International Journal of Geosciences, 2016, 7, 1102-1121
http://www.scirp.org/journal/ijg
ISSN Online: 2156-8367
ISSN Print: 2156-8359

Physical and Metals Impact of Traditional Gold Mining on Soils in Kombo-Laka Area (Meiganga, Cameroon)

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How to cite this paper: Léopold, E.N., Sabine, D.D., Philémon, Z.Z. and Jung, M.C. (2016) Physical and Metals Impact of Traditional Gold Mining on Soils in Kombo-Laka Area (Meiganga, Cameroon). *International Journal of Geosciences*, **7**, 1102-1121.
http://dx.doi.org/10.4236/ijg.2016.79084

Received: August 15, 2016
Accepted: September 26, 2016
Published: September 29, 2016

Abstract

Concentrations of metals (As, Cr, Cd, Fe, Ni, Pb, Sb, and Zn) in soil samples from Kombo-Laka were investigated. The area under study is subjected to traditional gold mining and receives various wastes from miners and mining activities. Direct observations on the field displayed the destruction of soils by this activity. An assessment of pollution was performed using an Enrichment Factor (EF) and geoaccumulation index (I_{geo}). Levels of As, Cr, Cd, Cu, Pb and Sb in soil samples were above average in the Upper Continental Crust (UCC). EF revealed anthropogenic sources for Cd, As and Sb in these soils. I_{geo} indicates that Kombo-Laka soils are moderately to extremely polluted with As and Sb. There are high to very high positive correlations among the metals suggesting their possible common sources. This study reveals that traditional gold mining activities in the area are harmful to the environment.

Keywords

Kombo-Laka, Soils, Gold Mining, Pollution, Heavy Metals

1. Introduction

Though mining operation has considerable economic benefits, very useful for developing countries for their development, mining and its activities have great consequences on the environment and are mainly responsible for releasing massive amounts of hazardous metals into the surrounding environments [1] [2].

In most African countries, including Cameroon, mining operation is in full expansion. At all levels, the effects on the environment and society are perceptible [3], and become catastrophic, especially when the activity follows traditional methods and is poorly controlled. They use unsuitable technologies that cause negative impacts on both the natural resources and the environment, in the present case, the soils. Even though this activity certainly contributes to poverty reduction especially in rural areas, it generates a lot of environmental problems such as deforestation, land degradation, air, soil and water pollution, loss of biodiversity and the landscape shaping [4]-[6].

According to Bamba *et al.* [7], the artisanal gold mining is usually accompanied by opening of trenches, shafts, scratching and the turning over of soils that lead to the embrittlement, the impoverishment of soils and the gradual destruction of arable land. It also contributes to the destruction of vegetation cover and predisposes soil to intense erosion processes [8]. In addition to the above listed problems, mining activities are also mainly responsible for releasing massive amounts of hazardous metals into the surrounding environments [1] [2].

According to literature [2] [9]-[12], heavy metals in our natural environment have received great attention worldwide by environmental, biological and chemical scientists as well as the general public, this is certainly due to their unique characteristics such as biological significance, toxic behavior, persistence, bioaccumulation and their tendency to be incorporated into food chains in harmful quantities [13]-[15].

In Cameroon, the increasing exploitation of natural resources such as cobalt, iron and gold in the last decades has severely polluted the natural environments surrounding mine fields with considerable amounts of heavy metals. The mining garbage will lead to the concentration of elements in soils that could be leached towards aquatic environments. Thus, soils in mining areas need to be monitored in view to control the levels of metallic pollutants emanating from this activity.

The locality of Kombo-Laka has been subjected to traditional gold exploitation for more than ten years and the activity has led to the destruction of the natural environment. In this regard, the study of the physical impact, the assessment of heavy metals concentration and the distribution in these soils are an absolute necessity. Data of this study will contribute to the future control of the negative impacts of mine fields exploitation and also contribute to the development of remediation techniques to preserve the environment.

2. Materials and Methods

2.1. Presentation of the Study Area

Kombo-Laka is located at about 130 km from Meiganga, capital of Mbere division. This gold district covers an area of approximately 90 km^2 and is about 17 km away from the border between Cameroon and the Central African Republic. It is located between latitude 6˚22'N and 6˚27'N and between longitude 14˚35'E and 14˚45'E (**Figure 1**). The geology is mainly dominated by shale beside which include dolerite dykes and sandstones. Even though the gold mining activity is dominant in the area, people also practice livestock, agriculture and small traders.

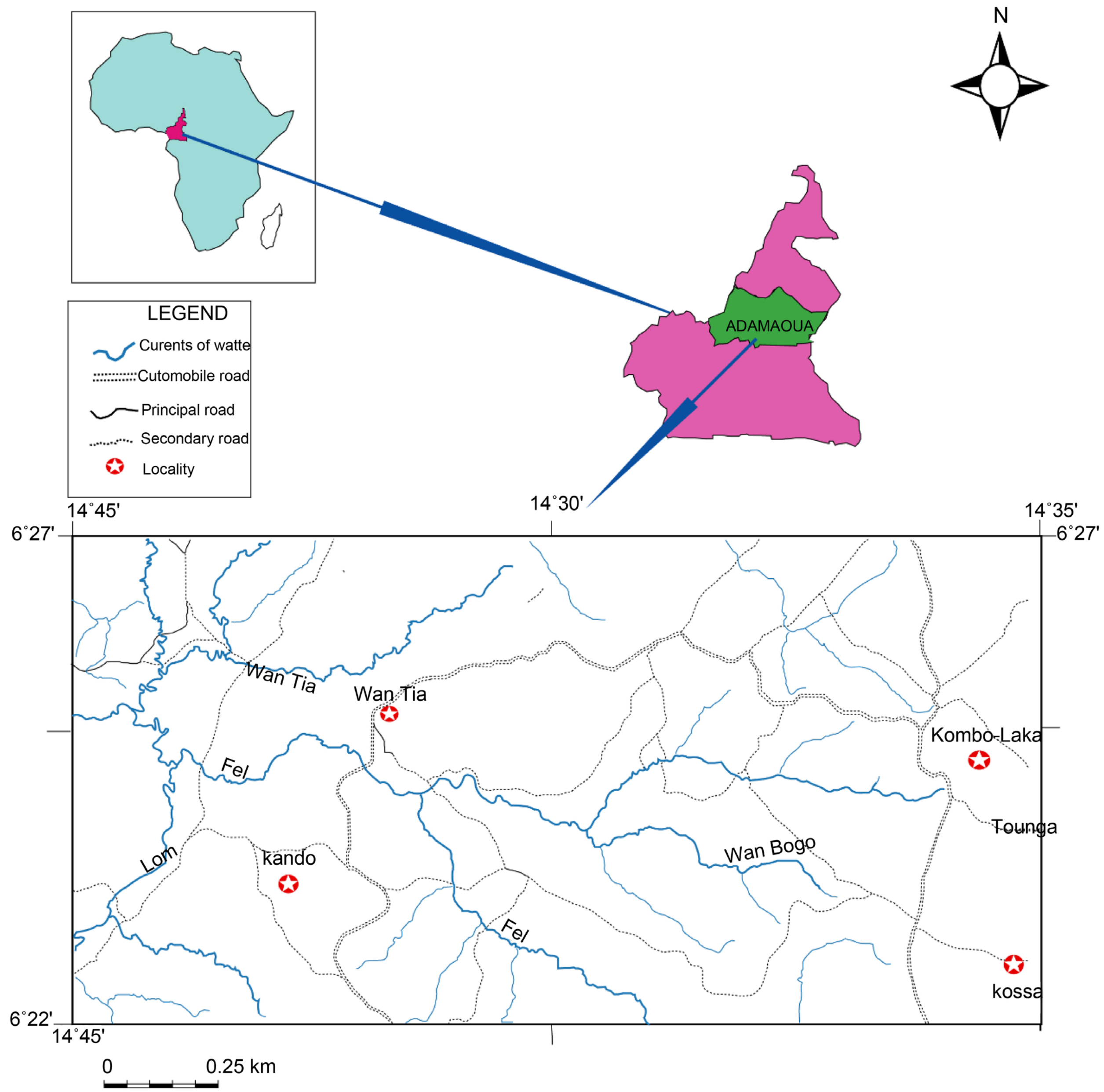

Figure 1. Location map of the studied area.

2.2. Sampling

Thirty one soil samples were taken randomly but evenly distributed in the area at 15 cm depth. The samples were taken in two exploited sites namely Fel, 12 samples and Wantia, 10 samples. The control soils were also taken very close to Fel (5 samples) and Wantia (4 samples) in non-exploited areas. At each sampling point, at least 250 g of soil were collected and stored in new plastic bags and transported to the laboratory.

2.3. Samples Preparation and Analytical Techniques

Once in the laboratory, soil samples were sun-dried to constant weight and pulverized to fine powder. One gramme of dried and homogenised soil was digested with a mixture of HNO_3 and HCl (aqua regia) in the ratio 1:3. Blanks and standard reference materials were included in the analysis to verify the efficiency of the extraction procedure. The digested samples were analysed for heavy metals by ICP-AES (Perkins- Elmer Optima 3000XL) under the conditions of RF power 1300 W, plasma flow 15 L/min, coolant flow 0.5 L/min, nebulizer flow 0.8 L/min at the Korea University, South Korea.

The reference standard materials SRM 2710 and SRM 2711 were used to assess the precision and accuracy of the procedure. The organic matter was determined by the loss on ignition at 550˚C [16]. The pH was determined using the method described by Mathieu and Pieltain [17].

2.4. Estimation of Contamination Intensity

To estimate the intensity of contamination, the enrichment factor and geo-accumulation index were calculated. Their principle relies on comparison of the measured values with the relative amounts of continental crust (UCC: Upper Continental Crust) of Wedepohl [18].

2.4.1. The Enrichment Factor (EF)

The enrichment factor provides the number of times an item is enriched compared to the abundance of this element in the reference material. The reference material used in this study is the one defined by Wedepohl [18] and recognized worldwide as reference concentration in unpolluted areas.

The EF calculation has been defined by relating the content of a contaminating element of the sample to the concentration of a known element relatively immobile of the sample compared by the same ratio found in the reference material (UCC). Iron (Fe) was chosen as a stationary reference element to perform this calculation [19]. This choice is based on the fact that iron is naturally present in the soils of the studied area. In addition, it is part of the reference materials widely used in the literature [20]-[23].

$$EF = \frac{(Me/Fe)_{\text{sample}}}{(Me/Fe)_{\text{background}}}$$

where EF = enrichment factor; $(Me/Fe)_{\text{sample}}$ is the metal to Fe ratio in the sample of interest; $(Me/Fe)_{\text{background}}$ is the natural background value of metal to Fe ratio.

The EF values are interpreted based on the level of contamination of Acevedo-Figueroa [24] where $EF < 1$ indicates no enrichment; 1 - 3 is minor; 3 - 5 is moderate; 5 - 10 is moderately severe; 10 - 25 is severe; 25 - 50 is very severe and $EF > 50$ is extremely severe.

2.4.2. The Geoaccumulation Index (I_{geo})

A second criterion to evaluate the intensity of metal pollution in the Kombo-Laka soils is the geoaccumulation index introduced by Müller [25];

$$I_{geo} = \log_2 \frac{[Me]_{\text{sediment}}}{1.5[Me]_{\text{background}}}$$

where $[Me]_{sediment}$ is the concentration of a given heavy metal in the sediment sample of the lake and $[Me]_{background}$ is the natural background value of metal using average shale and 1.5 is the background matrix correlation factor. The factor 1.5 is used for possible variations in the background data due to lithogenic effects.

The interpretation of the obtained results is as follows: class 0: $I_{geo} \le 0$ unpolluted, class 1: $0 < I_{geo} \le 1$ unpolluted to moderately polluted, class 2: $1 < I_{geo} \le 2$ moderately polluted, class 3: $2 < I_{geo} \le 3$ moderately to strongly polluted, class 4: $3 < I_{geo} \le 4$ strongly polluted, class 5: $4 < I_{geo} \le 5$ strongly to very strongly polluted and class 6: $I_{geo} > 5$ very strongly polluted.

2.5. Statistical Analyses

All statistical analyses were performed using XLSTAT 2007 with the level of significance maintained at 95% for all tests. The correlation coefficients were calculated in view to measure the intensity of relationship between the different variables.

3. Results and Discussion

3.1. Impacts of Gold Mining in the Studied Area

3.1.1. Deforestation (and Destruction of Vegetation Cover) and Soil Destruction

Gold mining activities include the opening of yard which causes an abusive and anarchic trees felling (**Figure 2**). This massive deforestation is in part responsible for the disappearance of the plant cover (**Figure 3**). The degradation of the plant cover is the cause of the strong erosion observed in the area (**Figure 4**).

3.1.2. Soil Destruction

Deep wells and galleries (up to 30 m) from gold mining activity are never closed up. They occupy farmland permanently and constitute a danger for humans and animals. This irreversible process of deterioration if left unchecked can become catastrophic for several generations to come. Traditional gold mining could also be the cause of soil infertility, as a result of the disappearance of humus layer. The soils are then destroyed, and therefore not suitable for agriculture.

Figure 2. Deforested area.

Figure 3. Destruction of the plant cover.

Figure 4. Destruction of soil by erosion.

The traditionally exploited sites can also be a place for hydraulic erosion which causes the destruction of the soil structure and the transport of particles rich in trace elements in the dissolved or particulate forms that could cause the degradation of water and sediments quality and therefore might constitute a danger for aquatic organisms and populations through food chain.

3.2. Physicochemical Parameters and Heavy Metals in Kombo-Laka Soils

The results of pH, Electrical Conductivity (EC) and Organic Matter (OM) are presented in Table 1 and Table 2. These results revealed that, the pH varies from 5.20 to 6.62 (mean 5.77) in Fel exploited soil; from 4.22 to 5.70 (5.10) in non-exploited soils (Fel). In Wantia, the pH varies from 4.00 to 6.20 (5.46) in exploited soils and from 4.20 to 5.80 (5.32) in non-exploited soils. From the results, one can notice that the pH varies from

Table 1. Heavy metal concentration (mg·kg^{-1}, dry weight) in the exploited soils of the studied area.

ID	Fe	As	Cr	Cd	Cu	Ni	Pb	Sb	Zn	pH	EC (μS/cm)	% OM
FE1	32,047.7	12.21	15.54	0.32	10.74	3.48	12.42	3.25	11.45	5.83	257.00	0.62
FE2	36,646.9	5.79	20.89	0.37	6.17	3.1	13.59	3.30	7.83	5.20	188.60	1.24
FE3	33,989.6	14.38	21.01	0.33	11.89	3.54	12.12	3.76	10.10	5.83	167.40	0.29
FE4	29,511.9	12.65	20.75	0.31	11.71	4.05	12.33	3.60	10.31	6.62	156.50	0.95
FE5	37,107.1	14.35	33.04	0.38	14.25	7.68	14.19	5.33	22.49	6.10	239.00	0.77
FE6	26,726.1	9.12	22.76	0.27	9.57	3.83	11.42	3.54	9.94	5.24	153.40	0.15
FE7	17,225.8	7.167	7.45	0.21	7.66	1.47	21.44	2.61	9.33	5.52	161.30	0.65
FE8	58,243.9	6.57	28.77	0.52	10.07	4.18	19.26	5.08	10.82	5.76	137.10	1.49
FE9	69,605.9	11.53	27.21	0.60	11.12	3.48	17.90	7.53	11.57	5.85	102.20	1.33
FE10	77,357.5	11.26	35.59	0.66	12.87	4.23	19.89	7.02	12.40	5.63	98.00	1.36
FE11	26,679.1	10.80	16.03	0.28	7.84	1.47	11.12	5.07	7.23	5.44	144.60	0.95
FE12	37,037.2	14.20	15.96	0.34	12.12	1.94	11.97	5.59	10.97	5.90	167.00	0.71
Min.	**17,225.8**	**5.79**	**7.45**	**0.21**	**6.17**	**1.47**	**11.12**	**2.61**	**7.23**	**5.20**	**98.00**	**0.15**
Max.	**77,357.5**	**14.38**	**35.59**	**0.66**	**14.25**	**7.68**	**21.44**	**7.53**	**22.49**	**6.62**	**257.00**	**1.49**
Mean	**41,197.29**	**10.73**	**22.00**	**0.39**	**10.46**	**3.69**	**15.02**	**4.70**	**11.73**	**5.77**	**166.22**	**0.87**
WE 1	66,176.7	47.29	47.02	0.58	15.65	7.13	24.39	7.74	27.50	4.89	188.90	0.35
WE 2	120,123	33.36	165.51	1.23	19.86	7.58	25.18	19.48	39.77	6.17	136.70	0.64
WE 3	102,010.1	27.46	147.75	0.92	16.51	7.20	23.38	18.85	33.30	4.00	143.70	0.32
WE 4	50,208.3	14.56	23.19	0.43	12.60	6.03	14.82	4.24	13.02	5.63	134.80	0.39
WE 5	40,975.9	11.35	21.75	0.37	7.09	6.00	15.75	3.57	13.30	5,13	174.50	0.39
WE 6	49,788.7	23.59	27.27	0.45	11.70	3.71	16.35	5.29	14.52	6.20	142.50	0.70
WE 7	61,866.3	24.12	19.06	0.55	14.46	4.92	22.84	5.54	15.01	5.79	149.00	0.95
WE 8	44,784,4	11,55	23,31	0,39	8,94	5,31	13,96	4.48	10.84	6.10	119.90	0.61
WE 9	45,886.60	13.81	15.74	0.39	8.47	3.63	16.75	3.75	12.89	5.73	126.00	0.36
WE 10	48,192.70	11.94	18.45	0.44	8.18	4.46	15.62	4.42	12.65	5.70	141.80	1.08
Min.	**40,975.90**	**11.35**	**15.74**	**0.37**	**7.09**	**3.63**	**13.96**	**3.57**	**10.84**	**4.00**	**119.90**	**0.32**
Max.	**120,123.00**	**47.29**	**165.51**	**1.23**	**19.86**	**7.58**	**25.18**	**19.48**	**39.77**	**6.20**	**188.90**	**1.08**
Mean	**65,925.97**	**23.14**	**57.53**	**0.61**	**12.53**	**5.60**	**19.02**	**8.37**	**20.28**	**5.46**	**147.22**	**0.60**
[30]	16,620	24.8	33.46	34.46	22.12	16.54	120.50	-	124.17			
[7]	-	2 - 54	-	0.3 - 1.1	11 - 110	5.5 - 84	5 - 27	-	8 - 34			
[29]	-	0.3 - 39.5	104 - 938.7	0.5 - 3.8	0.8 - 38.3	1.2 - 41.4	-	1.2 - 3.1	7.0 - 110.3			
[31]	-	450	-	5.372	-	-	-	1.214	-			
[18]	46,700	2	35	0.1	14	19	17	0.31	52			

FE = exploited soil of Fel; WE = exploited soil of Wantia.

one site to the other. It is generally lower in exploited soils of Wantia than those from Fel. These results show however that the pH of Kombo-Laka soils is acidic.

The pH is considered as the main chemical parameter that controls the bio- availability of heavy metals in soil and that easily modifies the behavior of metals easily

Table 2. Heavy metal concentration (mg·kg^{-1}, dry weight) in the non-exploited soils of the studied area.

ID	Fe	As	Cr	Cd	Cu	Ni	Pb	Sb	Zn	pH	EC (µS/cm)	% OM
FT1	48,548.6	21.00	26.46	0.52	23.27	13.38	15.76	4.90	38.07	4.22	183.50	1.81
FT2	52,158.7	20.91	27.49	0.46	21.76	11.09	15.70	5.30	31.56	4.59	287.00	1.33
FT3	50,061.1	21.32	28.52	0.48	20.25	10.65	15.53	5.11	30.00	5.63	156,10	1.21
FT4	43,344.5	19.40	24.6	0.46	21.45	12.12	14.72	4.77	34.83	5.66	333.00	1.80
FT5	41,415.8	18.73	23.61	0.42	24.33	13.88	15.28	4.50	37.28	5.70	309.00	2.23
Min.	**41,415.8**	**18.73**	**23.61**	**0.42**	**20.25**	**10.65**	**14.72**	**4.50**	**30.00**	**4.22**	**156.10**	**1.21**
Max.	**52,158.7**	**21.32**	**28.52**	**0.52**	**24.33**	**13.88**	**15.76**	**5.30**	**38.07**	**5.70**	**333.00**	**2.23**
Mean	**47,014.74**	**20.20**	**26.12**	**0.47**	**22.23**	**12.24**	**15.35**	**4.91**	**34.26**	**5.10**	**251.10**	**1.69**
WT 1	39,868.3	15.18	20.00	0.40	18.70	10.41	16.03	4.59	31.78	5.80	322.00	1.94
WT 2	45,278.3	13.62	23.75	0.37	**0.47**	8.76	16.20	4.46	23.87	5.64	231.00	2.03
WT 3	32,512.9	12.22	27.40	0.33	0.40	6.54	16.07	4.67	22.39	5.63	250.40	1.63
WT 4	22,496.6	7.56	26.97	0.26	7.26	2.63	14.77	4.02	12.11	4.20	157.00	1.24
Min.	**22,496.6**	**7.56**	**20.00**	**0.26**	**7.26**	**2.63**	**14.77**	**4.02**	**12.11**	**4.20**	**157.00**	**1.24**
Max.	**45,278.3**	**15.18**	**27.40**	**0.40**	**18.70**	**10.41**	**16.20**	**4.67**	**31.78**	**5.80**	**322.00**	**2.03**
Mean	**35,039.03**	**12.15**	**24.53**	**0.34**	**13.52**	**7.09**	**15.77**	**4.44**	**22.54**	**5.32**	**240.10**	**1.71**

FT = non-exploited soil of Fel; WT = non-exploited soil of Wantia.

[26] [27]. The variation of pH observed can be explained by that of the organic matter. Thus, these values are higher in exploited soils of Fel compared to those of Wantia due to their high OM contents. Indeed, in soils, the oxidation of sulphides in the OM promotes decreasing pH. Different pHs on the studied sites are less than 7, thus tending to the acidity. Besides the organic matter that plays an important role in this soil acidity, the geology of the area would also be of a considerable contribution especially with the presence of sandstone. For most metals, the acidification of soil rather results so much in a higher solubility than in a decrease of adsorption. The acidic pH promotes the mobility of metals [28]. Thus, Pb, Zn, Ni, Cd are more mobile at acidic pH than neutral one.

The electrical conductivity (µS/cm) varies from 98.00 to 257.00 (mean 166.22) in Fel exploited soils; from 156.10 to 333.00 (251.10) in non-exploited soils. In Wantia, EC varies from 119.90 to 188.90 (147.22) in exploited soils and from 157.00 to 322.00 (240.10) in non-exploited ones. It can be observed that non exploited soils are more conductive than exploited ones. Also, the EC and MO follow the same patterns as EC displayed high values in non-exploited soils.

The organic matter percentage varies between 0.15 and 1.49 (mean 0.87) in exploited soils of Fel and between 1.21 and 2.23 (1.69) in non-exploited soils. In Wantia, OM varies from 0.32 to 1.08 (0.60) in exploited soils and from 1.24 to 2.03 (1.71) in non- exploited one. OM contents are higher in non-exploited soils than exploited soils in both studied areas. This is justified by the presence of the humus horizon (topsoil) in non-exploited areas that did not undergo any disruption contrary to the exploited zones where this horizon is strongly disrupted by this mining activity. Furthermore, the higher OM contents in non-exploited soils are also due to the domestic garbage thrown by miners and by cattle dung.

The concentrations of heavy metals in exploited and non-exploited soils of Fel as well as exploited and non-exploited soils of Wantia are displayed in **Table 1** and **Table 2**. In the light of these results, it appears generally that the elements are more concentrated in Fel non-exploited soils than in the ones exploited, contrary to what is observed at Wantia where elements are more concentrated in the exploited soils than in non- exploited one.

The contents of As in exploited soils of Fel vary between 5.79 and 14.38 mg/kg, which is lower than the amount of As found in non-exploited soils (18.73 to 21.32 mg/kg). This could be the result of the leaching of mining residues rich in heavy metals. In Wantia exploited soils, the metal contents (11.35 to 47.29 mg/kg) are above those gotten in non-exploited soils (7.56 to 15.18 mg/kg). The As values obtained in the present study are similar to those obtained by Bamba *et al.* [7] and Arthin *et al.* [29] (2 to 54 mg/kg) in soils near a gold panning site in Burkina Faso and in a traditional gold mining site in Ghana respectively. However, the results recorded in the present study are higher than those obtained by Pahimi *et al.* [30] in traditional gold tailings in East Cameroon. But the results are lower than the mean As recorded by Hailin *et al.* [31]. Thus, high levels of As obtained in Kombo-Laka exploited soils are derived from the gold mining activity. Indeed, at the end of the mining activity, there are not less toxic elements than at the beginning, even if a large amount of elements was taken [32]. In the same way, the As is among the elements that are always associated with gold mineralization.

The mean concentration of Cr (22.1 mg/kg) in exploited soils of Fel is lower than the one in non-exploited soils (26.1 mg/kg). It is lower than that of continental crust [18]. In the exploited soils of Wantia, the mean concentration (50.9 mg/kg) is greater than that of non-exploited soils (24.52 mg/kg) and that of the UCC. The overall mean concentration of Cr recorded in this study is lower than that of pahimi *et al.* [30] and Arthin *et al.* [29].

The concentrations of Cd in the exploited soils of Fel ranging from 0.21 to 0.66 mg/kg are lower than those of non-exploited soils (0.42 - 0.52 mg/kg). On the other hand, they are higher in exploited soils of Wantia (0.37 to 1.23 mg/kg) compared to non-exploited (0.26 to 0.40 mg/kg). It is observed that these results are all higher than those of UCC (0.1 mg/kg). But only exploited soils of Wantia have concentrations higher than those obtained by Bamba *et al.* [7]. The results are also lower than that of Pahimi *et al.* [30]; Arthin *et al.* [29] and Hailin *et al.* [31]. The low contents of Cd in the exploited soils of Fel, compared to Wantia would be explained by the fact that these soils have very low OM content. Indeed Cd is very often associated with colloids in soils. On the other hand, the high values of Cd recorded in exploited soil of Wantia mainly come from the batteries used for lighting and thrown in the environment.

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Cu contents in exploited soils of Fel (6.17 to 14.25 mg/kg) are lower than those of non-exploited soils (20.25 to 24.33 mg/kg). However, the exploited soils of Wantia display values (7.09 to 19.86 mg/kg) similar to those of non-exploited (7.26 to 18.70 mg/kg). In the exploited site of Fel like that of Wantia, these values are below the UCC values and the reference values used [7] [29] [30]. The reduction in Cu in the exploited soils of Fel could be explained by a possible migration of this element towards the subjacent horizons of the soil. The high contents in non-exploited soils of Wantia would be related to the high percentage of OM. In fact, in the soils, copper is well distributed along the profile and is fixed preferentially on the organic matter. This is confirmed by a positive and significant correlation between OM and Cu.

The average contents of Nikel in the exploited soils of Fel as well as that of Wantia are lower than those of non-exploited ones. All these values are lower than the UCC values and the values recorded by Bamba *et al.* [7] (5.5 to 84 mg/kg). The low Ni content is due to the fact that these soils have weak OM content. The high percentages of Ni in non-exploited soils can be explained by the strong correlation existing between Ni and OM in the non-exploited soils of Fel (0.94) and Wantia (0.93); nickel being mainly related to OM in the surface horizons because of its strong propensity to bind to the organic matter [33].

In the exploited soils of Fel like those of Wantia, Pb concentrations are higher than those of the non-exploited soils and also than those of the UCC in some samples. They are however lower compared to some contents obtained by Bamba *et al.* [7] and Pahimi *et al.* [30]. The presence of Pb in the studied area would be explained by the atmospheric inputs resulting from the mining activities. In fact, the accumulation of Pb from atmospheric deposits or from wastes deposited on soil is done mainly in the surface horizons [34] and especially in the horizons rich in organic matter. The high percentages of Pb in the exploited sites of Fel and Wantia compared to the non-exploited ones could be the result of the impact of mining residues from abandoned mines. It could also be explained by the use of fuel in motor-driven pumps for the draining of the flooded mining wells.

Antimony is the most enriched element in the studied area. Its average concentration in the exploited soils of Fel (4.6 mg/kg) is close to that of the non-exploited soils (4.9 mg/kg). On the other hand, in the exploited soils of Wantia, the average concentrations (7.87 mg/kg) are higher than those of non-exploited soils (4.4 mg/kg). The values in one or other exploited sites are all largely higher than the UCC recommended values. They are also, higher than that of Arthin *et al.* [29] and Hailin *et al.* [31]. This could be explained by the gold bearing context of mineralization of the studied zone. Indeed, antimony is generally associated with gold in the sulphides [35] and can also come from the combustion of fuels used by the motor-driven pumps. Moreover, the positive and significant correlation between Sb and As would be an indication that these elements are probably from a common source; in the non-exploited soils of Wantia, the correlation is perfect. Antimony, just as arsenic would thus be associated with gold and would be released in the soils by oxidation processes, from where strong enrichment in this element is observed in the various sites.

The Zn contents in the exploited soils of Fel (7.2 - 22.5 mg/kg) are lower than those of the non-exploited ones (30.0 - 38.1 mg/kg). The higher contents in the non-exploited soils can be explained by the positive and significant correlation between Zn and OM (0.89); OM content being higher in the non-exploited soils. The reduction of Zn in the exploited soils could be explained by the fact that zinc is very mobile and can migrate easily in depth [36]. In the exploited soils of Wantia, these contents (10.8 - 39.8 mg/kg) are higher than those of the non-exploited (12.1 - 31.8 mg/kg). They are lower than those of the UCC (52 mg/kg) and than those of Pahimi *et al*. [7] and Arthin *et al*. [29]. The higher Zn contents in the non-exploited soils would come from the worn-out batteries abandoned on the site.

Generally, the highest metal contents are found in the exploited soils of Wantia since the activity of gold exploitation is more intense than in Fel. The site of Fel has been abandoned for several years and part of heavy metals would have been washed, therefore pulled by abundant rainfall in the area. The river Fel which flows nearby would certainly receives part of this surface flow rich in metals and could, in turn be contaminated.

3.3. Estimation of Soils Contamination Intensity of Kombo-Laka

3.3.1. Enrichment Factor

Calculating enrichment factor (EF) is an essential part of geochemical studies in distinguishing heavy metals that originated from human activities and those from natural weathering [37]. **Table 3** and **Table 4** present EF values of the investigated metals. The results revealed no enrichment for Ni and Zn in all sites. EFs for Cr and Cu vary from no enrichment to minor in all sites; Cd displays an EF varying from no enrichment to moderate. Meanwhile, Pb indicates no enrichment for the study except for non-exploited soils of Wantia where it was severe. Higher EF values are observed for As and Sb. The EF for these elements varies from minor to moderately severe and severe to very severe respectively, reiterating the close association between contamination of these soils in As and Sb with gold mineralization.

3.3.2. Geoaccumulation Index

Commonly, I_{geo} index is employed in order to determine and define metal contamination in sediments by comparing current concentrations with background levels [38]. Calculated I_{geo} index for heavy metal concentrations in Fel and Wantia soils ranged from −4.28 to 5.39 (**Table 5** and **Table 6**), suggesting pollution in some sampling locations. Based on this scale, the soils were unpolluted in Ni, Pb and Zn. The I_{geo} for Cr and Cu in some stations was found to be unpolluted to moderately polluted in classification in exploited soils of Wantia and non-exploited soils of Fel respectively. Cd displayed an I_{geo} varying from unpolluted to strongly polluted while As and Sb exhibited I_{geo} index from moderately to strongly polluted and from moderately to extremely polluted respectively.

Table 3. Enrichment factor of exploited soils of Fel and Wantia.

ID	EF As	EF Cr	EF Cd	EF Cu	EF Ni	EF Pb	EF Sb	EF Zn
FE1	8.9	0.65	4.701	1.12	0.27	1.06	13.16	0.32
FE2	3.69	0.76	4.717	0.56	0.21	1.02	11.67	0.19
FE3	9.88	0.82	4.522	1.17	0.26	0.98	14.35	0.27
FE4	10.01	0.94	4.908	1.32	0.34	1.15	15.81	0.31
FE5	9.03	1.19	4.725	1.28	0.51	1.05	18.64	0.54
FE6	7.97	1.14	4.647	1.19	0.35	1.17	17.16	0.33
FE7	9.72	0.58	5.614	1.48	0.21	3.42	19.67	0.49
FE8	2.63	0.66	4.156	0.58	0.18	0.91	11.31	0.17
FE9	3.87	0.52	4.013	0.53	0.12	0.71	14.03	0.15
FE10	3.4	0.61	3.953	0.55	0.13	0.71	11.78	0.14
FE11	9.45	0.8	4.955	0.98	0.14	1.15	24.67	0.24
FE12	8.95	0.58	4.229	1.09	0.13	0.89	19.58	0.27
WE1	9.7	0.95	0.37	0.79	0.26	1.01	17.63	0.37
WE2	7.73	1.84	0.43	0.55	0.16	0.58	24.43	0.3
WE3	7.62	1.93	0.38	0.54	0.17	0.63	27.83	0.29
WE4	6.05	0.62	0.37	0.84	0.3	0.81	12.72	0.23
WE5	7.58	0.71	0.38	0.58	0.36	1.06	13.11	0.29
WE6	6.81	0.73	0.38	0.78	0.18	0.9	15.99	0.26
WE7	5.66	0.41	0.38	0.78	0.2	1.01	13.5	0.22
WE8	5.65	0.69	0.37	0.67	0.29	0.86	15.07	0.22
WE9	6.56	0.46	0.36	0.62	0.19	1	12.32	0.25
WE10	6.13	0.51	0.39	0.57	0.23	0.89	13.81	0.24

Table 4. Enrichment factor of non-exploited soils of Fel and Wantia.

ID	EF As	EF Cr	EF Cd	EF Cu	EF Ni	EF Pb	EF Sb	EF Zn
FT1	10.09	0.73	0.014	1.6	0.68	0.89	15.21	0.7
FT2	9.36	0.7	0.012	1.39	0.52	0.83	15.29	0.54
FT3	9.94	0.76	0.013	1.35	0.52	0.85	15.38	0.54
FT4	10.45	0.76	0.014	1.65	0.69	0.93	16.59	0.72
FT5	10.56	0.76	0.014	1.96	0.82	1.01	16.38	0.81
WT1	8.89	0.67	4.7	0.03	0.64	11.05	17.35	0.72
WT2	7.02	0.7	3.86	0.03	0.48	9.83	14.83	0.47
WT3	8.77	1.12	47	0.03	0.49	13.57	21.65	0.62
WT4	7.84	1.6	5.33	0.04	0.29	18.03	26.89	0.48

3.3.3. Relationships between Heavy Metals in Exploited and Non-Exploited Soils of Fel and Wantia

Pearson's correlation coefficients (r) were calculated using XLSTAT software (Addinsoft 2013) to examine correlation ($p < 0.05$) between metal concentrations in different

Table 5. Geoaccumulation Index of exploited soils of Fel and Wantia.

ID	I_{geo} As	I_{geo} Cr	I_{geo} Cd	I_{geo} Cu	I_{geo} Ni	I_{geo} Pb	I_{geo} Sb	I_{geo} Zn
FE1	2.03	−1.76	1.10	−0.97	−3.03	−2.87	2.81	−2.77
FE2	0.95	−1.33	1.30	−1.77	−3.20	−3.04	2.83	−3.32
FE3	2.26	−1.32	1.13	−0.82	−3.01	−2.85	3.02	−2.95
FE4	2.08	−1.34	1.05	−0.84	−2.82	−2.66	2.95	−2.92
FE5	2.26	−0.67	1.32	−0.56	−1.89	−1.73	3.52	−1.79
FE6	1.60	−1.21	0.83	−1.13	−2.90	−2.74	2.93	−2.97
FE7	1.26	−2.82	0.47	−1.46	−4.28	−4.12	2.49	−3.06
FE8	1.13	−0.87	1.79	−1.06	−2.77	−2.61	3.45	−2.85
FE9	1.94	−0.95	2.13	−0.92	−3.03	−2.87	4.02	−2.75
FE10	1.91	−0.56	0.92	−0.71	−2.75	−2.59	3.92	−2.65
FE11	1.85	−1.71	1.16	−1.42	−4.28	−4.12	3.45	−3.43
FE12	2.24	−1.72	1.34	−0.79	−3.87	−3.71	3.59	−2.83
WE1	3.98	−0.16	1.94	−0.42	−2.00	−0.06	4.06	−1.50
WE2	3.48	1.66	3.04	−0.08	−1.91	−0.02	5.39	−0.97
WE3	3.19	1.49	2.62	−0.35	−1.98	−0.13	5.34	−1.23
WE4	2.28	−1.18	1.53	−0.74	−2.24	−0.78	3.19	−2.58
WE5	1.92	−1.27	1.30	−1.57	−2.25	−0.69	2.94	−2.55
WE6	2.97	−0.95	1.58	−0.84	−2.94	−0.64	3.51	−2.43
WE7	3.01	−1.46	1.88	−0.54	−2.53	−0.16	3.58	−2.38
WE8	1.95	−1.17	1.38	−1.23	−2.42	−0.87	3.27	−2.85
WE9	2.2	−1.74	1.38	−1.31	−2.97	−0.61	3.01	−2.60
WE10	1.99	−1.51	1.55	−1.36	−2.68	−0.71	3.25	−2.62

Table 6. Geoaccumulation index of non-exploited soils of Fel and Wantia.

ID	I_{geo} As	I_{geo} Cr	I_{geo} Cd	I_{geo} Cu	I_{geo} Ni	I_{geo} Pb	I_{geo} Sb	I_{geo} Zn
FT1	2.81	−0.99	1.78	0.15	−1.09	−0.69	3.40	−1.03
FT2	2.80	−0.93	1.62	0.05	−1.36	−0.70	3.51	−1.31
FT3	2.83	−0.88	1.67	−0.05	−1.42	−0.72	3.46	−1.38
FT4	2.69	−1.09	1.62	0.03	−1.23	−0.79	3.36	−1.16
FT5	2.64	−1.15	1.49	0.21	−1.04	−0.74	3.28	−1.07
WT1	2.34	−1.39	1.42	−0.17	−1.55	−0.67	3.30	−1.30
WT2	2.18	−1.14	1.32	−0.37	−1.79	−0.65	3.26	−1.71
WT3	2.03	−0.94	1.13	−0.82	−2.22	−0.67	3.33	−1.80
WT4	1.33	−0.96	0.77	−1.53	−3.53	−0.79	3.11	−2.69

sampling locations (**Tables 7-10**). Pearson's correlation matrix has proven to be useful in offering reliable classification of the metals and physicochemical properties of soils and sediments. This approach has been used widely in the classification of sites under investigation in geochemical and water quality analysis [39]-[41].

Table 7. Pearson correlation matrix between the physico-chemical parameters and heavy metals from exploited soils of Wantia.

	Fe	As	Cr	Cd	Cu	Ni	Pb	Sb	Zn	pH	EC	OM
Fe	**1**											
As	0.60	**1**										
Cr	**0.97**	0.50	**1**									
Cd	**0.99**	0.57	**0.96**	**1**								
Cu	**0.89**	**0.79**	**0.79**	**0.87**	**1**							
Ni	**0.71**	0.58	**0.73**	0.69	0.69	**1**						
Pb	**0.81**	**0.85**	**0.70**	**0.78**	**0.87**	0.63	**1**					
Sb	**0.98**	0.55	**0.99**	**0.96**	**0.82**	**0.71**	**0.74**	**1**				
Zn	**0.95**	**0.74**	**0.94**	**0.94**	**0.87**	**0.79**	**0.85**	**0.94**	**1**			
pH	−0.26	−0.29	−0.33	−0.17	−0.18	**−0.50**	−0.36	−0.36	−0.37	**1**		
EC	−0.01	0.54	−0.04	−0.03	0.12	0.39	0.39	−0.03	0.21	−0.48	**1**	
OM	−0.11	−0.2	−0.22	−0.06	−0.10	−0.41	−0.08	−0.18	−0.25	0.52	−0.22	**1**

Table 8. Pearson correlation matrix between the physico-chemical parameters and heavy metals from non-exploited soils of Wantia.

	Fe	As	Cr	Cd	Cu	Ni	Pb	Sb	Zn	pH	EC	OM
Fe	**1**											
As	0.67	**1**										
Cr	−0.66	−0.36	**1**									
Cd	**0.92**	**0.77**	**−0.83**	**1**								
Cu	**0.90**	**0.71**	**−0.87**	**0.99**	**1**							
Ni	**0.90**	**0.78**	**−0.83**	**0.99**	**0.99**	**1**						
Pb	**0.88**	**0.93**	−0.45	**0.87**	**0.82**	**0.87**	**1**					
Sb	0.65	**1.00**	−0.35	**0.76**	**0.70**	**0.77**	**0.92**	**1**				
Zn	**0.79**	**0.82**	**−0.82**	**0.96**	**0.95**	**0.97**	**0.82**	**0.82**	**1**			
pH	**0.85**	**0.95**	−0.55	**0.91**	**0.87**	**0.91**	**0.98**	**0.95**	**0.90**	**1**		
EC	0.65	**0.83**	**−0.76**	**0.89**	**0.88**	**0.90**	**0.76**	**0.83**	**0.97**	**0.87**	**1**	
OM	**0.99**	**0.72**	**−0.72**	**0.96**	**0.95**	**0.95**	**0.89**	**0.70**	**0.86**	**0.89**	**0.74**	**1**

As many elements are inter correlated, only correlation coefficients above 0.70 have been considered throughout this work and the correlations will be described as very strong with $r \geq 0.90$) and strong with $0.70 \leq r < 0.90$.

In the exploited soils of Wantia, strong to very strong positive correlations have been observed for Fe with Cr, Cd, Cu, Ni, Pb, Sb and Zn (with r ranging from 0.71 to 0.99); for Cr with Cd, Cu, Ni, Pb, Sb and Zn (0.70 - 0.99); for Cd with Cu, Pb, Sb and Zn (0.78 - 0.96) and between Sb and Zn (0.95). Strong positive correlations were also noticed for As with Cu, Pb and Zn (0.74 - 0.85); for Cu with Pb, Sb and Zn (0.82 - 0.87); for Ni with Sb and Zn (0.71 and 0.79); and for Pb with Sb and Zn (0.74 - 0.85).

Table 9. Pearson correlation matrix between the physico-chemical parameters and heavy metals from exploited soils of Fel.

	Fe	As	Cr	Cd	Cu	Ni	Pb	Sb	Zn	pH	EC	OM
Fe	**1**											
As	0.01	**1**										
Cr	**0.76**	0.15	**1**									
Cd	**0.99**	0.002	**0.78**	**1**								
Cu	0.39	**0.80**	0.58	0.38	**1**							
Ni	0.28	0.30	**0.77**	0.32	0.65	**1**						
Pb	0.50	−0.44	0.21	0.50	−0.03	0.007	**1**					
Sb	**0.84**	0.30	0.66	**0.82**	0.49	0.20	0.28	**1**				
Zn	0.19	0.48	0.57	0.22	**0.74**	**0.86**	0.09	0.31	**1**			
pH	0.06	0.63	0.16	0.07	0.68	0.39	−0.09	0.14	0.43	**1**		
EC	−0.55	0.22	−0.25	−0.52	0.06	0.31	−0.44	−0.55	0.39	0.13	**1**	
OM	**0.70**	−0.35	0.45	**0.74**	−0.06	0.06	0.53	0.56	−0.01	0.07	−0.43	**1**

Table 10. Pearson correlation matrix between the physico-chemical parameters and heavy metals from non-exploited soils of Fel.

	Fe	As	Cr	Cd	Cu	Ni	Pb	Sb	Zn	pH	EC	OM
Fe	**1**											
As	**0.93**	**1**										
Cr	**0.93**	**0.96**	**1**									
Cd	0.56	**0.75**	0.56	**1**								
Cu	−0.54	−0.57	**−0.70**	−0.26	**1**							
Ni	−0.69	−0.62	**−0.78**	−0.13	**0.93**	**1**						
Pb	**0.74**	**0.71**	0.64	0.46	0.08	−0.11	**1**					
Sb	**0.96**	**0.86**	**0.90**	0.44	−0.68	**−0.83**	0.54	**1**				
Zn	−0.62	−0.54	**−0.74**	0.04	**0.87**	**0.97**	−0.12	**−0.75**	**1**			
pH	−0.61	−0.56	−0.36	−0.68	−0.20	−0.08	**−0.72**	−0.47	−0.21	**1**		
EC	−0.58	**−0.79**	**−0.73**	**−0.70**	0.31	0.26	−0.66	−0.40	0.24	0.31	**1**	
OM	**−0.87**	**−0.84**	**−0.93**	−0.39	**0.87**	**0.94**	−0.38	**−0.93**	**0.89**	0.18	0.50	**1**

In the exploited soils of Fel, very strong positive correlation (r = 0.99) has been recorded between Fe and Cd while strong correlation was noticed for Fe with Cr, Sb and OM (0.70 - 0.84); for As and Cu (0.80); for Cr with Cd and Ni (0.77 - 0.78); for Cd with Sb and OM (0.74 - 0.82); between Cu and Zn (0.74) and Ni and Zn (0.86).

In non-exploited soils of Wantia, a perfect correlation has been recorded between As and Sb (r = 1.00); meanwhile, Fe displayed strong to very strong positive correlations with Zn, pH, Pb, Cu, Ni, Cd and OM (0.79 - 0.99); the same correlations have been noticed for As with Cd, Cu, Ni, Pb, Zn, pH, EC and OM (0.72 - 0.95); for Cd with Sb, Pb, EC, pH, OM, Zn, Ni and Cu (0.76 - 0.99); for Cu with Sb, Pb, pH, EC, OM, Zn and Ni

(0.70 - 0.99); for Ni with Sb, Pb, EC, pH, OM and Zn (0.77 - 0.97); for Pb with EC, Zn, OM, Sb and pH (0.76 - 0.98); for Sb with OM, Zn, EC and pH (0.70 - 0.95) and for Zn with OM, pH and EC (0.86 - 0.97). Strong positive correlations were also recorded for pH with EC and OM (0.87 and 0.89) and for EC and OM (0.74). Contrary to others parameters, Cr displayed strong negative correlations with OM, EC, Zn, Ni, Cd and Cu (−0.72 to −0.87).

In non-exploited soils of Fel, strong to very strong positive correlations were recorded for Fe with Pb, As, Cr and Sb (0.74 - 0.96); for As with Pb, Cd, Sb and Cr (0.71 - 0.96); for Cr and Sb (0.90); for Cu with OM, Zn and Ni (0.87 - 0.93); for Ni with Zn and OM (0.94 - 0.97) and strong positive correlation was noticed between Zn and OM (0.89). However, very strong negative correlations were shown by OM with Cr and Sb (−0.93) while strong negative correlations were observed between As with EC and OM (−0.79 and −0.84); Cr with Cu, Ni, Zn and EC (−0.70 to −0.78); OM and Fe (−0.87); EC and Cd (−0.70); Ni and Sb (−0.83); Pb and pH (−0.72); Sb and Zn (−0.75).

In this study, Pearson's correlation highlighted the high bond between As and Sb in the studied area confirming the association of these elements in gold mineralization areas.

The positive correlation among elements may reflect similarity in their occurrences or geochemical processes that contribute or control their behavior in soils. The study revealed a high affinity between iron and other elements in all sites. It is well established that organic matter and Fe oxide contents are important controlling factors in the abundance of trace metals [42]-[44]. Based on the correlation matrix obtained for surface soils, iron oxide is the dominant factor controlling trace metal distribution in the studied area.

Iron is sensitive to changes of redox, which strongly affects its mobility, and Fe with its oxyhydroxides has a high affinity for trace metals, resulting in the movement of some metals with Fe in the sediments or soils [42].

The elements were more inter correlated in non-exploited soils than in the exploited ones, this could be explained by possible pollution due to some anthropogenic activities in the areas because when pollution occurred, the concentration of pollutants could not be in correlation with other trace element concentrations due to the relative high input of these pollutants [41].

4. Conclusion

The purpose of this study was to assess the impact of traditional gold mining activities in Kombo-Laka soils. To achieve the assessment, direct observation and soils sampling for the determination of pollution level of some selected metals (As, Cr, Cd, Fe, Ni, Pb, Sb, and Zn) were conducted. It has been noticed that traditional mining has harmful effects on soils. The activity has an impact not only on the esthetic aspects of the locality landscape, but also on the quality of soil. The results of metals analysis have indicated that soils of Kombo-Laka have high EF values for Cd, As and Sb that vary from minor to very severe contamination, revealing anthropogenic sources. This was supported by

I_{geo} ranging from moderately to extremely polluted. The high inter correlation displayed by elements in this work confirm their common origin, especially for As and Sb in gold mineralization areas. The present study showed preliminary but still relevant information regarding the pollution status of artisanal gold exploitation on soils.

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