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Pollution Assessment of Heavy Metals As, Cu, Pb and Zn in the Sirba Greenstone Belt Soils (Liptako, Niger)

ABASS SALEY Abdoulatif [a*], MOUNKAILA Mohamed [b], SALEY Mahamadou [a] and ELHADJ DAOU Ibrahim [a]

[a] Ecole des Mines, de l'Industrie et de la Géologie (EMIG), BP 732, Niamey, Niger.
[b] Institut des Radio-Isotopes, Université Abdou Moumouni, BP 10727, Niamey, Niger.

Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

The Sirba greenstone belt was Niger's main gold province. Soil geochemical data from the Sirba gold prospecting campaign carried out from 1989 to 1994 by the Japanese International Cooperation, prior to the advent of gold mining in the region were used in this work. The aim of this work was to establish geochemical background and to assess soil pollution for As, Cu, Pb and Zn. Geochemical data from 16,696 soil samples (analyzed by AAS) had been used to define geochemical background. The median method to calculate the threshold value on log-transformed data was used. Geochemical background data were used to assess the pollution of each element using the Contamination Factor, and multi-element pollution using the Pollution Load Index. The

**Corresponding author: E-mail: abdoulatif.aa@gmail.com;*

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geochemical background values obtained were: As (27 mg/Kg), Cu (151.99 mg/Kg), Pb (12.50 mg/Kg) and Zn (145 mg/Kg). Soil Contamination Factor values for As (Min = 0.02, Mean = 0.99, Max = 442.07), Cu (Min = 0, Mean = 0.31, Max = 8.95), Pb (Min = 0.04, Mean = 0.29, Max = 43.12) and Zn (Min = 0, Mean = 0.39, Max = 8.58), and Pollution Load Index values (Min = 0.01, Mean = 0.28, Max = 3.86) show higher arsenic contamination and some samples with high global pollution (PLI > 1). The pollution and gold mining areas were mainly developed in the soils with high arsenic Contamination Factor values. The arsenic in the soils of the Sirba was therefore thought to have originated from gold mineralization.

Keywords: Sirba; geochemical background; soils; gold mining; contamination factor; pollution load index.

1. INTRODUCTION

Toxic elements such as As, Cd, Cu, Hg, Pb, Zn, etc. had given rise to major environmental concerns due to their toxicity, their non-biodegradable nature, their persistence, which means they have a strong tendency to accumulate in the food chain (Bing et al., 2016; Olivero-Verbel et al., 2015; Salam et al., 2016; Tyopine et al., 2018; Zhong et al., 2014). This accumulation posed a serious threat to living organisms, including humans (Radziemska and Fronczyk, 2015; Song et al., 2015; Vaverková and Adamcová, 2014). Accumulation of metals in soils beyond their natural cycle and control leaded to soil pollution (Tyopine et al., 2018). Pollution was the set of processes that cause toxicity and present a risk to human health (Thornton, 1995). Soil pollution had become a major environmental concern worldwide (Alshahri and El-Taher, 2018; Gupta et al., 2014; Liu et al., 2006). Soil was one of the main ecosystems on which human beings depended for their survival and development (Wang et al., 2019). Soils were an important reservoir for metals in terrestrial ecosystems (Gulan et al., 2017; Hamedan et al., 2016; Li et al., 2013; Santos-Francés et al., 2017; Tyopine et al., 2018). Food security remains an important aspect of human life, and the vital role of soil in agricultural and food production was evident in the fact that the quality of agricultural products consumed by people throughout the food chain depended on the condition of the soil (Okereafor et al., 2019).

Toxic metals in the natural environment existed as trace elements in the crust (Facchinelli et al., 2001; Gope et al., 2018). They were introduced into the environment through anthropogenic or natural processes (Barik et al., 2018; de-Lima et al., 2020; Ghrefat et al., 2021; Tyopine et al., 2018; Wang et al., 2019). The natural origin of heavy metals was linked to soil parent materials (Rodríguez Martín et al., 2013; Santos-Francés et al., 2017; Wang et al., 2019). Anthropogenic origin was due to industrial activities, urban planning, etc. (de-Lima et al., 2020; Sarkar et al., 2017; Wang et al., 2019).

Determining the level of pollution was the key to solving the problem of soil pollution (Jiang et al., 2020; Yuan et al., 2014). A soil quality assessment required knowledge of the background values of metals in soils (Baize and Sterckeman, 2001; Konstantinova et al., 2021). Establishing geochemical reference concentrations of metals in soil enabled precise pollution assessment and provided a basis for pollution control (Jiang et al., 2020). Reference geochemical concentrations refered to natural levels of metals in soil that were not influenced by anthropogenic activities (Jiang et al., 2020; Sierra et al., 2007). In many regions, reference geochemical data were not available, so it was necessary to establish local geochemical background or baselines (Li et al., 2015; Tian et al., 2017). Geochemical background had been defined as “the normal abundance of an element in a geological body whose equilibrium had not been disturbed by the presence of a mineral deposit” (Khan et al., 2021; Licht, 2020; Wei et al., 2021). The geochemical threshold corresponded to the upper limit of normal background fluctuation, i.e. the boundary between the geochemical background and the geochemical anomaly (Franklin et al., 1991; Konstantinova et al., 2021). It was used to identify areas where element concentrations were abnormally high (Reimann et al., 2018). It could also be used to assess soil contamination and pollution (Baize and Sterckeman, 2001). Several approaches had been used to determine the geochemical threshold value (Konstantinova et al., 2021; Reimann et al., 2005). For geochemical data with asymmetric distribution (Gonçalves et al., 2022; Suresh et al., 2012, Reimann *et al.*, 2005) had suggested calculating the threshold from the median (Gonçalves et al., 2022; Konstantinova et al., 2021; Santos-Francés et al., 2017; Suresh et al., 2012).

Assessing the degree of pollution through the content of chemical elements in the soil could be done by calculating pollution indices (Santos-Francés et al., 2017). Geochemical indices, such as Contamination Factor (CF) and Pollution Load Index (PLI), could be used to assess metal pollution in soil (Chon et al., 1998; Tomlinson et al., 1980). The Contamination Factor (CF) was used to express the level of contamination for each metal in the soil (Barik et al., 2018). The Pollution Load Index (PLI) as introduced by Tomlinson et al. (1980), assessed the extent of multi-element pollution (Barik et al., 2018; Gope et al., 2018; Hamedan et al., 2016; Hossain et al., 2022). Several authors had used the Contamination Factor (CF) and the Pollution Load Index (PLI) to assess soil pollution (Akay and Özaytekin, 2022; Baah et al., 2023; Fagbenro et al., 2021; Fodoué et al., 2022; González-Valoys et al., 2021; Luo et al., 2020; Quiroz et al., 2022; Raji et al., 2023; Sawadogo et al., 2023; Sutkowska et al., 2023; Wiafe et al., 2022).

The aim of this work is to determine geochemical background values of As, Cu, Pb and Zn for soils and to assess soil pollution in the Sirba greenstone belt.

2. MATERIALS AND METHODS

2.1 Study Area

The Sirba greenstone belt belongs administratively to the Tillabéri region in the south-western part of the Republic of Niger. The Tillabéri region was divided into three climatic zones: the Sahelo-Saharan zone in the north (150 and 300 mm/year), the Sahelian zone in the center (300 and 600 mm/year) and the Sahelo-Sudanian zone in the south (600 to 700 mm/year) (Abass-Saley, 2024). Temperatures range from 17°C in December to 45°C in May (Seyni et al., 2014). The relief comprised several geomorphological complexes: granitic domes, lateritic hills, quartz vein buttes and dune belts. Fig. 1c of the elevation map highlighted the geomorphic complexes. Three types of soil were associated with these geomorphological complexes: sandy soils made up of coarse sands forming more or less mobile dunes in places; sandy-clay soils in valley bottoms, depressions and ponds, characterized by dense vegetation; and highly eroded lateritic soils, located on plateaus and occupied by sparse vegetation. The study area's hydrographic network was made up of Niger and Sirba rivers.

Geologically, the Sirba greenstone belt is located in the Niger's Liptako. The latter corresponded to the NE end of the Léo-Man's ridge (Fig. 1a) on the West African craton (Machens, 1973). The Liptako geological formations (Fig. 1b) were Lower Proterozoic in age (Bessoles, 1977). They were formed by alternating greenstone belts, granitoids, Neoproterozoic and Mio-Pliocene sediments (Dupuis et al., 1991; Machens, 1973; Pons et al., 1995). The greenstone belts consist of meta-basalt, meta-sediments, meta-volcano-sediments, meta-volcano-plutonites, tuffs and rhyolitic breccias (Ama Salah et al., 1996; Soumaila et al., 2004). The granitoids consist of granites, tonalite, trondhjemite and granodiorite intersected by sills and basic dykes (Dupuis et al., 1991; Pons et al., 1995).

Gold mineralization in the Liptako is closely linked to major regional faults and to the nature of the metamorphism affected rocks (Klockner, 1995). Two types of gold mineralization had been identified in Liptako (Jica, 1995; Saint-Martin, 1999): syn-sedimentary exhalative gold mineralization associated with graphitic clays (Jica, 1995; Saint-Martin, 1999) and quartz vein gold mineralization controlled by fractures and regional faults (Jica, 1995; Klockner, 1995; Saint-Martin, 1999; St-Julien, 1992). Gold mineralization was also related to gabbro, quartz diorite and rhyolite dyke (Saint-Martin, 1999). Gold mineralization in the Sirba greenstone belt occurred mostly in quartz veins in association with sulfides (Saint-Martin, 1999). In this region, the gold mining was the main source of non-agriculture income. Traces of gold panning had existed since the advent of the 1984 drought in Niger (Amadou, 2002; Hilson et al., 2019; Pétot, 1995; Yonlihinza, 2011). Gold panning really took off in the region with the mining boom of the 2000s. Industrial gold mining began in the Sirba in 2007.

2.2 Geochemical Data

The geochemical data of the study come from the 1989-1994 geochemical prospecting campaign carried out by the International Cooperation of the Japanese Metals Mining Agency under the Jica project, at a time when gold mining was almost non-existent in the region. As, Cu, Pb and Zn analytical results from

16,696 Sirba soil samples were used. Fig. 2a shows the map of the sample collection points. The analysis was performed by Chemex Labs Ltd. North Vancouver, B.C, in Canada. As, Cu, Pb and Zn content of the soil samples were determined in ppm (1 ppm = 1 mg/Kg) by Atomic Absorption Spectrometry (AAS) after HNO_3-aqua regia digest of soil samples. Fig. 2b shows the situation in 2024 of the Sirba greenstone belt with the development of gold mining.

2.3 Geochemical Threshold Calculation

The distribution of geochemical data is generally asymmetrical and strongly skewed to the right (Gonçalves et al., 2022; Reimann et al., 2018). The Kolmogorov-Smirnov normality test (Mishra et al., 2019) was applied to the data to check their distribution. This test is applied if the number of samples is greater than fifty (Nornadiah and Yap, 2011). The correct approach for determining the geochemical threshold would therefore be to calculate it on log-transformed data (base 10), then retransform the result and use these values as the threshold according to formula 1 (Gonçalves et al., 2022; Konstantinova et al., 2021; Reimann et al., 2018).

$$\text{Threshold} = \text{Median} + 2 * \text{MAD} \qquad (1)$$

where MAD is the Median Absolute Deviation.

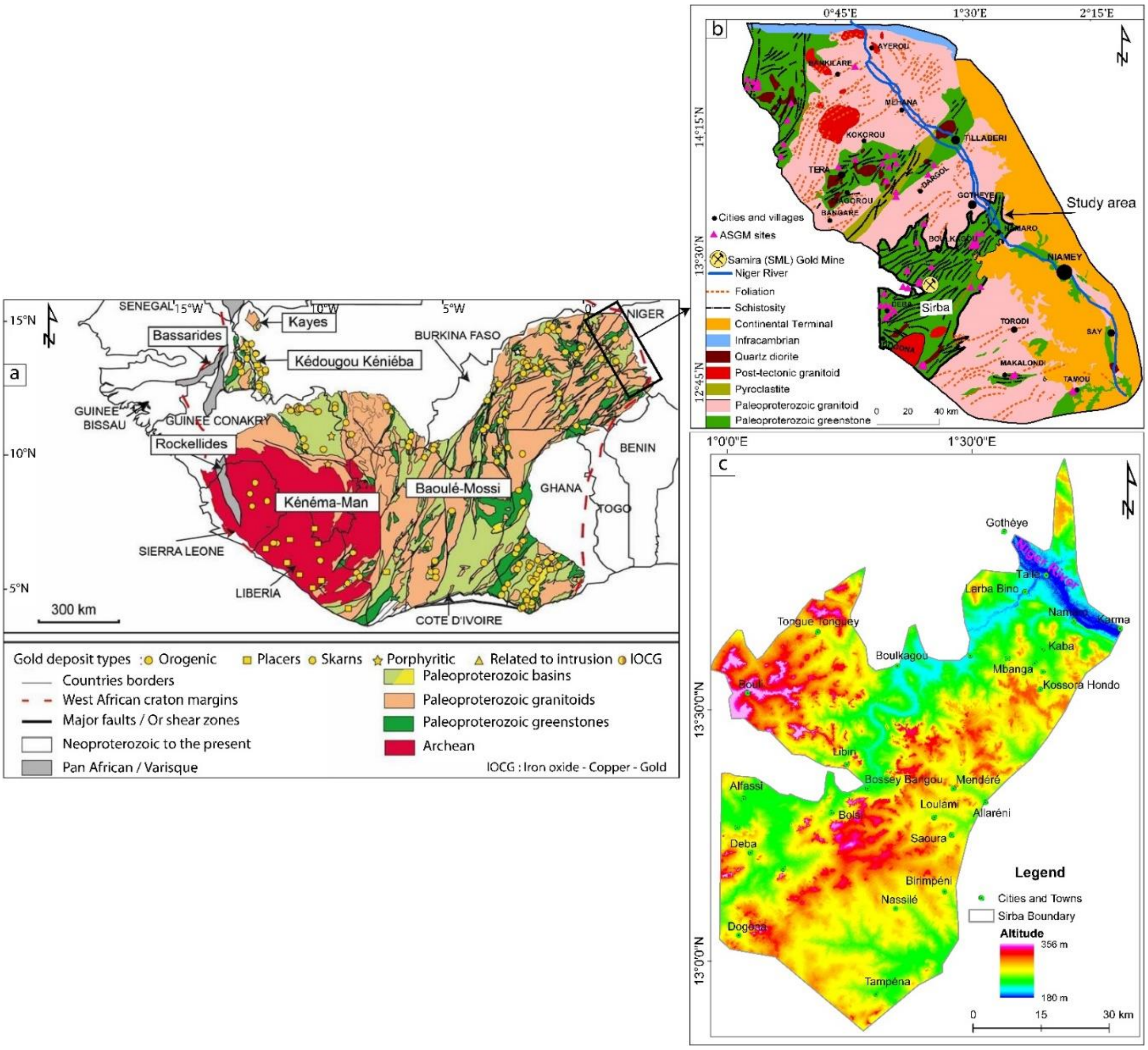

Fig. 1. Geological map of the Léo-Man Ridge (a) (Milési et al., 2004) and location of gold deposits (Markwitz et al., 2016), geological map of the Liptako area (b) (Machens, 1967) and the Sirba area elevation map (c)

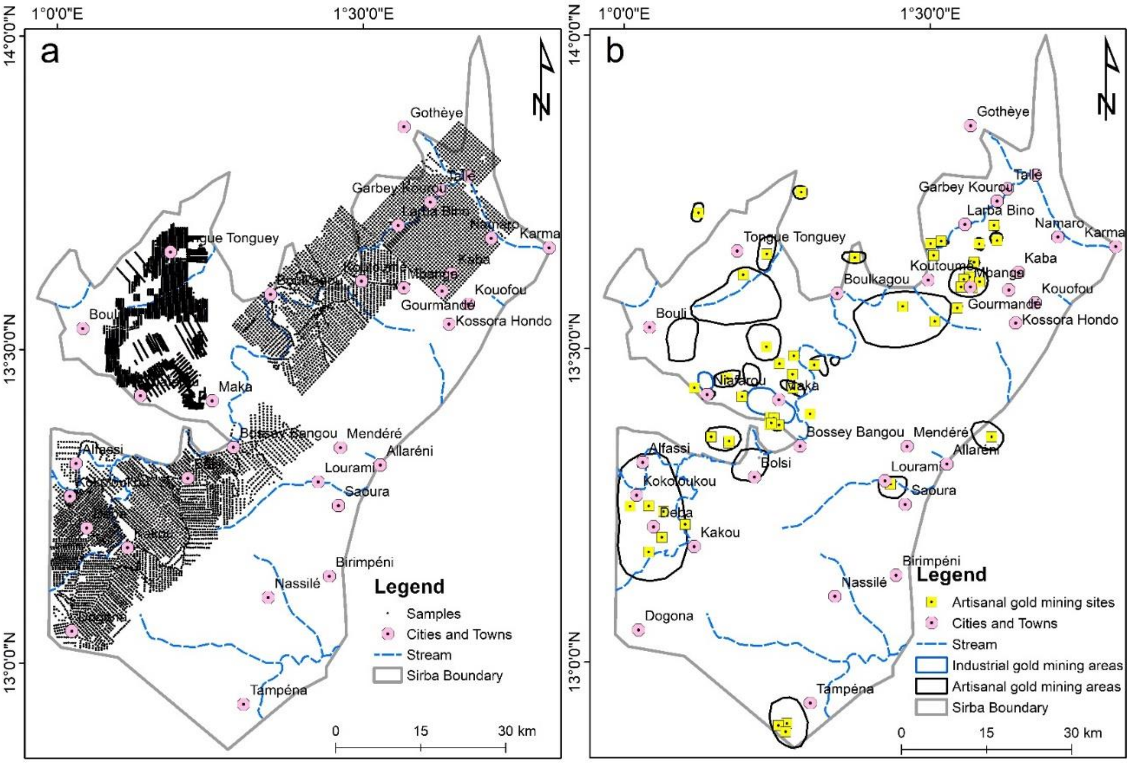

Fig. 2. Map of the sample collection points (a) and the Sirba greenstone belt situation in 2024 (b)

2.4 Pollution Assessment Indexes

Two indices were used to assess the level of contamination of each element and the level of multi-element pollution of the soil: the Contamination Factor and the Pollution Load Index.

The Contamination Factor (CF) was used to assess the level of contamination for each metal in a soil sample (Alshahri and El-Taher, 2018; Barik et al., 2018; Ferati et al., 2015). It was the ratio of the concentration of each element in the soil sample (Cm) to the value of the geochemical background of the same element (GB) (Formula 2) (Gope et al., 2018; Haris et al., 2017; Hossain et al., 2022).

$$\mathrm{CF} = \frac{\mathrm{Cm}}{\mathrm{GB}} \qquad (2)$$

CF values have been classified into four groups to reflect the soil contamination levels: Low contamination (CF < 1); Moderate contamination (1 < CF ≤ 3); Considerable contamination (3 < CF ≤ 6); Very high contamination (CF > 6) (Barik et al., 2018; Gope et al., 2018; Tashakor et al., 2018).

The Pollution Load Index (PLI) as suggested by Tomlinson et al. (1980) (Formula 3), was the root n of the n number of Contamination Factor (CF) values multiplied together (Bassey et al., 2015; Bhuiyan et al., 2015; Ferati et al., 2015; Gope et al., 2018; Hossain et al., 2022; Tian et al., 2017; Zhao et al., 2014).

$$\mathrm{PLI} = \sqrt[n]{(\mathrm{CF_1} \times \mathrm{CF_2} \times \mathrm{CF_3} \cdots \times \mathrm{CF_n})} \qquad (3)$$

where n is the number of studied metals and CF is the Contamination Factor.

There is no pollution if PLI < 1. Soil is polluted by several metals if its PLI > 1 (Hossain et al., 2022).

To better represent the spatial distribution of Contamination Factor (CF) and Pollution Load Index (PLI) values for Sirba soil samples, a GIS-based mapping approach was used to represent the different CF and PLI classes according to the coordinates of the sampling points.

3. RESULTS AND DISCUSSION

3.1 Geochemical Threshold

Table 1 shows the descriptive statistics and p-value of the Kolmogorov-Smirnow normality test (decision 5%). The data do not follow a normal distribution (p-value = 0). They were skewed to the right (Skewness > 0). Table 2 shows the statistics of the transformed data. Table 3 shows the threshold values and the determined values for the geochemical background (in mg/Kg) for As, Cu, Pb and Zn, elements in the Sirba soils. The obtained geochemical background values for Sirba soils are: As (27 mg/Kg), Cu (151.99 mg/Kg), Pb (12.50 mg/Kg) and Zn (145 mg/Kg).

3.2 Pollution Assessment

Table 4 shows the descriptive statistics for the Contamination Factor (CF) and Pollution Load Index (PLI) values for As, Cu, P and Zn elements in the Sirba soils. Fig. 3 shows the spatial distribution of As (Fig. 3a), Cu (Fig. 3b), Pb (Fig. 3c) and Zn (Fig. 3d) Contamination Factor (CF) assessment classes for the Sirba soils in 1994, at a time when gold mining did not exist in the region. Fig. 4 shows the spatial distribution of As (Fig. 4a), Cu (Fig. 4b), Pb (Fig. 4c) and Zn (Fig. 4d) Contamination Factor assessment classes of the Sirba soils in 1994, with the spatial distribution of the gold mining areas and sites in 2024, thirty years after sampling.

Fig. 5a shows the spatial distribution of As, Cu, Pb and Zn PLI assessment classes for Sirba soils in 1994, at a time when gold mining did not exist in the region. Fig. 5b shows the spatial distribution of As, Cu, Pb and Zn PLI assessment classes of Sirba soils in 1994, with the spatial distribution of gold mining areas and sites in 2024.

Table 1. Descriptive statistics and p-value of the normality test

Element	NT	Mean	SD	Skewness	Min	Max	p-value
As (mg/Kg)	16696	26.73	135.69	44.78	0.5	11936	0
Cu (mg/Kg)	16696	46.97	47.57	3.36	0.5	1360	0
Pb (mg/Kg)	16696	3.67	6.04	47.43	0.5	539	0
Zn (mg/Kg)	16696	56.83	67.61	3.57	0.5	1250	0

NT: Total number; SD: Standard deviation; Min: Minimum; Max: Maximum

Table 2. Log transform data statistical values

Element	NT	Mean	SD	Min	Median	Max	MAD
Log10_As	16696	0.63	0.73	-0.30	0.48	4.08	0.48
Log10_Cu	16696	1.46	0.47	-0.30	1.49	3.13	0.35
Log10_Pb	16696	0.35	0.45	-0.30	0.30	2.73	0.40
Log10_Zn	16696	1.53	0.44	-0.30	1.51	3.10	0.33

Table 3. Threshold and geochemical background values

Element	NT	TH	GB (mg/Kg)
As	16696	1.43	27.00
Cu	16696	2.18	151.99
Pb	16696	1.10	12.50
Zn	16696	2.16	145.64

TH: Threshold; GB: Geochemical Background

Table 4. Descriptive statistics for CF and PLI values for As, Cu, P and Zn in Sirba soils

Index	NT	Mean	SD	Min	Maximum
CF As	16696	0.99	5.03	0.02	442.07
CF Cu	16696	0.31	0.31	0	8.95
CF Pb	16696	0.29	0.48	0.04	43.12
CF Zn	16696	0.39	0.46	0	8.58
PLI	16696	0.28	0.27	0.01	3.86

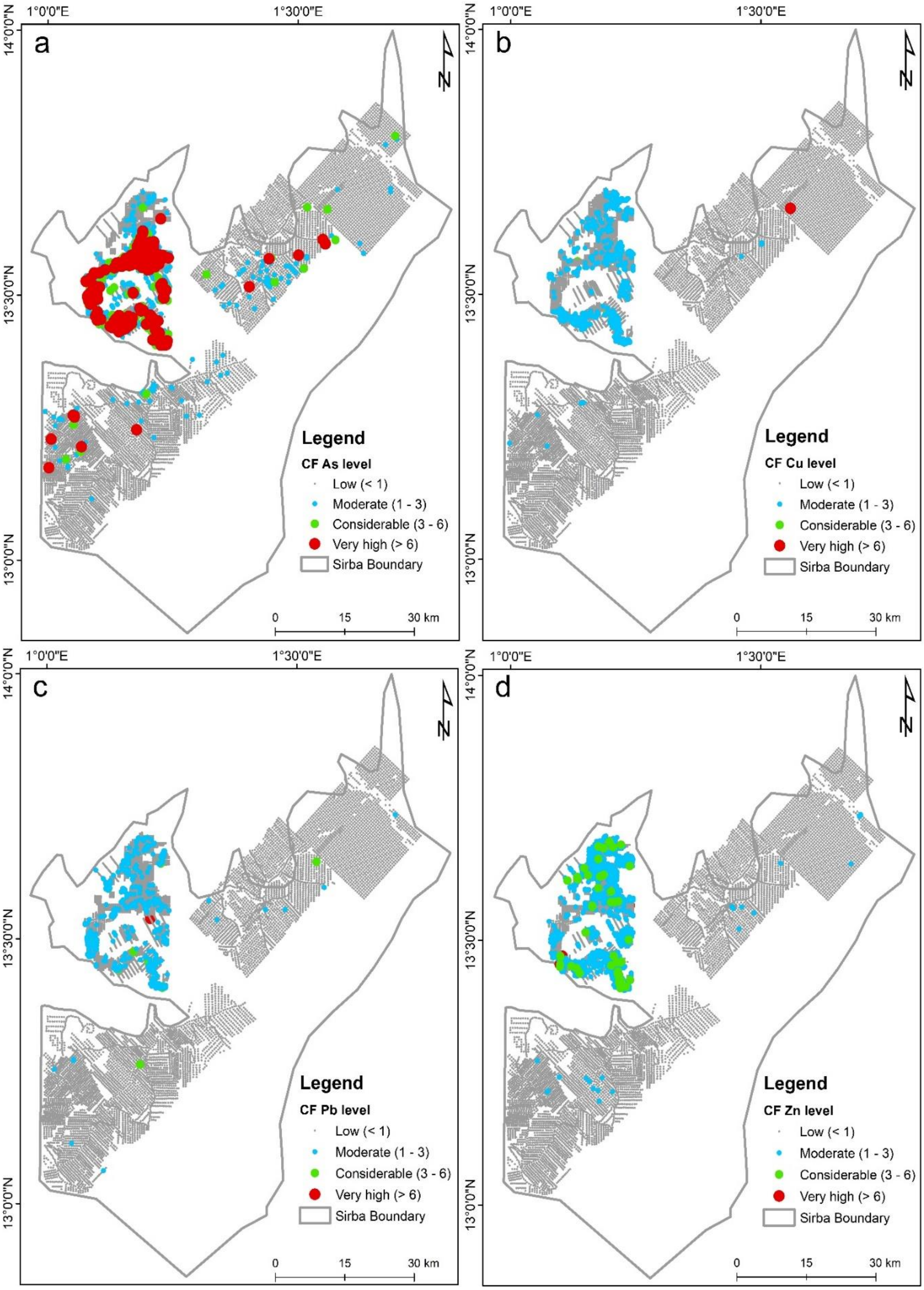

Fig. 3. Spatial distribution of As, Cu, Pb and Zn CF assessment classes for Sirba soils in 1994

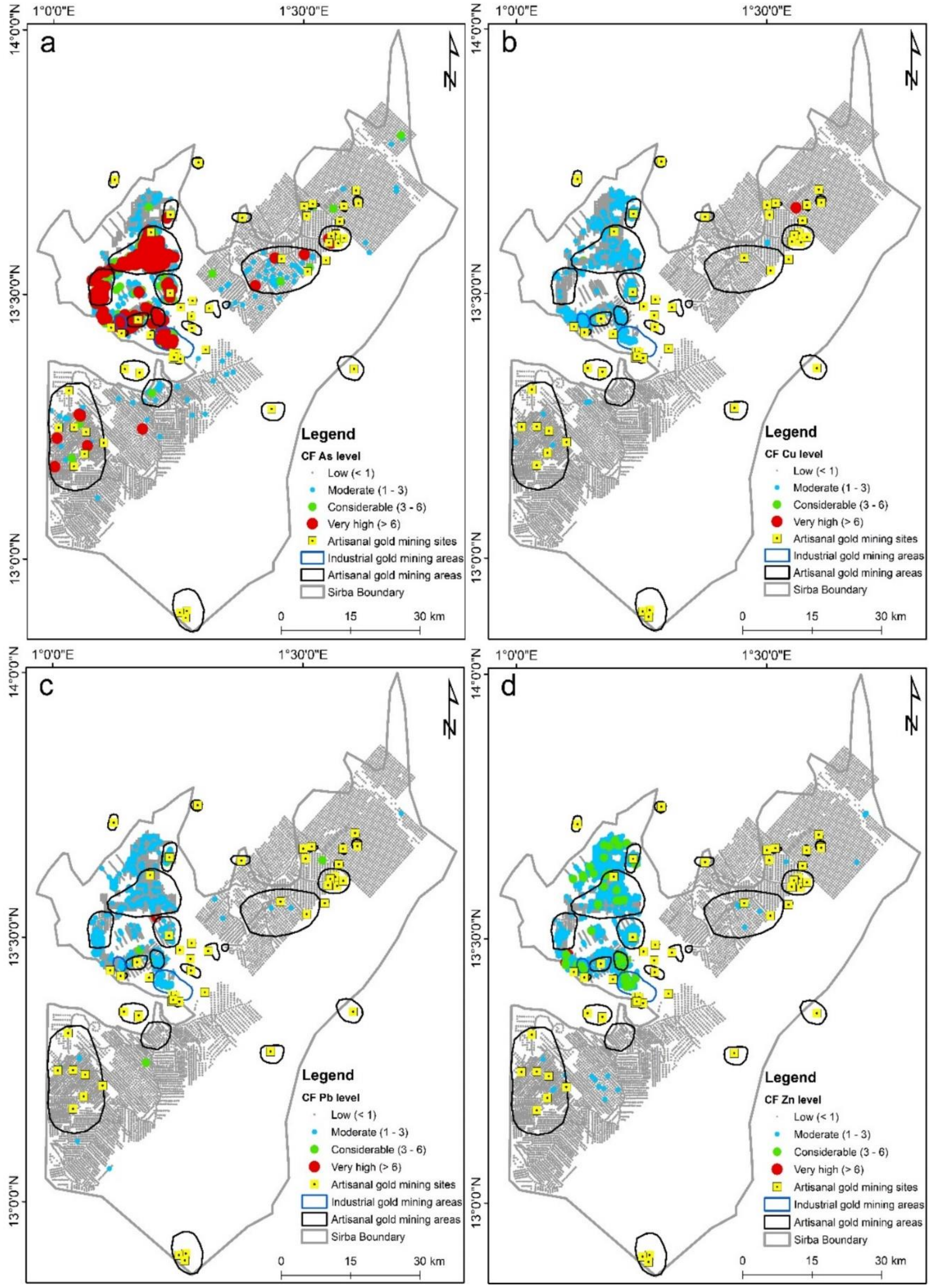

Fig. 4. Spatial distribution of Sirba soils CF classes in 1994 and gold mining areas and sites in 2024

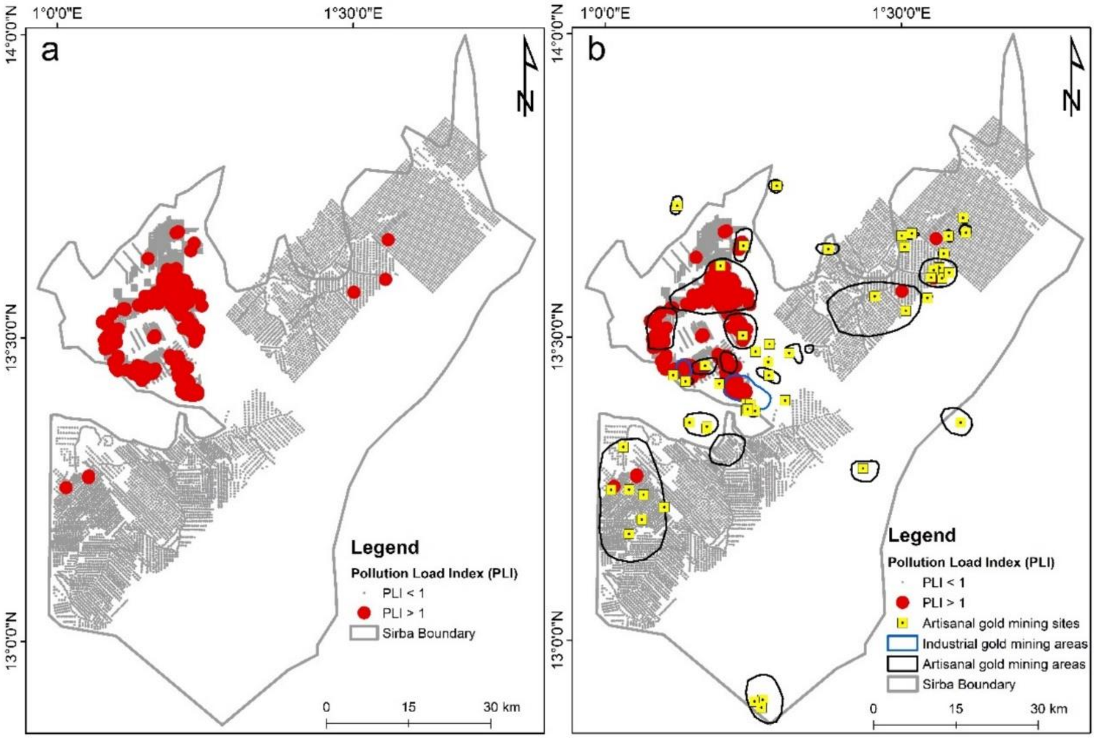

Fig. 5. Spatial distribution of Sirba soils PLI classes in 1994 (a) gold mining areas and sites in 2024 (b)

3.3 Discussion

As, Cu, Pb and Zn elements show an asymmetrical distribution in the Sirba greenstone belt soils. As (Min = 0.5 mg/Kg, Max = 11936 mg/Kg, Skewness = 44.78) and Pb (Min = 0.5 mg/Kg, Max = 539 mg/Kg, Skewness = 47.43) were more asymmetric than Cu (Min = 0.5 mg/Kg, Max = 1360 mg/Kg, Skewness = 3.36) and Zn (Min = 0.5 mg/Kg, Max = 1250 mg/Kg, Skewness = 3.57).

The geochemical background values for the Sirba soils (1994 pre-industrial period) obtained from the geochemical threshold values were: GB As = 27 mg/Kg, GB Cu = 151.99 mg/Kg, GB Pb = 12.50 mg/Kg and GB Zn = 145 mg/Kg. The GB As (27 mg/Kg), GB Cu (151.99 mg/Kg) and GB Zn (145 mg/Kg) values for the Sirba soils were higher than the values for the average concentration of these elements in the upper continental crust, as given by Hans-Wedepohl (1995): As (2 mg/Kg), Cu (14.3 mg/Kg) and Zn (52 mg/Kg). This difference could be explained by the fact that the geochemical threshold was always higher than the natural geochemical background, as well explained by ADEME (2018). Only the GB Pb value (12.50 mg/Kg) of the Sirba soils was slightly lower than the average lead concentration in the upper continental crust (Pb = 17 mg/Kg) as given by Hans-Wedepohl (1995).

Geochemical background values for Sirba soils were used to calculate pollution assessment indices (Contamination Factor and Pollution Load Index) for As, Cu, Pb and Zn. The arsenic Contamination Factor (CF As) gives higher values (Min = 0.02, Mean = 0.99, Max = 442.07) than copper (CF Cu) (Min = 0, Mean = 0.31, Max = 8.95), lead (CF Pb) (Min = 0.04, Mean = 0.29, Max = 43.12) and zinc (CF Zn) (Min = 0, Mean = 0.39, Max = 8.58). Only the mean value of the arsenic Contamination Factor is very close to 1 (CF As ≈ 1). This shows that Sirba soils have overall moderate arsenic contamination. The overall average Cu, Pb and Zn contamination of the Sirba soils was very low. The pollution Load Index values (Min = 0.01, Mean = 0.28, Max = 3.86) show that multi-element pollution was low (Mean PLI = 0.28), even though some samples have PLI > 1 (Max PLI = 3.86), thus presenting high global pollution. The multi-element (As, Cu, Pb, Zn) pollution was mainly concentrated in the soils of the NE part of the Sirba greenstone belt.

Overlaying the gold mining areas on the CF and PLI classification shows that areas presenting high multi-element pollution and high levels of As, Cu, Pb and Zn Contamination Factor were areas that had subsequently been subjected to gold mining. High arsenic concentrations in gold mining areas may be associated with gold mineralization. In fact, gold mineralization at Sirba and Liptako was associated with sulfides rich in As and other metals (Cd, Cu, Pb, Zn, Hg, etc.) such as pyrite, arsenopyrite, chalcopyrite, sphalerite, galena, etc., as shown by Abass-Saley (2024), Jica (1995) and Saint-Martin (1999). The weathering of sulfide-rich rocks (pyrite, arsenopyrite, etc.) could mobilize their metals and metalloids, which end up in soils. The release of metals and metalloids into soils from the weathering of sulfide-rich rocks was observed by Weightman (2020). This could explain the presence of As, and Cu, Hg, Pb, Zn in the soils of the Sirba greenstone belt which is the Niger's largest gold province. Arsenic in the soils of the Sirba greenstone belt therefore came from the gold mineralization.

4. CONCLUSION

Soil geochemical data from the Sirba greenstone belt had made it possible to define As, Cu, Pb and Zn geochemical background values for the Sirba region. The geochemical background values were used to calculate pollution assessment indices (Contamination Factor, Pollution Load Index) for As, Cu, Pb and Zn elements. The Contamination Factor values showed that arsenic contamination was highest in soils, while copper, lead and zinc contamination was low in Sirba soils. The average of Sirba soils multi-element (As, Cu, Pb and Zn) pollution (PLI) was low. There was, however, some heavily polluted areas. This multi-element pollution developed mainly in the soils of the NE part of the Sirba belt, which had high arsenic Contamination Factor values. The Sirba gold mining areas had developed on zones with high pollution indices, particularly arsenic. The arsenic in the soils of the Sirba greenstone belt was therefore thought to have originated from gold mineralization.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of this manuscript.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

REFERENCES

Abass-Saley, A. (2024). Apport de la télédétection et de la géochimie à l'évaluation de l'impact environnemental de l'exploitation minière artisanale de l'or à Koma Bangou (Liptako, Niger). Thèse de Doctorat, Institut National Polytechnique Houphouët-Boigny, Yamoussoukro, Côte d'Ivoire, 260p.

ADEME (2018). Méthodologie de détermination des valeurs de fonds dans les sols : Echelle territoriale., Groupe de travail sur les valeurs de fonds. Groupe de travail sur les valeurs de fonds, 112p.

Akay, A., Özaytekin, H.H. (2022). Using Contamination Indices for Assessments of Heavy Metals Status of Soils around Mercury Mine, in Kurşunlu, (Konya) Province. Selcuk Journal of Agriculture and Food Sciences 36, 312–319. https://doi.org/10.15316/SJAFS.2022.040

Alshahri, F., El-Taher, A. (2018). Assessment of Heavy and Trace Metals in Surface Soil Nearby an Oil Refinery, Saudi Arabia, Using Geoaccumulation and Pollution Indices. Arch Environ Contam Toxicol 75, 390–401. https://doi.org/10.1007/s00244-018-0531-0

Ama Salah, I., Liegeois, J.-P., Pouclet, A. (1996). Evolution d'un arc insulaire océanique birimien précoce au Liptako nigérien (Sirba) : géologie, géochronologie et géochimie. Journal of African Earth Sciences 22, 235–254.

Amadou, A.R. (2002). Propositions pour l'optimisation de la mine artisanale au Niger. Proposals for optimising artisanal mining in Niger. Pangea Infos, Société Géologique de France 37, 18.

Baah, D.S., Gikunoo, E., Arthur, E.K., Agyemang, F.O., Foli, G., Koomson, B., Opoku, P. (2023). Anthropogenic Sources and Risk Assessment of Heavy Metals in Mine Soils: A Case Study of Bontesso in

Amansie West District of Ghana. Journal of Chemistry 2023, e6760154. https://doi.org/10.1155/2023/6760154

Baize, D., Sterckeman, T. (2001). Of the necessity of knowledge of the natural pedo-geochemical background content in the evaluation of the contamination of soils by trace elements. Science of The Total Environment 264, 127–139. https://doi.org/10.1016/S0048-9697(00)00615-X

Barik, S.K., Muduli, P.R., Mohanty, B., Rath, P., Samanta, S. (2018). Spatial distribution and potential biological risk of some metals in relation to granulometric content in core sediments from Chilika Lake, India. Environ Sci Pollut Res 25, 572–587. https://doi.org/10.1007/s11356-017-0421-4

Bassey, A., Ama, K., Esien, E., Alex, A. (2015). Evaluation And Characterization Of Trace Metals Contamination In The Surface Sediment Using Pollution Load Index (PLI) And Geo-Accumulation Index (Igeo) Of Ona River, Western Nigeria. IJSTR 4(1), 6.

Bessoles, B. (1977). Geology of Africa: The West African craton. BRGM. ed, Memory of BRGM. Paris, 402p.

Bhuiyan, M.A.H., Dampare, S.B., Islam, M.A., Suzuki, S. (2015). Source apportionment and pollution evaluation of heavy metals in water and sediments of Buriganga River, Bangladesh, using multivariate analysis and pollution evaluation indices. Environ Monit Assess 187, 4075. https://doi.org/10.1007/s10661-014-4075-0

Bing, H., Zhou, J., Wu, Y., Wang, X., Sun, H., Li, R. (2016). Current state, sources, and potential risk of heavy metals in sediments of Three Gorges Reservoir, China. Environmental Pollution 214, 485–496. https://doi.org/10.1016/j.envpol.2016.04.062

Chon, H.-T., Ahn, J.-S., Jung, M.C. (1998). Seasonal Variations and Chemical Forms of Heavy Metals in Soils and Dusts from the Satellite Cities of Seoul, Korea. Environmental Geochemistry and Health 20, 77–86. https://doi.org/10.1023/A:1006593708464

de-Lima, M.W., Hamid, S.S., de Souza, E.S., Teixeira, R.A., da Conceição Palheta, D., do Carmo Freitas Faial, K., Fernandes, A.R. (2020). Geochemical background concentrations of potentially toxic elements in soils of the Carajás Mineral Province, southeast of the Amazonian Craton. Environ Monit Assess 192, 649. https://doi.org/10.1007/s10661-020-08611-9

Dupuis, D., Pons, J., E Prost, A. (1991). Pluton emplacement and characterization of birimian deformation in western Niger. C. R. Acad. Sci. Paris 312, 769–776.

Facchinelli, A., Sacchi, E., Mallen, L. (2001). Multivariate statistical and GIS-based approach to identify heavy metal sources in soils. Environmental Pollution 114, 313–324. https://doi.org/10.1016/S0269-7491(00)00243-8

Fagbenro, A.A., Taiwo, Y., Ajekiigbe, K., Oke, A., Obiajunwa, E. (2021). Assessment of Heavy Metal Pollution in Soil Samples from a Gold Mining Area in Osun State, Nigeria using Proton-Induced X-ray Emission. Scientific African 14, e01047. https://doi.org/10.1016/j.sciaf.2021.e01047

Ferati, F., Kerolli-Mustafa, M., Kraja-Ylli, A. (2015). Assessment of heavy metal contamination in water and sediments of Trepça and Sitnica rivers, Kosovo, using pollution indicators and multivariate cluster analysis. Environ Monit Assess 187, 338. https://doi.org/10.1007/s10661-015-4524-4

Fodoué, Y., Ismaila, A., Yannah, M., Wirmvem, M.J., Mana, C.B. (2022). Heavy Metal Contamination and Ecological Risk Assessment in Soils of the Pawara Gold Mining Area, Eastern Cameroon. EARTH 3, 907–924. https://doi.org/10.3390/earth3030053

Franklin, J.M., Duke, J.M., Shilts, W.W., Coker, W.B., Friske, P.W.B., Maurice, Y.T., Ballantyne, S.B., Dunn, C.E., Hall, G.E.M., Garrett, R.G. (1991). Exploration geochemistry workshop. Geological Survey of Canada 9.1-9.41. https://doi.org/10.4095/132397

Ghrefat, H., Zaman, H., Batayneh, A., El Waheidi, M.M., Qaysi, S., Al-Taani, A., Jallouli, C., Badhris, O. (2021). Assessment of Heavy Metal Contamination in the Soils of the Gulf of Aqaba (Northwestern Saudi Arabia): Integration of Geochemical, Remote Sensing, GIS, and Statistical Data. Journal of Coastal Research 37. https://doi.org/10.2112/JCOASTRES-D-20-00137.1

Gonçalves, D.A.M., Pereira, W.V. da S., Johannesson, K.H., Pérez, D.V., Guilherme, L.R.G., Fernandes, A.R. (2022). Geochemical Background for Potentially Toxic Elements in Forested

Soils of the State of Pará, Brazilian Amazon. Minerals 12, 674. https://doi.org/10.3390/min12060674

González-Valoys, A.C., Esbrí, J.M., Campos, J.A., Arrocha, J., García-Noguero, E.M., Monteza-Destro, T., Martínez, E., Jiménez-Ballesta, R., Gutiérrez, E., Vargas-Lombardo, M., Garcia-Ordiales, E., García-Giménez, R., García-Navarro, F.J., Higueras, P. (2021). Ecological and Health Risk Assessments of an Abandoned Gold Mine (Remance, Panama): Complex Scenarios Need a Combination of Indices. IJERPH 18, 9369. https://doi.org/10.3390/ijerph18179369

Gope, M., Masto, R.E., George, J., Balachandran, S. (2018). Tracing source, distribution and health risk of potentially harmful elements (PHEs) in street dust of Durgapur, India. Ecotoxicology and Environmental Safety 154, 280–293. https://doi.org/10.1016/j.ecoenv.2018.02.042

Gulan, L., Milenkovic, B., Zeremski, T., Milic, G., Vuckovic, B. (2017). Persistent organic pollutants, heavy metals and radioactivity in the urban soil of Priština City, Kosovo and Metohija. Chemosphere 171, 415–426. https://doi.org/10.1016/j.chemosphere.2016.12.064

Gupta, S., Jena, V., Matic, N., Kapralova, V., Solanki, J.S. (2014). Assessment of geo-accumulation index of heavy metal and source of contamination by multivariate factor analysis. International Journal of Hazardous Materials 2, 18–24.

Hamedan, I., Sobhanardakani, S., Ghoochian, M. (2016). Analysis of Heavy Metals in Surface Sediments from Agh Gel Wetland, Iran. IJT 10, 41–46. https://doi.org/10.32598/IJT.10.4.210.10

Hans-Wedepohl, K. (1995). The composition of the continental crust. Geochimica et Cosmochimica Acta 59, 1217–1232. https://doi.org/10.1016/0016-7037(95)00038-2

Haris, H., Looi, L.J., Aris, A.Z., Mokhtar, N.F., Ayob, N.A.A., Yusoff, F.Md., Salleh, A.B., Praveena, S.M. (2017). Geo-accumulation index and contamination factors of heavy metals (Zn and Pb) in urban river sediment. Environ Geochem Health 39, 1259–1271. https://doi.org/10.1007/s10653-017-9971-0

Hilson, G., Goumandakoye, H., Diallo, P. (2019). Formalizing artisanal mining 'spaces' in rural sub-Saharan Africa: The case of Niger. Land Use Policy 80, 259–268. https://doi.org/10.1016/j.landusepol.2018.09.023

Hossain, M.B., Aftad, Md.Y., Yu, J., Choudhury, T.R., Noman, Md.A., Hossain, Md.S., Paray, B.A., Arai, T. (2022). Contamination and Ecological Risk Assessment of Metal(loid)s in Sediments of Two Major Seaports along Bay of Bengal Coast. Sustainability 14, 12733. https://doi.org/10.3390/su141912733

Jiang, H.-H., Cai, L.-M., Wen, H.-H., Luo, J. (2020). Characterizing pollution and source identification of heavy metals in soils using geochemical baseline and PMF approach. Sci Rep 10, 6460. https://doi.org/10.1038/s41598-020-63604-5

Jica (1995). Rapport de la prospection minière dans la région de la Sirba, République du Niger. Agence japonaise pour la coopération internationale, Agence minière japonaise, Rapport Final, 205p.

Khan, M.Z., Islam, M.R., Salam, A.B.A., Ray, T. (2021). Spatial Variability and Geostatistical Analysis of Soil Properties in the Diversified Cropping Regions of Bangladesh Using Geographic Information System Techniques. Applied and Environmental Soil Science 2021, e6639180. https://doi.org/10.1155/2021/6639180

Klockner (1995). Gold research in Liptako. Ministry of Mines and Energy, Niamey. Final report n° 6500-11-40-026, 162p.

Konstantinova, E., Minkina, T., Nevidomskaya, D., Bauer, T., Fedorov, Y., Zamulina, I., Mandzhieva, S., Kravtsova, N., Voloshina, M., Dudnikova, T., Shcherbakov, A. (2021). Establishment of regional background for heavy metals in the soils of the Lower Don and the Taganrog Bay coast. E3S Web Conf. 265, 03004. https://doi.org/10.1051/e3sconf/202126503004

Li, X., Liu, L., Wang, Y., Luo, G., Chen, X., Yang, X., Hall, M.H.P., Guo, R., Wang, H., Cui, J., He, X. (2013). Heavy metal contamination of urban soil in an old industrial city (Shenyang) in Northeast China. Geoderma 192, 50–58. https://doi.org/10.1016/j.geoderma.2012.08.011

Li, Y., Duan, Z., Liu, G., Kalla, P., Scheidt, D., Cai, Y. (2015). Evaluation of the Possible Sources and Controlling Factors of Toxic

Metals/Metalloids in the Florida Everglades and Their Potential Risk of Exposure. Environ. Sci. Technol. 49, 9714–9723. https://doi.org/10.1021/acs.est.5b01638

Licht, O. (2020). Geochemical background - what a complex meaning has such a simple expression! Geochim. Bras. 34, 161–175. https://doi.org/10.21715/GB2358-2812.2020342161

Liu, X., Wu, J., Xu, J. (2006). Characterizing the risk assessment of heavy metals and sampling uncertainty analysis in paddy field by geostatistics and GIS. Environmental Pollution 141, 257–264. https://doi.org/10.1016/j.envpol.2005.08.048

Luo, X., Ren, B., Hursthouse, A.S., Thacker, J.R.M., Wang, Z. (2020). Soil from an abandoned manganese mining area (Hunan, China): significance of health risk from potentially toxic element pollution and its spatial context. International Journal of Environmental Research and Public Health 17. https://doi.org/10.3390/ijerph17186554

Machens, E. (1973). Contribution to the study of crystalline basement formations and sedimentary cover in the western Niger Republic. Memory of BRGM No. 82, 158p.

Machens, E. (1967). Carte Géologique du Niger occidental. Mémoires du BRGM.

Markwitz, V., Hein, K.A.A., Jessell, M.W., Miller, J. (2016). Metallogenic portfolio of the West Africa craton. Ore Geology Reviews 78, 558–563. https://doi.org/10.1016/j.oregeorev.2015.10.024

Milési, J.-P., Feybesse, J.-L., Pinna, P., Deschamps, Y., Kampunzu, H., Muhonogo, S., Lescuyer, J.-L., Toteu, S. (2004). Géologie et principaux gisements de l’Afrique, échelle 1/10,000,000.

Mishra, P., Pandey, C.M., Singh, U., Gupta, A., Sahu, C., Keshri, A. (2019). Descriptive Statistics and Normality Tests for Statistical Data. Ann Card Anaesth 22, 67–72. https://doi.org/10.4103/aca.ACA_157_18

Nornadiah, M.R., Yap, B.W. (2011). Power Comparisons of Shapiro-Wilk, Kolmogorov-Smirnov, Lilliefors and Anderson-Darling Tests. Journal of Statistical Modeling and Analytics 2, 21–33.

Okereafor, U., Makhatha, E., Mekuto, L., Mavumengwana, V. (2019). Dataset on assessment of pollution level of selected trace metals in farming area within the proximity of a gold mine dump, Ekuhurleni, South Africa. Data in Brief 26, 104473. https://doi.org/10.1016/j.dib.2019.104473

Olivero-Verbel, J., Caballero-Gallardo, K., Turizo-Tapia, A. (2015). Mercury in the gold mining district of San Martin de Loba, South of Bolivar (Colombia). Environ Sci Pollut Res 22, 5895–5907. https://doi.org/10.1007/s11356-014-3724-8

Pétot, J. (1995). Réorganisation et modernisation de la petite industrie de l’orpaillage au Liptako (Niger). UNIDO Projet SI/NER/93/803/11-51 No. 21201, 83p.

Pons, J., Barbey, P., Dupuis, D., Léger, J.M. (1995). Mechanisms of pluton emplacement and structural evolution of a 2.1 Ga juvenile continental crust: the Birimian of southwestern Niger. Precambrian Research 70, 281–301. https://doi.org/10.1016/0301-9268(94)00048-V

Quiroz, C.J.C., Choque, G.J.M., Mamani, M.C., Quispe, G.D.L.F. (2022). Evaluation of the content of metals and contamination indices generated by environmental liabilities, in Tacna, Peru (preprint). In Review. https://doi.org/10.21203/rs.3.rs-2203478/v1

Radziemska, M., Fronczyk, J. (2015). Level and Contamination Assessment of Soil along an Expressway in an Ecologically Valuable Area in Central Poland. IJERPH 12, 13372–13387. https://doi.org/10.3390/ijerph121013372

Raji, I.B., Palamuleni, L.G., Raji, I.B., Palamuleni, L.G. (2023). Toxic Heavy Metals in Soil and Plants from a Gold Mining Area, South Africa, in: Heavy Metals - Recent Advances. IntechOpen. https://doi.org/10.5772/intechopen.109639

Reimann, C., Fabian, K., Birke, M., Filzmoser, P., Demetriades, A., Négrel, P., (2018). GEMAS: Establishing geochemical background and threshold for 53 chemical elements in European agricultural soil. Applied Geochemistry 88, 302–318. https://doi.org/10.1016/j.apgeochem.2017.01.021

Reimann, C., Filzmoser, P., Garrett, R.G. (2005). Background and threshold: critical comparison of methods of determination. Science of The Total Environment 346, 1–16. https://doi.org/10.1016/j.scitotenv.2004.11.023

Rodríguez Martín, J.A., Ramos-Miras, J.J., Boluda, R., Gil, C. (2013). Spatial relations of heavy metals in arable and greenhouse soils of a Mediterranean environment region (Spain). Geoderma 200–201, 180–188. https://doi.org/10.1016/j.geoderma.2013.02.014

Saint-Martin, M. (1999). Projet de prospection minière du Liptako (Rapport Final). Ministère des Mines et de l'énergie, Direction de la Recherche Géologique et Minière.

Salam, M.M.A., Kaipiainen, E., Mohsin, M., Villa, A., Kuittinen, S., Pulkkinen, P., Pelkonen, P., Mehtätalo, L., Pappinen, A. (2016). Effects of contaminated soil on the growth performance of young Salix (Salix schwerinii E. L. Wolf) and the potential for phytoremediation of heavy metals. Journal of Environmental Management 183, 467–477. https://doi.org/10.1016/j.jenvman.2016.08.082

Santos-Francés, F., Martinez-Graña, A., Alonso Rojo, P., García Sánchez, A. (2017). Geochemical Background and Baseline Values Determination and Spatial Distribution of Heavy Metal Pollution in Soils of the Andes Mountain Range (Cajamarca-Huancavelica, Peru). IJERPH 14, 859. https://doi.org/10.3390/ijerph14080859

Sarkar, S.K., Mondal, P., Biswas, J.K., Kwon, E.E., Ok, Y.S., Rinklebe, J. (2017). Trace elements in surface sediments of the Hooghly (Ganges) estuary: distribution and contamination risk assessment. Environ Geochem Health 39, 1245–1258. https://doi.org/10.1007/s10653-017-9952-3

Sawadogo, Y.Z., Bambara, T.L., Zongo, I., Kaboré, K., Zougmoré, F. (2023). Pollution and Ecological Risk Assessment of Heavy Metals in the Agricultural Soils Around a Gold Mine in BISSA Village, Burkina-Faso. Journal of Environment Pollution and Human Health 11, 51–59. https://doi.org/10.12691/jephh-11-3-1

Seyni, H.H., Ousmane, B., Soumana, I., Yamba, B. (2014). Impacts des activités socio-économiques sur les ressources en eau du barrage de Téra au Niger. Afrique Science 10, 149–172.

Sierra, M., Martínez, F.J., Aguilar, J. (2007). Baselines for trace elements and evaluation of environmental risk in soils of Almería (SE Spain). Geoderma 139, 209–219. https://doi.org/10.1016/j.geoderma.2007.02.003

Song, D., Zhuang, D., Jiang, D., Fu, J., Wang, Q. (2015). Integrated Health Risk Assessment of Heavy Metals in Suxian County, South China. Int J Environ Res Public Health 12, 7100–7117. https://doi.org/10.3390/ijerph120707100

Soumaila, A., Henry, P., Rossy, M. (2004). Contexte de mise en place des roches basiques de la ceinture de roches vertes birimienne de Diagorou-Darbani (Liptako, Niger, Afrique de l'Ouest) : plateau océanique ou environnement d'arc/bassin arrière-arc océanique. Comptes Rendus Geoscience 336, 1137–1147. https://doi.org/10.1016/j.crte.2004.03.008

St-Julien, P. (1992). Preliminary structural study of the Kourki, Dounga, Kosso and Borobon showings in the Gorouol belt (Liptako). ACDI Report N° 700/10417. 34p.

Suresh, G., Sutharsan, P., Ramasamy, V., Venkatachalapathy, R. (2012). Assessment of spatial distribution and potential ecological risk of the heavy metals in relation to granulometric contents of Veeranam lake sediments, India. Ecotoxicol Environ Saf 84, 117–124. https://doi.org/10.1016/j.ecoenv.2012.06.027

Sutkowska, K., Teper, L., Czech, T., Walker, A. (2023). Assessment of the Condition of Soils before Planned Hard Coal Mining in Southern Poland: A Starting Point for Sustainable Management of Fossil Fuel Resources. Energies 16, 737. https://doi.org/10.3390/en16020737

Tashakor, M., Modabberi, S., van der Ent, A., Echevarria, G. (2018). Impacts of ultramafic outcrops in Peninsular Malaysia and Sabah on soil and water quality. Environ Monit Assess 190, 333. https://doi.org/10.1007/s10661-018-6668-5

Thornton, I. (1995). Metals in the global environment: facts and misconceptions. International Council on Metals and the Environment, Ottawa. International Council on Metals and the Environment, 103p.

Tian, K., Huang, B., Xing, Z., Hu, W. (2017). Geochemical baseline establishment and ecological risk evaluation of heavy metals in greenhouse soils from Dongtai, China. Ecological Indicators 72, 510–520. https://doi.org/10.1016/j.ecolind.2016.08.037

Tomlinson, D.L., Wilson, J.G., Harris, C.R., Jeffrey, D.W. (1980). Problems in the assessment of heavy-metal levels in estuaries and the formation of a pollution index. Helgolander Meeresunters 33, 566–575. https://doi.org/10.1007/BF02414780

Tyopine, A.A., Jayeoye, T.J., Okoye, C.O.B. (2018). Geoaccumulation assessment of heavy metal pollution in Ikwo soils, eastern Nigeria. Environ Monit Assess 190, 58. https://doi.org/10.1007/s10661-017-6423-3

Vaverková, M.D., Adamcová, D. (2014). Heavy Metals Uptake by Select Plant Species in the Landfill Area of Štěpánovice, Czech Republic. Pol. J. Environ. Stud. 23, 2265–2269. https://doi.org/10.15244/pjoes/26106

Wang, S., Cai, L.-M., Wen, H.-H., Luo, J., Wang, Q.-S., Liu, X. (2019). Spatial distribution and source apportionment of heavy metals in soil from a typical county-level city of Guangdong Province, China. Science of The Total Environment 655, 92–101. https://doi.org/10.1016/j.scitotenv.2018.11.244

Wei, L., Wang, M., Liu, G., Wu, D. (2021). Geochemical Anomaly Characteristics of Cd in Soils around Abandoned Lime Mines: Evidence from Multiple Technical Methods. Molecules 26, 5127. https://doi.org/10.3390/molecules26175127

Weightman, E. (2020). Environmental geochemistry of mine waste and waters at Macraes gold mine, Otago. Master thesis, University of Otago, Dunedin,191p.

Wiafe, S., Awuah Yeboah, E., Boakye, E., Ofosu, S. (2022). Environmental risk assessment of heavy metals contamination in the catchment of small-scale mining enclave in Prestea Huni-Valley District, Ghana. Sustainable Environment 8, 2062825. https://doi.org/10.1080/27658511.2022.2062825

Yonlihinza, I.A. (2011). Transports et désenclavement dans la problématique du développement local à Téra au Niger. Thèse de Doctorat, Université Toulouse le Mirail - Toulouse II; Université Abdou Moumouni,417p. https://tel.archives-ouvertes.fr/tel-00675205

Yuan, G.-L., Sun, T.-H., Han, P., Li, J., Lang, X.-X. (2014). Source identification and ecological risk assessment of heavy metals in topsoil using environmental geochemical mapping: Typical urban renewal area in Beijing, China. Journal of Geochemical Exploration 136, 40–47. https://doi.org/10.1016/j.gexplo.2013.10.002

Zhao, N., Lu, X., Chao, S. (2014). Level and Contamination Assessment of Environmentally Sensitive Elements in Smaller than 100 µm Street Dust Particles from Xining, China. IJERPH 11, 2536–2549. https://doi.org/10.3390/ijerph110302536

Zhong, B., Liang, T., Wang, L., Li, K. (2014). Applications of stochastic models and geostatistical analyses to study sources and spatial patterns of soil heavy metals in a metalliferous industrial district of China. Science of The Total Environment 490, 422–434. https://doi.org/10.1016/j.scitotenv.2014.04.127

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