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ORIGINAL ARTICLE **OPEN ACCESS**

Modeling anthropogenic pollution of soils used in market gardening in Daloa (Côte d'Ivoire) by heavy metals

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ABSTRACT

The increase in the population observed in the sub-Saharan countries leads to an increase in the discharge flows, which generally contain significant quantities of heavy metals. These metals accumulate in soils over the long term, particularly in the urban and peri-urban lowlands where most of the fresh vegetables found in the markets of African cities are produced. This research aims to predict the degree of pollution by heavy metals of these soils. It is based on the combined use of the Analytical Hierarchy Process (AHP) and the Geographical Information System (GIS) to extract and structure criteria, cross layers of information and spatially analyze the different themes. This process has shown its relevance for prioritizing the criteria and evaluating the soils studied. It has been found that heavy metals are released into the environment through the various informal uses of soils and then transported by runoff to valley bottoms as a result of the slope of the soil. The study thus made it possible to better understand the process of contamination of the studied soils and can thus be used by the municipal authorities to put in place measures of control of the informal activities carried out near the plains soils in general.

Keywords: *Heavy metals, Analytic Hierarchy Process, Geographic Information System, pollution, soil.*

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INTRODUCTION

In developing countries, particularly in sub-Saharan Africa, market gardening plays an important role in the food security of urban populations. Indeed, the supply of cities with fresh products is one of the assets of this agriculture [1]. However, because of their proximity to habitats and urban activity sites, soils used in gardening are exposed to pollutions of various origins (fertilizers, pesticides, nature, etc.) that discharge there significant quantities of heavy metals [2]. Thus, the study conducted by [3] that revealed high levels of zinc and iron in some of these soils in Daloa, raises the interest of evaluating all the soils used in market gardening in this city with respect to heavy metals in general. This research is part of this process. It aims to determine not only the anthropogenic origins of the heavy metals pollution of the soils used in market gardening in Daloa, but also the mechanism of this pollution. From this general objective, three specific objectives have been defined. They aim to: i) build a multiform database with spatial reference on the studied soils; ii) map these soils; and (iii) modeling the mechanism of their anthropogenic pollution by heavy metals.

MATERIAL AND METHODS

Description of the Study Site

The perimeter of the study, namely, the city of Daloa covers an area of 54.33 km². This space is located in the center-west part of Côte d'Ivoire; it is delimited by the western longitudes 6.48° and 6.41° and the latitudes north 6.91° and 6.84° (figure 1). The climatic regime of the Haut-Sassandra region, of which Daloa is the chief town, is that of the Guinean domain characterized by an equatorial and subequatorial regime with two maximum rainfall [4]. The relief is little contrasted, little varied and dominated by plateaus of 200 to 400 m of altitude [5]. The geological formations that cover the Haut-Sassandra administrative region date from the Middle Precambrian. These formations are dominated by granites. The soils of the zone are generally ferralitic moderately leached on firm, sandy, hydromorphic soils on river terraces [6]. These sandy soils sometimes have large areas and are more or less usable according to their texture, their chemical richness and their possibility of irrigation or drainage [6]. In Daloa, they are found in all areas of the city, where they are regularly used in market gardening [3].

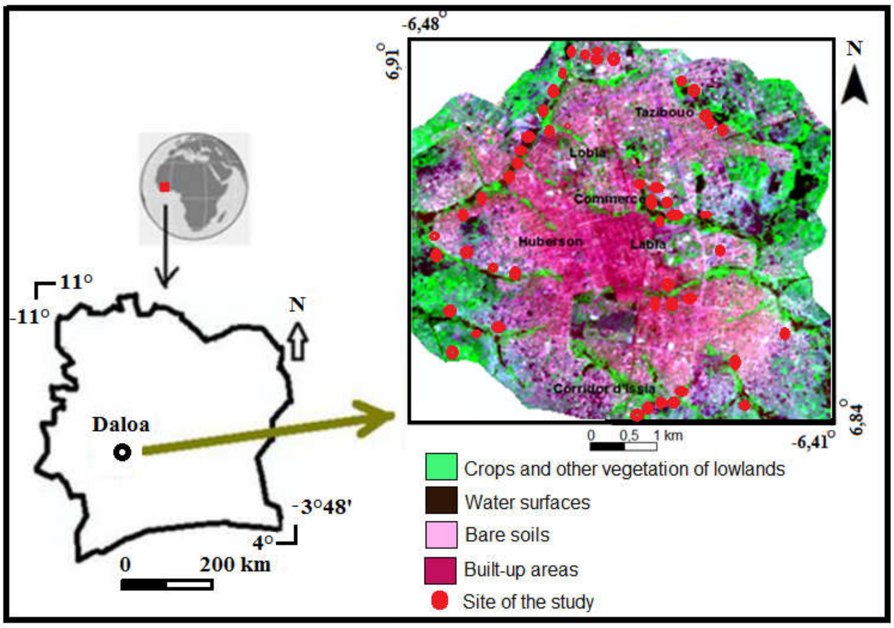

FIGURE 1: LOCATION MAP OF THE STUDY AREA AND SITES

Prediction of the degree of soil pollution

Choice of criteria

The criteria selected for this study are: the altitude and the slope of the land, as well as the density and diversity of informal land uses around market garden sites. The choice of these criteria is based on the assumption that the informal activities that abound in the vicinity of market gardening sites, beyond the control of the municipal authorities, are potential sources of heavy metals discharges into the soil. In addition, because of their location in the valley bottoms, soils used in market gardening are natural receptacles for waste of any kind that are driven by vertical transfers or flows due to the slope of the land.

Extraction, structuring and classification of criteria

Using the ArcMap function of the ArcGIS 9.3 software, the elevations of the study area were extracted by digitizing the curves of the topographic map, which is at a scale of 1/25000 [7]. During this process, each curve has been assigned an attribute value that corresponds to its elevation. A vector file of altitudes was thus obtained. From this file, the digital elevation model (DEM) of the study area was realized after discretization of the curves in points-sides, and interpolation of these points by the method of the "nearest neighbor". The slope layer of the terrain was then extracted from the DEM.

With regard to informal land use, the aim was to identify them during several field visits and to position them on the map of the study area. From the cloud of points thus formed, the diversity layer of the informal uses was carried out by interpolation of the numbers of the types of uses recorded on the various sites visited. Then, the density layer of these uses was obtained by automatically calculating, using the ''Kernel Density'' tool of the ArcGIS software, the density of the points of use in their neighborhood [8, 9].

The evaluation criteria being extracted and structured, it was finally decided to classify them in order to specify the capacity of each class to predispose the soil to pollution by heavy metals. This classification was established on a continuous scale of competencies ranging from 0 (the least adapted) to 3 (the most adapted) (Table 1).

TABLE 1: CATEGORIZATION OF CRITERIA

Criteria	Values	Degree of aptitude	Interpretations
Diversity of informal uses	= 4	4	High diversity, source of important releases of heavy metals
	= 3	3	Moderately high diversity, source of moderate releases of heavy metals
	= 2	2	Low diversity, source of low releases of heavy metals
	= 1	1	No diversity, no releases of heavy metals
Density of informal uses (per 500 m^2)	≥ 4	3	High density, source of important releases of heavy metals
	[4 ; 2]	2	Moderate density, source of moderate releases of heavy metals
	[2 ; 1]	1	Low density, source of low releases of heavy metals
	[1 ; 0]	0	No informal uses, no release of heavy metals
Soil altitudes (m)	≥ 275	1	Summit, unfavorable to the accumulation of heavy metals
	[275 ; 260]	0	Top area of slopes, place of transit of the transported materials, very unfavorable to the accumulation of heavy metals
	[260 ; 245]	2	Low area of slopes, favorable to the accumulation of heavy metals
	[245 ; 230]	3	Bottom of valleys, receptacle of the transported materials, very favorable to the accumulation of heavy metals
Slope of soils (%)	[21 ; 6]	0	High slopes, very unfavorable to an accumulation of heavy metals
	]6 ; 4]	1	Moderate slopes, unfavorable to heavy metal accumulation
	]4 ; 2]	2	Low slopes, favorable for accumulation of heavy metals
	]2 ; 0]	3	Very low slopes, very favorable for the accumulation of heavy metals

Weighting of criteria

The weighting of the criteria was carried out using the Analytic Hierarchy Process (AHP) method developed by Saaty [10]. This method compares the different elements of a hierarchical level in order to determine they importance or contribution to solving a problem according to a predefined scale of values (Table 2). This leads to a pairwise criterion comparison matrix. Once the comparison matrix has been obtained, its eigenvalue and the corresponding eigenvector are determined. The eigenvector indicates the hierarchy of the studied characteristics whereas the eigenvalue makes it possible to evaluate the coherence of this hierarchy.

TABLE 2: SCALE OF COMPARISON OF CRITERIA DEFINED BY SAATY [10]

Degree of importance	Explication
1	Equal importance: two characteristics contribute in the same way
3	Low importance: the personal experience and appreciation slightly favor one characteristic over another
5	Critical importance: the experience and appreciation highly favor one characteristic over another
7	Evidenced importance: a characteristic is highly favored and its dominance is attested in practice
9	Absolute importance: Evidences favoring one characteristic over another are as convincing as possible
2, 4, 6, 8	Values associated to judgments when a compromise is needed

Verification of the consistency of the comparison

The coherence index (CI) defined by Saaty [10] is calculated by the formula of equation 1. This index measures the reliability of the comparison: the lower its value, the more the judgments expressed in the comparison matrix are contradictory and vice versa. Similarly, the coherence ratio (CR) calculated by the formula 2 measures the logical coherence of the judgments: if CR is greater than 0.1, there is inconsistency in the matched comparisons and therefore the resulting matrix comparisons will have to be reevaluated [10]

$$CI = \frac{(\lambda max - N)}{(N-1)} \qquad \text{(Eq. 1)}$$

With N the number of elements compared and λmax, a value calculated on the basis of the average of the eigenvalues of the Saaty matrix (Table 3).

$$CR = \frac{CI}{RI} \qquad \text{(Eq. 2)}$$

Where RI is the random index set according to the number of criteria. Here, this number being equal to 4, IA has 0.9 as value.

TABLE 3: VALUES OF THE RANDOM INDICES [10]

N	1	2	3	**4**	5	6	7	8	9	10	11	12	13	14	15
RI	0	0	0.58	**0.9**	1.12	1.24	1.32	1.41	1.45	1.49	1.51	1.48	1.56	1.57	1.59

2.2.5. Criteria aggregation

The technique used to combine the different criteria to synthesize a composite decision over the entire study area is a multicriteria analysis also called aggregation of criteria [10]. This method multiplies, according to equation 3, each factor layer by its respective weighting coefficient and adds the results to produce an index for each pixel [11].

$$V_i = \sum_{i=1}^{n} aij * wj \qquad \text{(Eq. 3)}$$

With:

- aij = ai / aj;
- ai and aj are the weights that evaluate the relative importance of the criteria;
- wj: the weight of each criterion;
- Vi: synthesis index.

Verification of predictions

The prediction check consisted of determining the soil content of certain heavy metals. In addition, earthworms being the most sensitive animal species to heavy metals compared to other soil invertebrates [12], their abundance in soil was also determined according the potential degree of soil pollution.

In practice, five soil profiles, wide and long, one meter each, were opened for each soil class in six sites regularly used for market gardening. The maximum depth of these profiles was 1.2 m. In each of them, a soil sample was collected in the topsoil, between 0 and 40 cm deep, for the determination of soil pH and heavy metal contents (cadmium, copper, lead and zinc) using respectively electrometric and atomic absorption spectrometric methods [13, 14]. The soil variables thus determined were subjected to an analysis of variance using the non-parametric Kruskal-Wallis test at the 5% significance level. To do this, the Statistica 7.0 software (Statsoft, Tulsa, USA) was used. The earthworms were extracted from each soil profile by direct manual sorting of the soil stratum studied (0-40 cm). The collected specimens were stored in boxes containing 4% of diluted formaldehyde and transported to the Lamto Ecological Station for they identification using [15] and [16] keys.

RESULTS

Layers of soil pollution factors

Layers of altitudes and slopes of soils

Figure 2.A shows the digital elevation model (DEM) as well as the slope layer of the study area. On the DEM, we can see that the highest soils (≥275 m), which do not favor the accumulation of heavy metals, occupy the South-West-North axis of the study area. From this axis, the altitudes of the soils decrease progressively, on the one hand, towards the east, and on the other hand, towards the west, reaching 230 to 245 m, which constitute the class of the soils of the valleys very favorable to the accumulation of heavy metals.

For soil slopes, the values obtained vary from 0 to 27% (Figure 2.B): the lowest slopes (0 to 2%) potentially very favorable to the accumulation of heavy metal fluxes characterize the zones generally located on the periphery of the study area. Areas with slightly higher slopes (2-4%) are potentially favorable for the accumulation of heavy metals in soils; these zones occupy mainly the median axis of the zone. Between the zones occupied by these first two classes, there are, from the periphery within the study area, the slopes that are potentially unfavorable (4 to 6%) and very unfavorable (6 to 27%) to the accumulation of heavy metals in soils.

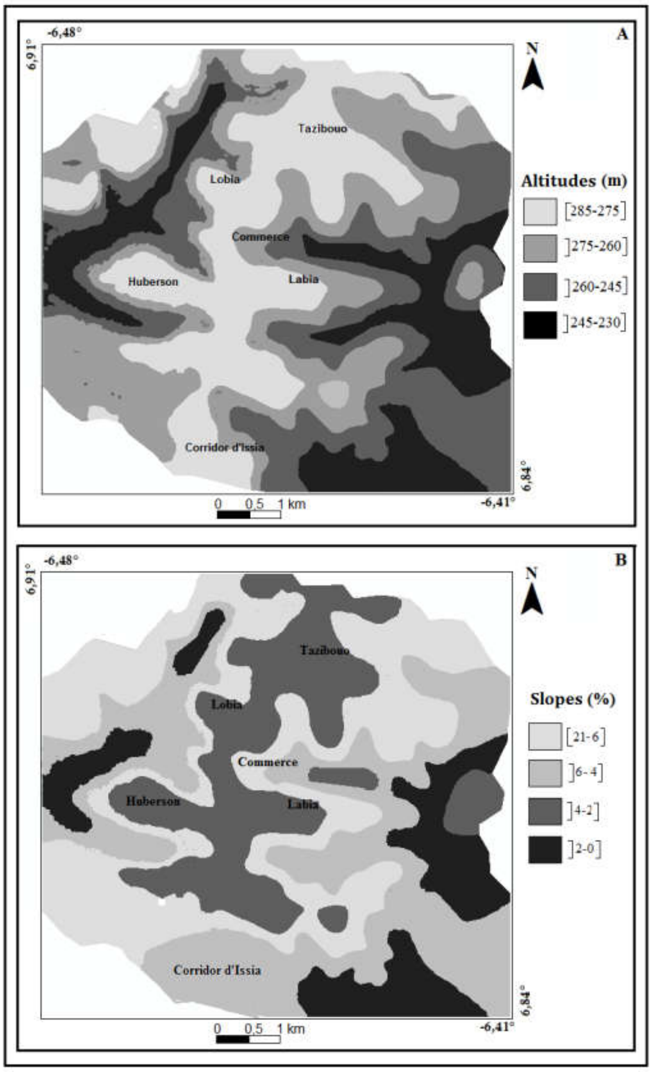

FIGURE 2: DIGITAL TERRAIN MODEL (A) AND SLOPES (B) LAYERS OF THE STUDY AREA.

Layers of types and densities of informal land uses

The types of informal land uses identified in the surrounding areas (0 to 200 m) of the lowlands are diverse. These are mainly livestock pastures, wild garbage dumps, wastewater discharges and various mechanical activities (automobile mechanics, ironwork, etc.). In total, these uses were observed in 260 sites including 76 wastewater discharges, 43 livestock pastures, 77 landfills and 64 mechanical activities.

On the map of Figure 3.A which represents the layer of these uses, it appears that three to four types of identified uses were observed in the north-west sector (Lobia) and especially in downtown (Commerce and Labia). In the northeast (Tazibouo), south (Issia Corridor), west (Huberson) and a few areas of downtown (Labia), there were two types of uses. Elsewhere, very often garbage dumps have been observed. The land use density layer (Figure 3.B) shows that the districts of Commerce, Lobia and Labia districts where a wide variety of informal land uses have been observed are also the most densely populated areas with these uses: three points of uses were observed there every 500 m^2. However, in the south of the city (Issia Corridor), the densities of the two or three types of uses identified are low. Indeed, one use was observed on average every 500 m^2.

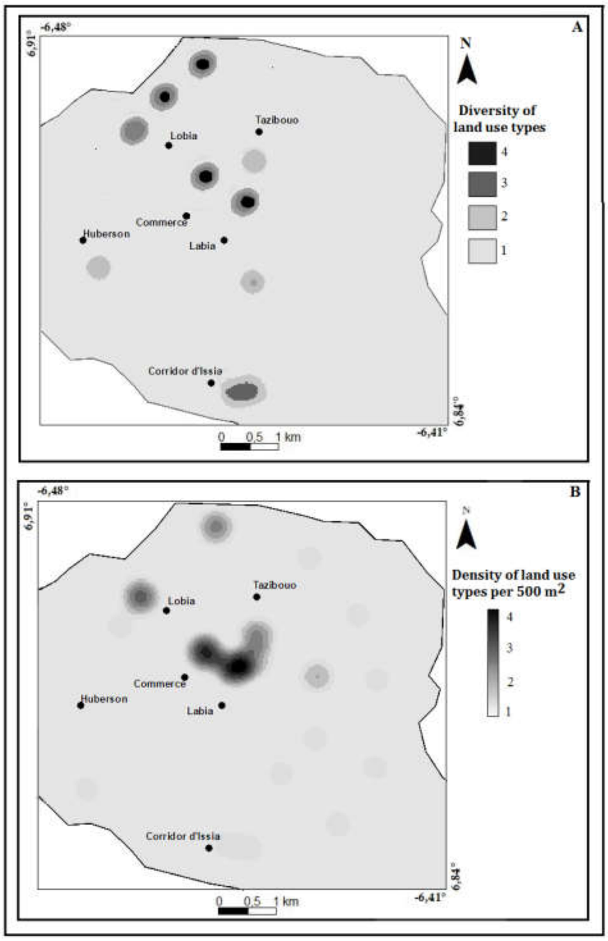

FIGURE 3: LAYERS OF TYPES (A) AND DENSITIES (B) OF INFORMAL LAND USES IN AREAS SURROUNDING THE LOWLANDS.

Potential levels of soil pollution by heavy metals

Table 2 summarizes the judgment of the soil assessment criteria. It should be noted that the consistency ratio (CR) resulting from pair wise comparisons is 0.04. Since this value is less than 0.10, the basic judgment made is consistent. The aggregation of the different maps of the criteria according to the defined weights made it possible to classify the study area on a scale of 1 to 4, so that the highest pixels correspond to the zones most potentially polluted by heavy metals, and conversely (Figure 4). In summary, it appears that the soils used for market gardening at Commerce, Labia and Lobia are potentially very highly and highly polluted while those used at Corridor Issia and Huberson are potentially slightly and very slightly polluted.

TABLE 4: JUDGMENT MATRIX OF CRITERIA

Criteria	Density of informal uses	Diversity of informal uses	Slope of the ground	Altitude of the ground	**Weight**
Density of informal uses	1	1/2	1/4	1/9	0,06
Diversity of informal uses	2	1	1/3	1/7	0,10
Slopes of the ground	4	3	1	1/5	0,20
Altitudes of the ground	9	7	5	1	0,64
λmax = 4.10		**IC = 0.033**		**RC = 0.04 %**	

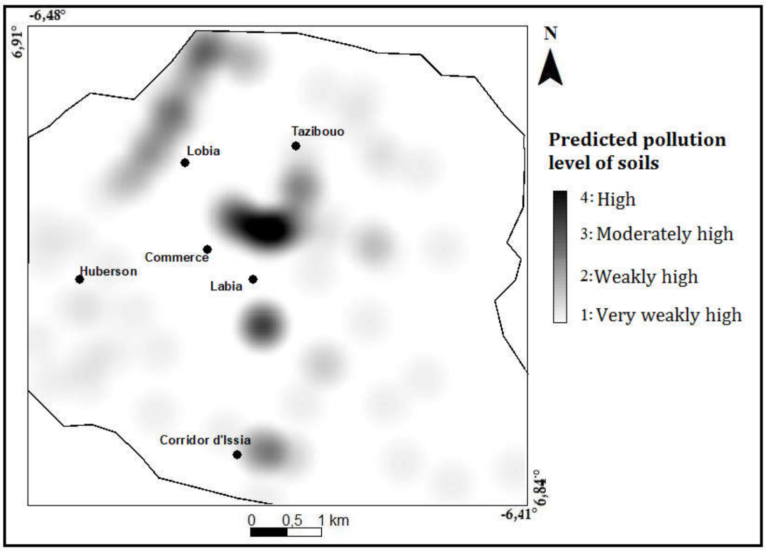

FIGURE 4: MAP OF POTENTIAL LEVELS OF SOIL POLLUTION BY HEAVY METALS.

Properties of soils according to their potential pollution levels by heavy metals

The chemical properties of the soils resulting from the laboratory analyzes are summarized in Table 5. It is noted that the pH values distinguish, on the one hand, highly acidic soils represented by potentially highly and very slightly polluted soils and on the other hand, acid soils represented by potentially moderately high and slightly polluted soils (P <0.05). In addition, the heavy metal content of potentially highly and moderately polluted soils was found to be significantly higher than that of poorly and very slightly polluted soils (P <0.05).

TABLE 5: DIVERSITY PARAMETERS OF SOIL CHEMICAL PROPERTIES ACCORDING TO THEIR POTENTIAL LEVELS OF POLLUTION BY HEAVY METALS

Variables		**Level of pollution predicted**			**Kruskall-Wallis *P***
	High	**Moderately high**	**Weakly high**	**Very weakly high**	
pH	4.9±0.0	6.2±0.1	6.1±0.1	5.3±0.1	0.023
Cadmium (mg.kg-1)	2.35±0.02	2.44±0.04	0.18±0.01	0.11±0.01	0.015
Zinc(mg.kg-1)	310.13±6.8	41.11±2.9	27.23±2.5	27.11±2.2	0.015
Plomb (mg.kg-1)	39.16±1.7	10.14±0,5	9.16±0.75	2.11±0.55	0.016
Cuivre (mg.kg-1)	136.11±8.23	20.12±2.3	12.44±1.8	13.23±1.5	0.014

As shown in Table 6, the earthworm population in the study area is rich in eleven species, seven of which have been observed in potentially very low and slightly polluted soils and four or five species in potentially very or moderately polluted soils. This difference between soils did not appear significant (P> 0.05).

TABLE 6: PRESENCE OF EARTHWORM SPECIES IN THE DIFFERENT SOIL CLASSES

	Worm species	**Levels of soil pollution**			
		Very high	**Moderately high**	**Weakly high**	**Very weakly high**
	Millsonia sp.	+	+	+	+
	Dichogaster baeri			+	
	Dichogaster leroyi				+
	Dichogaster saliens		+		
	Dichogaster papillosa				
	Dichogaster sp.1		+	+	+
	Dichogaster sp.2		+		+
	Agastrodrilus multivesiculatus	+		+	
	Hyperiodrilus africanus			+	+
	Eudrilus eugeniae	+	+	+	+
	Stuhlmannia zielae	+		+	+
Total	11	4	5	7	7

+: Presence

DISCUSSIONS

Multicriteria analysis provides decision makers with tools to solve complex problems when multiple criteria must be considered in a choice of options [17]. In this study, we were particularly interested in the Analytical Hierarchy Process (AHP) [10] to highlight the degree of pollution by heavy metals of soils used regularly in market gardening in Daloa.

The result shows that the most potentially polluted soils are generally located in the low-lying areas of populated areas. This is because these sites are waste sites that contain pollutants measured in soils. This result also shows a correlation between the degree of soil pollution and the topography. If we refer to the defined base weights resulting from the comparison of the matched evaluation criteria, we observe that the hierarchy established in the importance of the criteria has been well reflected in the aggregation result of these criteria. Indeed, thanks to the calculation of the weights, the importance of the topography in the process of accumulation of heavy metals in soils was estimated at 84%, of which 64% for the altitude and 20% for the slope. The weight of the other criteria, namely the diversity and density of informal uses, which determine the sources of production of heavy metals, are in the order of 10% and 6%. Indeed, the approach taken on the basis of the decomposition of a complex system into a hierarchical structure where each level is composed of specific indicators has the advantage of highlighting the indicators that have the greatest impact in the final decision [17]. However, one of his main difficulties remains the choice of factor class boundaries. This choice is generally based, on the one hand, on the judgment of the operator and, on the other hand, on the values of the criteria [18]. The class limits established in this study derive essentially from these two fundamental principles. Thus, if the density and types of land use considered as soil pollutants change significantly near the studied soils, these limits should be reprocessed. In addition, the production of the DEM used has required a lot of digitization work, so that the method applied can be very difficult to reproduce in morphologically heterogeneous or spatially very large areas.

When verifying predictions, there was a significant reduction in the density and biomass of earthworms, depending on the degree of soil pollution predicted. Previous work [19] has shown that increasing the soil content of heavy metals above a certain threshold reduces the density of worms and negatively influences their weight growth and sexual development. This result is a good illustration of the observation made in this study where the population and density of earthworms observed in potentially polluted soils were generally lower than those of potentially unpolluted or less polluted soils. The predictive model developed is therefore reliable. This reliability is all the more true as the zinc, copper and lead contents (respectively: 310.13±8, 136.11±8.23 and 2,35±0.02 $mg.kg^{-1}$) revealed in the potentially polluted soils are actually toxic. In fact, the critical thresholds of these heavy metals are between 100 and 250 $mg.kg^{-1}$ for zinc, 60 and 125 $mg.kg^{-1}$ for copper and 0.7 and 2 $mg.kg^{-1}$ for lead [20, 21].

In sum, this study will have shown that although the geochemical and anthropogenic origins of heavy metals in agriculture are very often mentioned [22], the fact remains that for valley soils, the processes of transfer of these elements to the soils are paramount.

CONCLUSION AND PERSPECTIVES

This research aimed to formalize an approach for the construction of a model for assessing heavy metal accumulation in lowland soils used for market gardening in Daloa. To do this, it was necessary to judiciously choose criteria for evaluating these soils. The use of the Analytical Hierarchy Process (AHP) method to calculate the weight to be assigned to each criterion yielded reliable results for the scale of the study area. Indeed, following field verifications, a very good agreement appeared between the reality of the terrain described by the chemical and biological properties of the studied soils and the expected pollution levels. Thus, this approach can be applied to the evaluation of other environmental problems existing in the study area. But before, in the face of soil contamination observed, it is urgent that tools for diagnosis and monitoring of these soils be designed for their long-term protection.

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CONFLICT OF INTEREST

Authors have declared that no competing interests exist.

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