

Contents and spatial distribution patterns of heavy metals in the hinterland of the Tengger Desert, China postprint

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Abstract

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Full Text

Preamble

Contents and Spatial Distribution Patterns of Heavy Metals in the Hinterland of the Tengger Desert, China

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Abstract: The deserts of northern China represent important sources of loess and significant contributors of material for Asian sandstorms. During sandstorm events, wind-blown sand and dust from these deserts can damage crop growth, cause serious economic losses, threaten life safety, and pollute the natural environment. Consequently, research into heavy metals in surface deposits of the vulnerable arid lands in northern China is crucial for guiding local industrial and agricultural development and improving environmental protection. In this study, we analyzed ten heavy metal elements (Cr, Mn, Fe, Co, Ni, Cu, Zn, Cd, Pb, and Th) in 33 soil samples collected from the hinterland of the Tengger Desert in northern China. The results revealed that the average abundance of Th exceeded the Chinese soil background value by more than 5.2 times, indicating Th contamination in the Tengger Desert. Based on principal component analysis, spatial differentiation, and correlation analysis, we identified the sources of elements with coefficient of variation greater than 0.5 or concentrations exceeding Chinese background soil values.

Principal component and correlation analyses demonstrated that Cr, Mn, Fe, Co, Ni, Cu, and Cd shared similar sources, whereas Th and Zn originated from different sources. Furthermore, based on the content and spatial distribution characteristics of these heavy metal elements, we found that enrichment areas formed due to industrial pollution, irrigated agricultural development, geological and geomorphic conditions, and the sedimentary environment of the study area. Our results provide baseline environmental data for soils in the Tengger Desert hinterland.

Keywords: Tengger Desert; terrestrial deposit; environmental pollution; industrial and agricultural production; natural factors

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1 Introduction

Terrestrial surface deposits constitute not only the dominant component of the Earth's crustal surface but also the fundamental zone for animal and plant survival [?, ?]. Under natural conditions, the abundance and spatial distribution of heavy metals in surface deposits are primarily influenced by soil parent material [?, ?] and soil structure [?, ?]. However, human activities such as irrational agricultural practices [?, ?], natural resource mining [?, ?], fossil fuel combustion [?, ?], and other anthropogenic influences increasingly affect heavy metal abundance and distribution. The growing enrichment of heavy metals has become a major environmental threat [?, ?, ?].

Previous studies on heavy metal abundance and distribution in China have focused on regions such as the Leizhou Peninsula [?, ?], Xiong'an New Area [?, ?], Jinan City [?, ?], and Shanxian County [?, ?], primarily addressing environmental quality assessments [?, ?] and the main sources affecting heavy metal distribution [?, ?]. Elevated heavy metal concentrations have been attributed to human activities. Researchers have analyzed spatial distribution characteristics, sources, and input pathways using principal component analysis (PCA) [?, ?], positive matrix factorization (PMF) [?, ?], cluster analysis (CA) [?, ?], geographic information systems (GIS) [?, ?], contamination factors (CF) [?, ?, ?], geoaccumulation index (I-geo) [?, ?, ?], and potential ecological risk index (PERI) [?, ?, ?]. These integrated methods help identify heavy metal sources and transport routes under different land-use patterns, providing more reliable data for ecological risk assessment.

The Tengger Desert, China's fourth largest desert, is surrounded by industrial cities including Zhongwei, Wuwei, and Yinchuan. Industrial activities primarily consist of coal mining, coal-electricity-chemical production, clean energy, and building materials chemicals [?, ?]. These frequent industrial activities, dominated by mining and chemical engineering, lead to element enrichment in topsoil, particularly metals [?, ?]. Furthermore, heavy metals emitted by industries in or around cities can combine with atmospheric water to form aerosols, which are then dispersed by wind or rainfall, polluting soils [?, ?]. Previous studies on heavy metals in the Tengger Desert have concentrated mainly on marginal areas [?, ?], with limited research covering the entire desert region. Our study examined ten heavy metals in 33 soil samples across the entire Tengger Desert using PCA, spatial differentiation, and correlation analysis to determine distribution characteristics, causes, and sources. These results will guide source identification, risk assessment, and comprehensive management of soil heavy metal pollution in the Tengger Desert region.

2.1 Study Area

The Tengger Desert is located at 37°–40°N, 102°–106°E, covering approximately 3.0×10^4 km² at an altitude of about 1200–1400 m a.s.l. (Fig. 1 [Figure

1: see original paper]). Situated on the southern Inner Mongolia Plateau, it is bounded by Helan Mountain and the Ulan Buh Desert to the east, Yabulai Mountain and the Badain Jaran Desert to the north, and the Qilian Mountains to the southwest. The desert experiences a typical inland arid climate with abundant sunshine, drought, low precipitation, and strong evaporation. Annual precipitation ranges from 50–100 mm, while evaporation reaches 3000–3500 mm. The region experiences high wind speeds and large daily temperature variations [?, ?]. Prevailing wind directions are NW (northwest), WNW (west-northwest), and NNW (north-northwest) [?, ?, ?].

Geologically, the Tengger Desert belongs to the Alxa platform depression, an intermountain tectonic basin [?, ?, ?]. The natural landscape is dominated by mobile and semi-mobile sand dunes [?, ?, ?]. Within the desert, residual hills, mountains, lake basins, and plains intersect, with the Yellow River flowing through the southeastern edge. The desert contains 422 lake basins, most being small lakes with little or no water, predominantly fed by long-term phreatic water leakage [?, ?]. The Tengger Desert has low vegetation coverage and loose soil texture, resulting in low soil organic matter and CaCO_3 content [?, ?, ?]. Aeolian sandy soil, saline, and alkaline soils (pH 7.5–11.2) are the main soil types [?, ?, ?, ?].

2.2 Sample Collection

Samples were collected along traffic roads in the Tengger Desert. To eliminate vehicle exhaust influence, sampling sites were located more than 1 km from roads. A total of 33 surface samples (0–10 cm depth) were collected, with locations shown in Figure 1 and Table 1 .

3.1 Determination of Heavy Metal Elements

Element measurements were completed using an Inductively Coupled Plasma Mass Spectrometer (Agilent-7700X, Agilent Technologies Co. Ltd., USA) at the Key Laboratory of Western China's Environmental Systems (Ministry of Education), Lanzhou University, China. The analytical procedure was as follows: samples were first ashed in a muffle furnace to remove organic matter, then ground and sieved through a 200-mesh screen. Approximately 20–30 mg of each sample was placed in a Teflon container, moistened with ultrapure water, and treated with 1 mL nitric acid and 1 mL hydrofluoric acid. The mixture was ultrasonicated for 20 minutes, then heated on a hot plate at 150°C until nearly dry. This acid treatment was repeated once more. The sealed Teflon containers were transferred to a stainless-steel tank and heated in an oven at 190°C for over 48 hours for sample digestion. After cooling, containers were opened and heated at 150°C to evaporate water until nearly dry. Nitric acid (1 mL) was

added and evaporated to near dryness, repeated twice. Finally, 2 mL nitric acid and 3 mL ultrapure water were added, and the containers were heated at 150°C for over 48 hours to complete digestion. Digested samples were transferred to labeled low-density polyethylene bottles and diluted with ultrapure water to approximately 2000 times the original sample weight. Solutions were gently shaken and refrigerated before measurement. For analysis, prepared solutions were poured into 25-mL clean centrifuge tubes and placed in the autosampler for element detection.

To control measurement precision and accuracy, rhodium (Rh) and indium (In) were used as internal standards. Standard curves were prepared using BCR-2 (USGS basalt standard material), loess, and blank samples. Analytical precision was less than 4%, with results expressed in mg/kg.

3.2 Data Processing

Statistical analysis was performed using Excel software to calculate abundance ranges, averages, standard deviations (SD), and coefficients of variation (CV) for the ten elements across 33 samples. Elements with excessive concentrations were identified by comparing measured averages with corresponding environmental background values. CV reflects spatial variability of soil elements, defined as $CV = SD/average$ [?, ?]. Based on CV analysis and comparison with background values, elements with $CV > 0.5$ or concentrations notably exceeding background values were selected for PCA, spatial distribution, and correlation analysis.

Spatial distribution contour maps for selected elements were generated using Golden Software Surfer v.19.0 (Golden Software, Colorado, USA) based on Kriging interpolation. Enrichment areas were identified from these maps and interpreted in the context of natural geography and human activities. PCA and correlation analysis were then used to examine differences in element origins.

4.1 Abundance of Heavy Metals

The abundance of ten heavy metal elements in the Tengger Desert hinterland is shown in Table 2. Iron exhibited the greatest variation (179.24–2254.08 mg/kg), followed by Th (24.19–208.32 mg/kg) and Mn (0.04–0.47 mg/kg), while the remaining seven elements showed the least variation (0.00–0.10 mg/kg). Average abundances followed the descending order: Fe > Th > Mn > Zn > Cr > Pb > Ni > Cu > Co > Cd. Compared with Chinese background values, nine elements (Cd, Co, Cr, Cu, Fe, Mn, Ni, Pb, and Zn) were far lower, while Th exceeded background values by 1.75–15.00 times (average 5.20 times), indicating Th contamination.

The coefficient of variation (CV) ranged from 0.24 to 0.76, in descending order:

Cr > Th > Ni > Zn > Mn = Co > Fe = Cu > Cd > Pb. Nine elements (Cd, Co, Cr, Cu, Fe, Mn, Ni, Th, and Zn) had CVs exceeding 0.50, indicating significant spatial variability. Based on these results, we selected these nine elements for further spatial distribution, correlation, and PCA analysis.

4.2 Spatial Distribution Patterns of Heavy Metals

The nine selected elements were mapped using Surfer v.19.0 software (Fig. 2 [Figure 2: see original paper]). Elements Cr, Mn, Fe, Co, Ni, Cu, and Cd displayed two high-value closed contour regions and one low-value region. High-value areas occurred near sample site 20 in the north-central Tengger Desert and near sample site 2 in the western region, while the low-value region appeared near sample site 19 in the southwest (Fig. 2a–g).

Elements Zn and Th showed three high-value closed contour regions and one low-value region. Th high-value areas occurred near sample site 6 in the northeast, sample site 2 in the west, and sample site 20 in the north-central region, with a low-value area near sample site 19 in the southwest (Fig. 2h–i). Zn differed from Th in that one high-value region was located near sample site 7 in the northeast, while the other two high-value regions and the low-value region matched those of Th.

4.3 Correlation Analysis of Heavy Metals

Pearson correlation coefficients (r) for the nine selected heavy metals are shown in Table 3. Cadmium, Co, Cr, Cu, Fe, Mn, and Ni showed high correlation coefficients ($r > 0.76$), indicating similar spatial distribution patterns and close relationships among these elements. Zinc showed low correlations with other elements ($r < 0.38$), indicating distinct spatial distribution patterns and weak relationships. Thorium showed moderate correlations with the other eight elements ($r = 0.50$ – 0.70), falling between Zn and the remaining seven elements.

4.4 PCA of Heavy Metals

Principal component analysis was used to identify anthropogenic and geogenic sources of heavy metals (Fig. 3 [Figure 3: see original paper]). PCA is a statistical procedure that identifies the most significant factors accounting for variance in multidimensional datasets. Based on correlation analysis, we specified three factor numbers for PCA, grouping Cd, Co, Cr, Cu, Fe, Mn, and Ni together, and treating Th and Zn as independent classes. Prior to PCA, Kaiser-Meyer-Olkin (KMO) and Bartlett sphericity tests confirmed data suitability (KMO = 0.815, $P = 0.000$).

The results showed that two principal components explained approximately 86.8% of total variance, adequately reflecting the original data. The first component (PC1) explained 77.0% and the second (PC2) explained 9.8% of total variance. The PCA plot revealed that Cd, Co, Cr, Cu, Fe, Mn, and Ni clustered closer together than Zn and Th on the PC1 axis, indicating PC1 was primarily controlled by these seven elements with similar positive loadings of 0.34–0.37, suggesting similar spatial distribution modes or common sources. On PC2, Zn showed a loading factor of 0.97, plotting far from other elements and indicating a distinct source. Although Th appeared close to the other seven elements on the PCA plot (Fig. 3), Table 4 shows Th (0.89) as the main factor on the PC3 axis, indicating Th also has a different source from the other elements.

5 Discussion

The spatial distribution maps revealed multiple high-value closed contour regions in the desert. The causes of these enrichment areas are discussed below.

Sample site 20 in the north-central Tengger Desert was a high-value region for all elements. Towns and villages such as Shuangcike, Hongshaliang, and Xiqu are located along national highway 569, with no mining, smelting, or other industrial activities nearby. Since heavy metals typically enter the environment through mining, smelting, forging, and processing [?, ?], local industrial activities are unlikely to have caused this enrichment. This area is located downstream of the Shiyang River, which originates in the Qilian Mountains and flows through industrial cities including Wuwei and Jinchang, China's largest nickel production center. Mining activities in Jinchang have increased Ni accumulation in soils [?, ?], and these enriched elements are transported to the Minqin Oasis via the Shiyang River [?, ?]. At the beginning of the 21st century, Shiyang River water quality continuously deteriorated, with middle and lower reaches classified as class IV–V according to national standards (GB3838-2002) [?, ?], while even the better-quality upper mountainous areas (class I–II) were declining [?, ?]. Although water quality has improved recently after environmental treatment [?, ?], heavy metals deposited during previous pollution events remain.

Irrigated agriculture development in the Minqin Oasis leads to heavy metal accumulation in topsoil through pesticide and fertilizer use [?, ?, ?]. Studies have shown relatively high concentrations of Cd, Cr, Ni, and Pb in chicken manure; Cd, Cu, and Zn in pig manure; and Cd and Ni in sheep manure [?, ?, ?]. According to Minqin County economic data for the first half of 2020, vegetable and fruit planting areas increased by 14.23% and 38.63%, respectively [?, ?], increasing manure demand and intensifying heavy metal enrichment risk. Irrigation water contaminated with industrial wastewater causes major heavy metal contamination in soils and crops [?, ?]. The area is dry with low precipitation, abundant sunshine, and high evaporation. However, moisture in sand layers shows positive equilibrium due to rapid infiltration and reduced evaporation effects [?, ?].

Atmospheric precipitation replenishes groundwater rather than upward groundwater movement [?, ?], ruling out salinization from groundwater rise. Vegetables and fruits are the main commercial crops in the Minqin Oasis, with wheat and corn as primary grain crops and alfalfa as the main forage [?, ?]. These crops require 4–9 irrigation events during the growing season [?, ?], primarily in spring and summer when large irrigation volumes and high temperatures cause significant evaporation. Water vapor combines with particulate pollutants from the industrial zone near sample site 2, forming precipitation transported to the Minqin Oasis by prevailing NW, WNW, and NNW winds [?, ?, ?], exacerbating soil heavy metal enrichment. Therefore, the high-value region formed due to influences from the upstream Shiyang River industrial zone and local irrigated agriculture development. High water demand also intensifies local salinization, resulting in heavy metal enrichment in surface soil layers [?, ?, ?].

Additionally, nine elements (Cd, Co, Cr, Cu, Fe, Mn, Ni, Th, and Zn) showed a high-value region near sample site 2 in the western Tengger Desert. Heavy industry is a major source of soil heavy metal pollution [?, ?]. Hongshagang Town, located south of this site, is a chemical production base for coal, electricity, and chemical industries. Industrial activities in Hongshagang Town are responsible for heavy metal enrichment in nearby deposits, particularly for Zn [?, ?].

According to Th and Zn contour maps, high-value regions for these elements also occurred at sample sites 6 and 7 in the northeast Tengger Desert, with dense contour lines. However, no evidence of human activities (cities, villages, mining, chemicals, or agriculture) was observed near this area. Sample site 6 is located at the junction of the Tengger and Badain Jaran Deserts. The Badain Jaran Desert is an important sediment source for the Tengger Desert, with annual sediment transport of 372 t [?, ?]. North of sample site 6, a mountain pass formed by Yabulai Mountain and the Alxa Plateau creates a narrow tube effect that strengthens the Asian winter monsoon. After passing through this pass, wind transport capacity weakens, potentially forming deposition near sample site 6 and enriching heavy metals. A study in both deserts found that geochemical elements at their intersection tended to decrease from northwest to southeast, with more uniform distribution farther from the sand source, consistent with our results [?, ?]. The Th abundance in the Tengger Desert is much higher than background values, possibly related to high monazite content in the heavy mineral composition [?, ?], as monazite is a primary Th source. Monazite content is significantly higher in the northwest and southwest than in other desert areas [?, ?], explaining Th enrichment near sample sites 2 and 6.

Sample site 7 is a Zn enrichment area located on a windward slope facing the northeast Asian winter monsoon, where wind-transported sand deposition may occur. Additionally, sample site 7 is situated on lower hillside slopes where heavy metals are transported by water from upslope areas during precipitation events. Therefore, this site is also influenced by local-scale soil-forming source materials, explaining the low correlation between Zn and other elements.

6 Conclusions

By comparing heavy metal concentrations from 33 sample sites in the Tengger Desert hinterland, we analyzed spatial distribution characteristics of nine heavy metals. Combined with geographical characteristics and human activities, we discussed enrichment patterns and sources using PCA and correlation analysis. The results indicate: (1) The average Th abundance exceeded Chinese background values by more than 5.2 times, suggesting Th contamination in the study area. The other nine elements were considerably lower than Chinese soil background values, implying that surface sediments from the Tengger Desert are not the dominant source of soil heavy metal pollution under natural conditions. (2) High spatial variability was observed for Cd, Co, Cr, Cu, Fe, Mn, Ni, Th, and Zn. Cadmium, Co, Cr, Cu, Fe, Mn, and Ni shared common sources, while Zn and Th showed distinctly different sources. (3) Based on spatial distribution characteristics and desert conditions, human activities (agriculture and industry) were the main causes of heavy metal accumulation, followed by natural factors. Therefore, regular monitoring, source control, and integrated management should be implemented to control and reduce heavy metal pollution. These results provide a reference for investigating heavy metals in other desert soils.

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References

- Adimalla N. 2020. Heavy metals contamination in urban surface soils of Medak Province, India, and its risk assessment and spatial distribution. *Environmental Geochemistry and Health*, 42(1): 59–75.
- Ali H, Khan E, Ilahi I. 2019. Environmental chemistry and ecotoxicology of hazardous heavy metals: environmental persistence, toxicity, and bioaccumulation. *Journal of Chemistry*, 2019: 6730305, doi: 10.1155/2019/6730305.

- Anaman R, Peng C, Jiang Z C, et al. 2022. Identifying sources and transport routes of heavy metals in soil with different land uses around a smelting site by GIS based PCA and PMF. *Science of the Total Environment*, 823: 153759, doi: 10.1016/j.scitotenv.2022.153759.
- Baltas H, Sirin M, Gokbayrak E, et al. 2020. A case study on pollution and a human health risk assessment of heavy metals in agricultural soils around Sinop Province, Turkey. *Chemosphere*, 241: 125015, doi: 10.1016/j.chemosphere.2019.125015.
- Chen S K, Wu P. 2003. Effects of Tengger Desert on the ecological environment surrounding areas and its comprehensive control measures. *Pratacultural Science*, 20(2): 1–3. (in Chinese)
- Dai J R, Zhu D C, Pang X G, et al. 2015. Geochemical characteristics and environmental quality of soil elements in Jinan City. *Geology in China*, 42(1): 308–316. (in Chinese)
- Darnley A G. 1995. International geochemical mapping—a review. *Journal of Geochemical Exploration*, 55(1–3): 5–10.
- Dong Y, Sun L, Li H T, et al. 2021. Sources and spatial distribution of heavy metals and arsenic in soils from Xiong'an New Area, China. *Hydrogeology & Engineering Geology*, 48(3): 172–181. (in Chinese)
- Guan Q Y, Wang F F, Xu C Q, et al. 2018. Source apportionment of heavy metals in agricultural soil based on PMF: A case study in Hexi Corridor, Northwest China. *Chemosphere*, 193: 189–197.
- He M Z, Dijkstra F A, Zhang K, et al. 2016. Influence of life form, taxonomy, climate, and soil properties on shoot and root concentrations of 11 elements in herbaceous plants in a temperate desert. *Plant and Soil*, 398(1–2): 339–350.
- He Y J, Pan X B. 2003. The changes of planting structure and rational use of water resource in the oasis of Minqin County, Gansu Province. *Chinese Journal of Eco-Agriculture*, 11(4): 121–123. (in Chinese)
- Huang J H, Peng S Y, Mao X M, et al. 2019. Source apportionment and spatial and quantitative ecological risk assessment of heavy metals in soils from a typical Chinese agricultural county. *Process Safety and Environmental Protection*, 126: 339–347.
- Hunag S W, Tang J W, Li C H. 2017. Status of heavy metals, nutrients, and total salts in commercial organic fertilizers and organic wastes in China. *Journal of Plant Nutrition and Fertilizers*, 23(1): 162–173. (in Chinese)
- Integrative Investigation Team for Vegetation of Inner Mongolia. 1985. *Vegetation of Inner Mongolia*. Beijing: Science Press, 10–15. (in Chinese)
- Islam M S, Ahmed M K, Raknuzzaman M, et al. 2015. Heavy metal pollution in surface water and sediment: A preliminary assessment of an urban river in a developing country. *Ecological Indicators*, 48: 282–291.

- Kelepertzis E. 2014. Accumulation of heavy metals in agricultural soils of Mediterranean: Insights from Argolida basin, Peloponnese, Greece. *Geoderma*, 221–222: 82–90.
- Kharazi A, Leili M, Khazaei M, et al. 2021. Human health risk assessment of heavy metals in agricultural soil and food crops in Hamadan, Iran. *Journal of Food Composition and Analysis*, 100: 103890, doi: 10.1016/j.jfca.2021.103890.
- Kong S F, Lu B, Ji Y Q, et al. 2011. Levels, risk assessment and sources of PM10 fraction heavy metals in four types dust from a coal-based city. *Microchemical Journal*, 98(2): 280–290.
- Kusin F M, Azani N N M, Hasan S, et al. 2018. Distribution of heavy metals and metalloid in surface sediments of heavily-mined area for bauxite ore in Pengerang, Malaysia and associated risk assessment. *CATENA*, 165: 454–464.
- Lamba D T, Ming H, Megharaj M, et al. 2009. Heavy metal (Cu, Zn, Cd and Pb) partitioning and bioaccessibility in uncontaminated and long-term contaminated soils. *Journal of Hazardous Materials*, 171(1–3): 1150–1158.
- Li E J. 2011. Comparative study on sediment characteristics between Badain Jaran Desert and Tengger Desert. PhD Dissertation. Xi'an: Shaanxi Normal University. (in Chinese)
- Li H T, Xu X G, Xiao D N. 2007. Analysis on the utilization of water resources in the Minqin Oasis. *Arid Zone Research*, (3): 287–295. (in Chinese)
- Li X R, He M Z, Zerbe S, et al. 2010. Micro-geomorphology determines community structure of biological soil crusts at small scales. *Earth Surface Processes and Landforms*, 35(8): 932–940.
- Li X R, Zhao Y, Hui R, et al. 2014. Progress and trend of development of restoration ecology research in the arid regions of China. *Progress in Geography*, 33(11): 1435–1443. (in Chinese)
- Li Z J, Sun D H, Chen F H, et al. 2014. Chronology and paleoenvironmental records of a drill core in the central Tengger Desert of China. *Quaternary Science Reviews*, 85: 85–98.
- Ma J Z, Ding Z Y, Wei G X, et al. 2009. Sources of water pollution and evolution of water quality in the Wuwei basin of Shiyang River, Northwest China. *Journal of Environmental Management*, 90(2): 1168–1177.
- Ma L, Wu J L, Zeng H A, et al. 2014. Element assemblages and its distribution of surface soil samples from Kyrgyzstan. *Arid Land Geography*, 37(4): 639–645. (in Chinese)
- Maanan M, Saddik M, Maanan M, et al. 2015. Environmental and ecological risk assessment of heavy metals in sediments of Nador lagoon, Morocco. *Ecological Indicators*, 48: 616–626.

Marrugo-Negrete J, Pinedo-Hernandez J, Diez S. 2017. Assessment of heavy metal pollution, spatial distribution and origin in agricultural soils along the Sinu River Basin, Colombia. *Environmental Research*, 154: 380–388.

Ministry of Ecology and Environment of People's Republic of China. 2002. Environmental quality standards for surface water (GB 3838-2002). [2002-04-28]. https://www.mee.gov.cn/ywgz/fgbz/bz/bzwb/shjbh/shjzlbz/200206/t20020601_{66497}.shtml. (in Chinese)

Minqin County Bureau of Statistics. 2021. Analysis of county national economy operation in the first half of 2020. Minqin: <http://www.minqin.gov.cn/gk/xzfgbmxxgk/xzfgzbm/tjj1/fdzdgnr4>. (in Chinese)

Monaci F, Moni F, Lanciotti E, et al. 2000. Biomonitoring of airborne metals in urban environments: new tracers of vehicle emission, in place of lead. *Environmental Pollution*, 107(3): 321–327.

National Bureau of Statistics Rural Social and Economic Investigation Division. 2019. *County Statistical Yearbook of China, 2018 (Township)*. Beijing: China Statistics Press, 614. (in Chinese)

Nicholson F A, Smith S R, Alloway B J, et al. 2003. An inventory of heavy metals inputs to agricultural soils in England and Wales. *Science of the Total Environment*, 311(1–3): 205–219.

Niu L L, Yang F X, Xu C, et al. 2013. Status of metal accumulation in farmland soils across China: From distribution to risk assessment. *Environmental Pollution*, 176: 55–62.

Qi J H, Liu Y B, Wang Z R, et al. 2021. Variations in microbial functional potential associated with phosphorus and sulfur cycling in biological soil crusts of different ages at the Tengger Desert, China. *Applied Soil Ecology*, 165: 104022, doi: 10.1016/j.apsoil.2021.104022.

Qiao P L, Zhang J X, Lin Z X. 2003. The application of remote sensing technique to monitoring and evaluating water pollution in the Shiyang River valley. *Remote Sensing for Natural Resources*, 15(4): 39–41. (in Chinese)

Shallari S, Schwartz C, Hasko A, et al. 1998. Heavy metals in soils and plants of serpentine and industrial sites of Albania. *Science of the Total Environment*, 209(2–3): 133–142.

Ustaoglu F, Islam M S. 2020. Potential toxic elements in sediment of some rivers at Giresun, Northeast Turkey: A preliminary assessment for ecotoxicological status and health risk. *Ecological Indicators*, 113: 106237, doi: 10.1016/j.ecolind.2020.106237.

Vargas-Machuca B D, Zanetta-Colombo N, de Pol-Holz R, et al. 2021. Variations in local heavy metal concentrations over the last 16,000 years in the central Atacama Desert (22°S) measured in rodent middens. *Science of the Total Environment*, 775: 145849, doi: 10.1016/j.scitotenv.2021.145849.

- Wang J H, Li S W, Cui X Y, et al. 2016. Bioaccessibility, sources and health risk assessment of trace metals in urban park dust in Nanjing, Southeast China. *Ecotoxicology and Environment Safety*, 128: 161–170.
- Wang L J. 2014. Researches on the meteorological factors effecting the southern border of the Tengger Desert and the topsoil trace elements. MSc Thesis. Lanzhou: Lanzhou University. (in Chinese)
- Wang M, Li S T. 2014. Heavy metals in fertilizers and effect of the fertilization on heavy metal accumulation in soils and crops. *Journal of Plant Nutrition and Fertilizers*, 20(2): 466–480. (in Chinese)
- Wang N, Guan Q Y, Sun Y F, et al. 2021. Predicting the spatial pollution of soil heavy metals by using the distance determination coefficient method. *Science of the Total Environment*, 799: 149452, doi: 10.1016/j.scitotenv.2021.149452.
- Wang N A, Zhang H C, Cao J X, et al. 1997. Preliminary study on magnetic stratigraphy of Wuwei loess section in southern Tengger Desert. *Journal of Lanzhou University: Natural Sciences*, 33(4): 149–151. (in Chinese)
- Wang T. 2003. *Desert and Desertification in China*. Shijiazhuang: Hebei Science & Technology Press, 602–610. (in Chinese)
- Wei F S, Chen J S, Wu Y Y, et al. 1991. Study on the background contents on 61 elements of soils in China. *Chinese Journal of Environmental Science*, (4): 12–19. (in Chinese)
- Wu Q M, Hu W Y, Wang H F, et al. 2021. Spatial distribution, ecological risk and sources of heavy metals in soils from a typical economic development area, Southeastern China. *Science of the Total Environment*, 780: 146557, doi: 10.1016/j.scitotenv.2021.146557.
- Xu Y, Shi H, Fei Y, et al. 2021. Identification of soil heavy metal sources in a large-scale area affected by industry. *Sustainability*, 13(2): 511, doi: 10.3390/su13020511.
- Yan M C, Gu T X, Chi Q H, et al. 1997. Abundance of chemical elements of soils in China and supergenesis geochemistry characteristics. *Geophysical and Geochemical Exploration*, (3): 161–167. (in Chinese)
- Yang H T, Li X R, Yan P J, et al. 2020. Soil types and spatial distribution in Tengger Desert. *Journal of Desert Research*, 40(4): 154–162. (in Chinese)
- Yang Q Q, Li Z Y, Lu X N, et al. 2018. A review of soil heavy metal pollution from industrial and agricultural regions in China: Pollution and risk assessment. *Science of the Total Environment*, 642: 690–700.
- Yang Y Y, Qu Z Q, Shi P J, et al. 2014. Wind regime and sand transport in the corridor between the Badain Jaran and Tengger deserts, central Alxa Plateau, China. *Aeolian Research*, 12: 143–156.

Zhang C. 2020. Heavy mineral assemblages and provenance analysis of eolian sand in the Alashan Desert, northwestern China. MSc Thesis. Lanzhou: Lanzhou University. (in Chinese)

Zhang H C, Ma Y Z, Peng J L, et al. 2002. Palaeolake and palaeoenvironment in Tengger Desert during 42–18 ka B.P. *Chinese Science Bulletin*, 47(24): 1847–1857. (in Chinese)

Zhang K C, Qu J J, An Z S. 2012. Characteristics of wind-blown sand and near-surface wind regime in the Tengger Desert, China. *Aeolian Research*, 6: 83–88.

Zhang N, He Z D, Wu W. 2009. Studies on the characteristics of soil organic matter and pedogenic calcium carbonate for three kinds of soil in the Tengri Desert. *Acta Ecologica Sinica*, 29(8): 4094–4101. (in Chinese)

Zhang Y, Zhu G F, Ma H Y, et al. 2019. Effects of ecological water conveyance on the hydrochemistry of a terminal lake in an inland river: a case study of Qingtu Lake in the Shiyang River Basin. *Water*, 11(8): 1673, doi: 10.3390/w11081673.

Zhao J B, Yu K K, Shao T J, et al. 2011. A preliminary study on the water status in sand layers and its sources in the Tengger Desert. *Resources Science*, 33(2): 259–264. (in Chinese)

Zhao J B, Xing S, Shao T J, et al. 2012. A study on content and balance of moisture in the Southern Tengger Desert. *Journal of Natural Resources*, 27(3): 480–488. (in Chinese)

Zhu B Q, Yu J J, Partrick R, et al. 2014. Atmospheric precipitation recharge on groundwater in desert areas and its environmental implications—A case review of the Late-Holocene records from the Alashan Plateau. *Quaternary Sciences*, 34(5): 994–1012. (in Chinese)

Zhu X, Wang S, Li T T. 2021. Study on geochemical background value of soils in the Leizhou Peninsula. *South China Geology*, 37(1): 103–112. (in Chinese)

Note: Figure translations are in progress. See original paper for figures.

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