects of vegetation restoration on accumulation and translocation of heavy metals in post-mining areas. Land Degradation and Development, 32: 2000–2012.

Xu Z.C., Chen X.Z., Liu J.G., Zhang Y., Chau S., Bhattarai N., Wang Y., Li Y.J., Connor T., Li Y.K. (2020): Impacts of irrigated agriculture on food-energy-water-CO_2 nexus across metacoupled systems. Nature Communications, 11: 5837.

Yang Y., Cai T., Gu J.F. (2013): Effects of different afforestation tree species on soil nutrients and heavy metal content and its assessment in coal mine waste dump of Gulian river. Journal of Soil and Water Conversation, 27: 115–119.

Yari A.A., Varvani J., Zare R. (2021): Assessment and zoning of environmental hazard of heavy metals using the Nemerow integrated pollution index in the vineyards of Malayer city. Acta Geophysica, 69: 149–159.

Yaylalı-Abanuz G. (2019): Application of multivariate statistics in the source identification of heavy-metal pollution in roadside soils of Bursa, Turkey. Arabian Journal of Geosciences, 12: 382.

Yu H., Li J., Luan Y. (2018): Meta-analysis of soil mercury accumulation by vegetables. Scientific Reports, 8: 1261.

Yu X., Wang G., Zou Y., Wang Q., Zhao H., Lu X. (2010): Effects of pipeline construction on wetland ecosystems: Russia-China oil pipeline project (Mohe-Daqing section). Ambio, 39: 447–450.

Zeng Q., Dong Y., An S. (2016): Bacterial community responses to soils along a latitudinal and vegetation gradient on the Loess Plateau, China. Plos One, 11: e0152894.

Zhang J. (2020): Effects of environment materials and plants on heavy metal migration in soil of mining areas. Beijing, Beijing Forestry University.

Zhang S., Hu C., Cheng J. (2022): A comprehensive evaluation system for the stabilization effect of heavy metal-contaminated soil based on analytic hierarchy process. International Journal of Environmental Research and Public Health, 19: 15296.

Zhang X. (2021): Bacterial diversity and screening of heavy metal tolerant endophytic bacteria associated with poplar in mining areas. Hunan, Hunan University.

Zhu N., Tan X. (2008): Selection of pioneer species for the restoration of ecosystem in Sahara desertification spreading areas. College of Forestry, Central South University of Forestry and Technology, 28: 66–70.

Received: September 2, 2023
Accepted: November 22, 2023
Published online: December 17, 2023