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Research Article

Direct Effects of Mining Activities on Land Resources Around the Pô-Nazinga-Sissili Ecological Complex in Burkina Faso

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Abstract

In Burkina Faso, protected areas have faced various pressures from local actors over the past decades, resulting in a loss of biodiversity. The PONASI ecological complex, the second-largest wildlife-oriented ecological continuum covering 327,000 hectares in the central west region of Burkina Faso, has experienced severe degradation, particularly due to mining activities. Therefore, it has become crucial to study the biophysical and biochemical impacts of mining effluents on land resources to mitigate their effects on the natural ecosystems and preserve biodiversity within the complex. This is particularly vital in ecologically sensitive areas such as the PONASI complex. Thus, SRTM images from the years 2011 were chosen and processed in order to highlight the contour lines of the environment, from which topographic profiles were drawn in order to determine the direction of the propagation of mining pollutants from the top of the slopes to the level of the lowlands. Also, Landsat satellite images from the years 2022 were processed in order to highlight the land cover units. The combination of these images made it possible to judiciously identify soil sampling sites. A total of 23 soil samples were taken, packaged in indelible bags and transported to the laboratory of the Bureau of Mines and Geology (BUMIGEB), for chemical analyses, in order to determine the levels of cyanide and mercury contained in the soils, and to study their impacts on soil fertility in the research area. The results reveal that soil degradation related to mining activities around the complex. Indeed, the analysis of soil samples in the laboratory revealed the presence of cyanide and mercury at mining sites at values higher than the WHO standard in Burkina Faso, for soil lethality to these heavy metals (<0.5mg/Kg for cyanide, and <50mg/Kg for mercury) in places. These mining pollutants used in the gold extraction process spread through the environment, leading to a reduction in soil organic matter, a decrease in the sums of exchangeable bases, a variation in hydrogen potential (PH) and a loss of soil fertility. In addition, the tracing of the toposequences crossing the mining sites have made it possible to identify the risks of runoff of these mining pollutants in the overall environment of the complex according to the topography, which could contaminate all the ecological entities of this protected area and thus degrade its biodiversity. Therefore, protective actions must be taken to ensure the conservation of biodiversity within the ecological complex.

Keywords

Mining Activities, Land Degradation, PONASI Ecological Complex

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1. Introduction

The issue of environmental degradation has become one of the world's major concerns since the beginning of the 21st century [6, 14, 17, 22]. This trend was confirmed in 1992 at the Rio Conference on Environment and Development, in 2000 with the Millennium Goals adopted by the United Nations General Assembly, and at the Earth Summit in Johannesburg in 2002. From then until the adoption of the 2030 Agenda in September 2015, the issue of environmental degradation has always remained a persistent topic in scientific discussions. Despite numerous reflections and recommendations made to reverse this trend, land degradation has worsened, particularly with the advent of mining activities in recent decades.

In Burkina Faso, there has been a rapid increase in the opening up of mining sites, despite the government's constant efforts to regulate them. According to several studies and reports, gold mining, whether artisanal or industrial, is one of the main factors contributing to the degradation of natural resources [16, 19, 22, 25]. Degradation of vegetation cover favors runoff, resulting in soil erosion, the loss of soil fertility, and conflicts between stakeholders exploiting natural resources [23, 27].

Unfortunately, the PONASI ecological complex is no exception to this trend. This protected area, a vast ecological space of 327,000 hectares located in the extreme south of Burkina Faso, is facing serious degradation problems, particularly due to mining activities in recent decades. From to the present day, there are at least five mining sites around the complex, insidiously impacting land resources in this environment.

2. Materials and Methods

2.1. Presentation of the Search Area

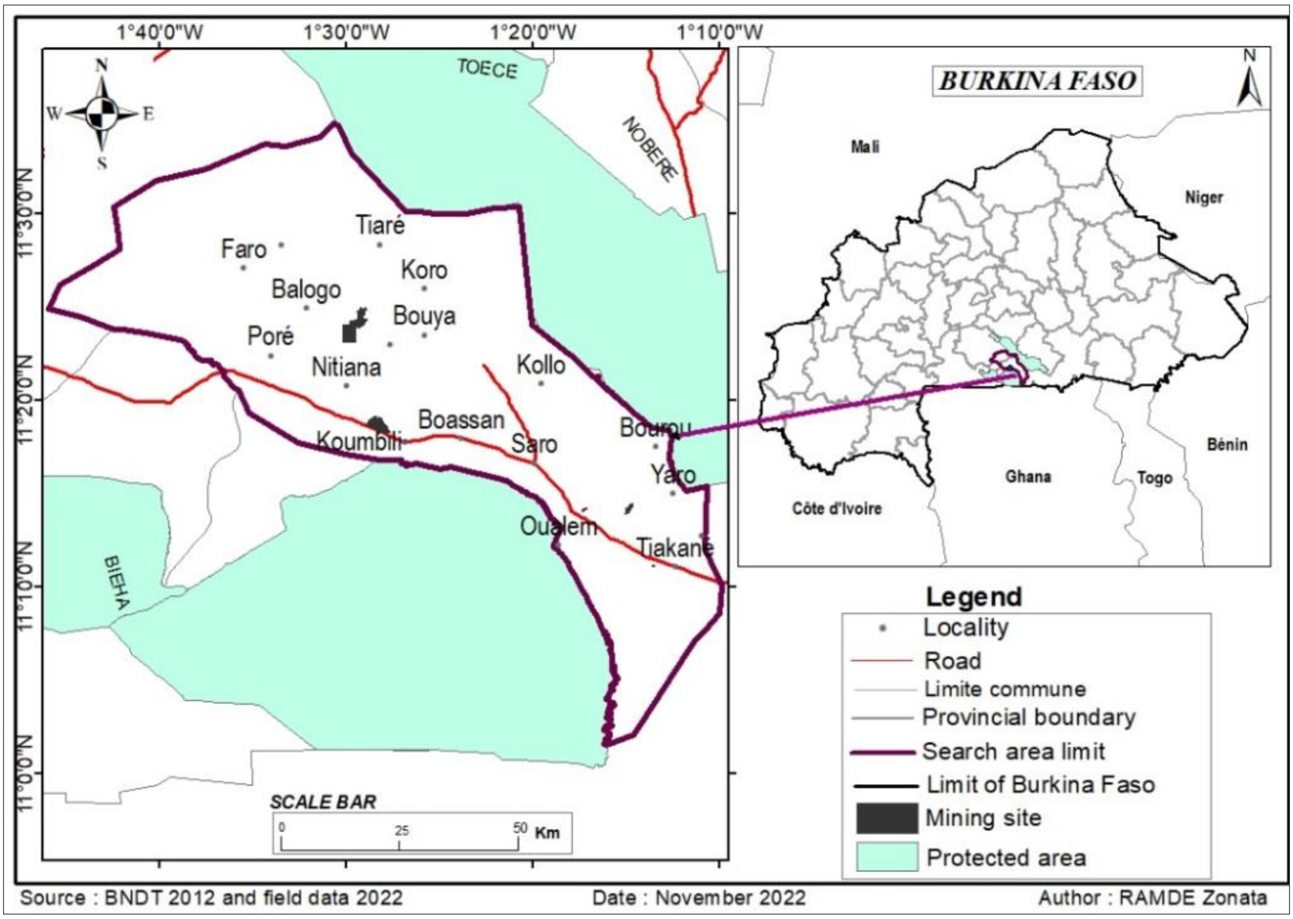

Figure 1. *Map of study area.*

The PONASI natural ecosystem is located between 11 °00'00" and 11 °30'00" N latitude and 1 °40'00' and 1 °10'00" W longitude in southern Burkina Faso, along the border with Ghana (Figure 1). It straddles two administrative regions, (the central-south and central -west regions). The municipalities of Pô, Guiaro and Sapouy at the center of the complex are potential areas of population influx for agropastoralists, herders and miners from various backgrounds, in search of economic opportunities [20]. This ecosystem covers an area of 3792 km^2 and includes the network of contiguous areas including the National Park Pô (155,000 hectares), the Nazinga game ranch (94,000 hectares), the Sissili classified forest designated as a hunting zone (32,700 hectares), the village hunting zones around Nazinga (54,300 hectares) and Sissili (5,700 hectares) and associated protected areas. However, the recognized importance of this entity contrasts with practices detrimental to its conservation and the sustainable development of agro-herder-forager populations and recently gold miners and a mining company (Nétiana Mining SA) that has set up there with a mining permit for around 200 hectares of surface area since 2017. The gold mine is located in the municipality of Guiaro, at the center of the ecological complex. Uncontrolled exploitation of NTFPs and abusive logging in protected areas threaten the integrity of this natural ecosystem and its biodiversity [22]. The choice of this area is justified by the exacerbation of the pressures exerted on this natural ecosystem [28, 36], worsened by the advent of mining activities around the PONASI ecological complex in recent decades.

The topography of the PONASI is relatively flat, with a few inselbergs, granite outcrops and low-lying, lateritic-capped tabular buttes not exceeding 380 m in altitude [15, 29]. The relief is gently undulating to the southeast and almost flat to the west. Overall, it forms a peneplain in which four (4) major geomorphological units can be identified: residual reliefs, glacis, interfluves and fluvio-alluvial complexes (Figure 2). The area is predominantly composed of soils suitable for cultivating maize, sorghum, cowpea, cotton and soya, although some areas are unsuitable for cultivating rice and cotton, etc.

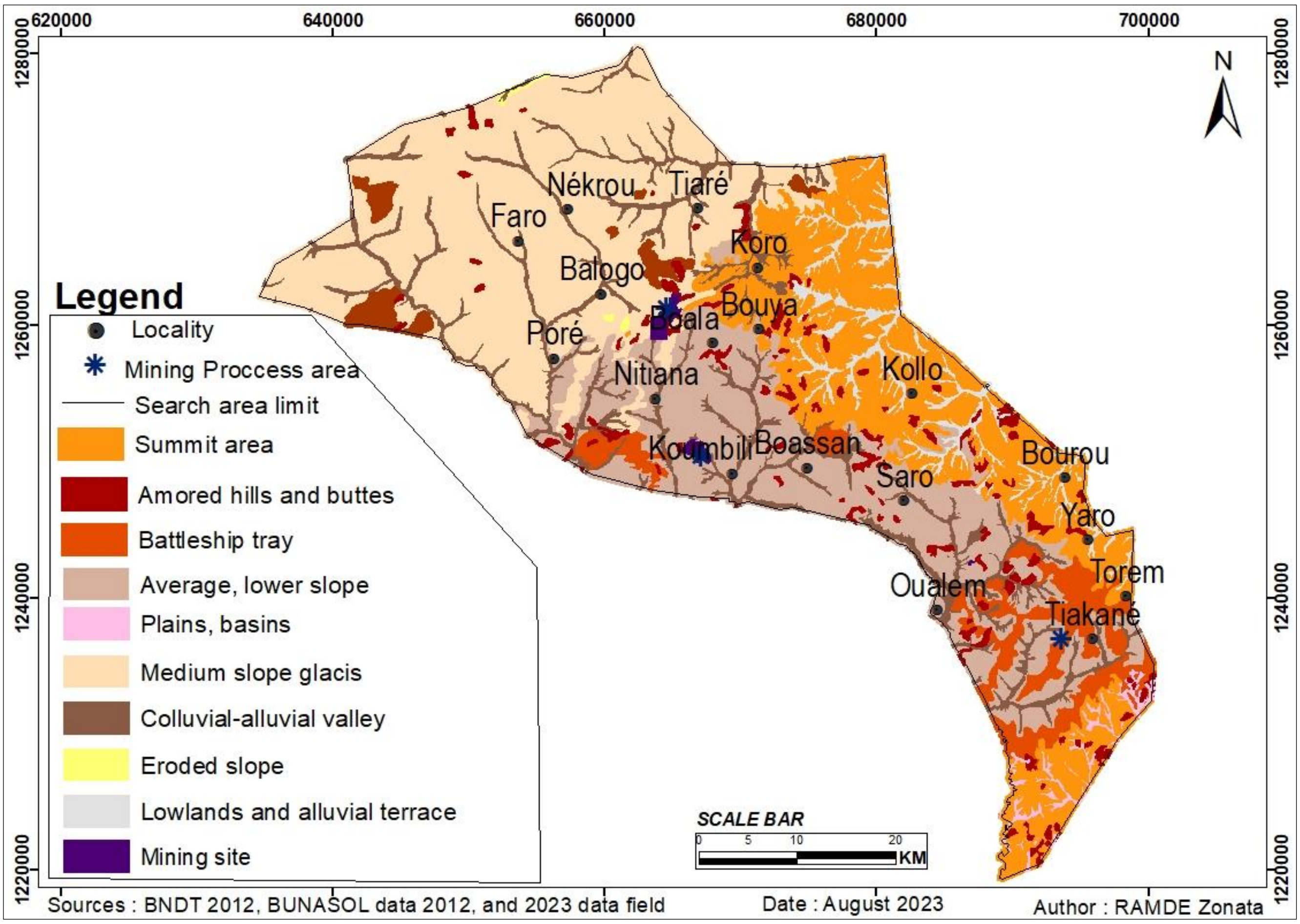

Figure 2. *Geomorphological units in the study area.*

Fluvio-alluvial complexes are areas of land that are closely associated with watercourses and shaped by the accumulation of alluvial materials. These areas are generally located along the banks of rivers and other watercourses, and are subject to periodic flooding. All drainage networks are made up of alluvial plains and terraces, settling basins, valleys and riverbeds.

2.2. Type of Data Used

The preliminary work consisted firstly in selecting the data needed to locate the sampling sites. These were LANDSAT OLI-TIR 2022 satellite images with 30m*30 resolution, which underwent pre-processing and processing steps in order to differentiate the cartographic units of the environment. Additionally, SRTM 2011 images, supported by BDOT 2012 and BNDT 2012, were also used as a basis for preparing the fieldwork. Table 1 summarizes the data used for the survey.

Table 1. *Type of data used.*

Data used	Dates
LANDSAT OLI-Tir	2022
SRTM	2011
BDOT	2012
BNDT	2012

2.3. Foundational Data Processing and Toposequence Selection

The preliminary work started with a study of the topography of the area using SRTM 2011 images, which allowed to assess the slope and generate the contours of the area using ArcGis software. This map was superimposed on the land use map produced using LANDSAT OLI-Tir 2022 images and ENVI software. This map, combined with the geomorphological map and the morpho-pedology of the environment, was used to draw three (02) topographical profiles.

2.4. Soil Survey and Sampling

Twenty-three (23) soil sampling sites were identified. The selection criteria were based on position in relation to operating or abandoned mining sites in the study area. A GPS was used to locate the soil pits (soil sample collection sites) on the site.

Figure 4 shows the location of the soil sampling sites.

The soil survey was carried out in single fieldwork session by four people. It was conducted from April 25 to 29, 2023 and was necessary to cover the periphery of the PONASI complex due to the risks of degradation in this protected area. The fieldwork enabled to open and record 23 soil profiles across all the geomorphological units. The depth of the pits ranged from 0 to 30 cm for the first horizons and from 30 to54 cm for the second horizons. Figure 3 shows the characteristics of the soil pits and his immediate environment.

Soil profiles Profile environment

Figure 3. *The "free" survey method was adopted, using mainly roads, tracks and paths.*

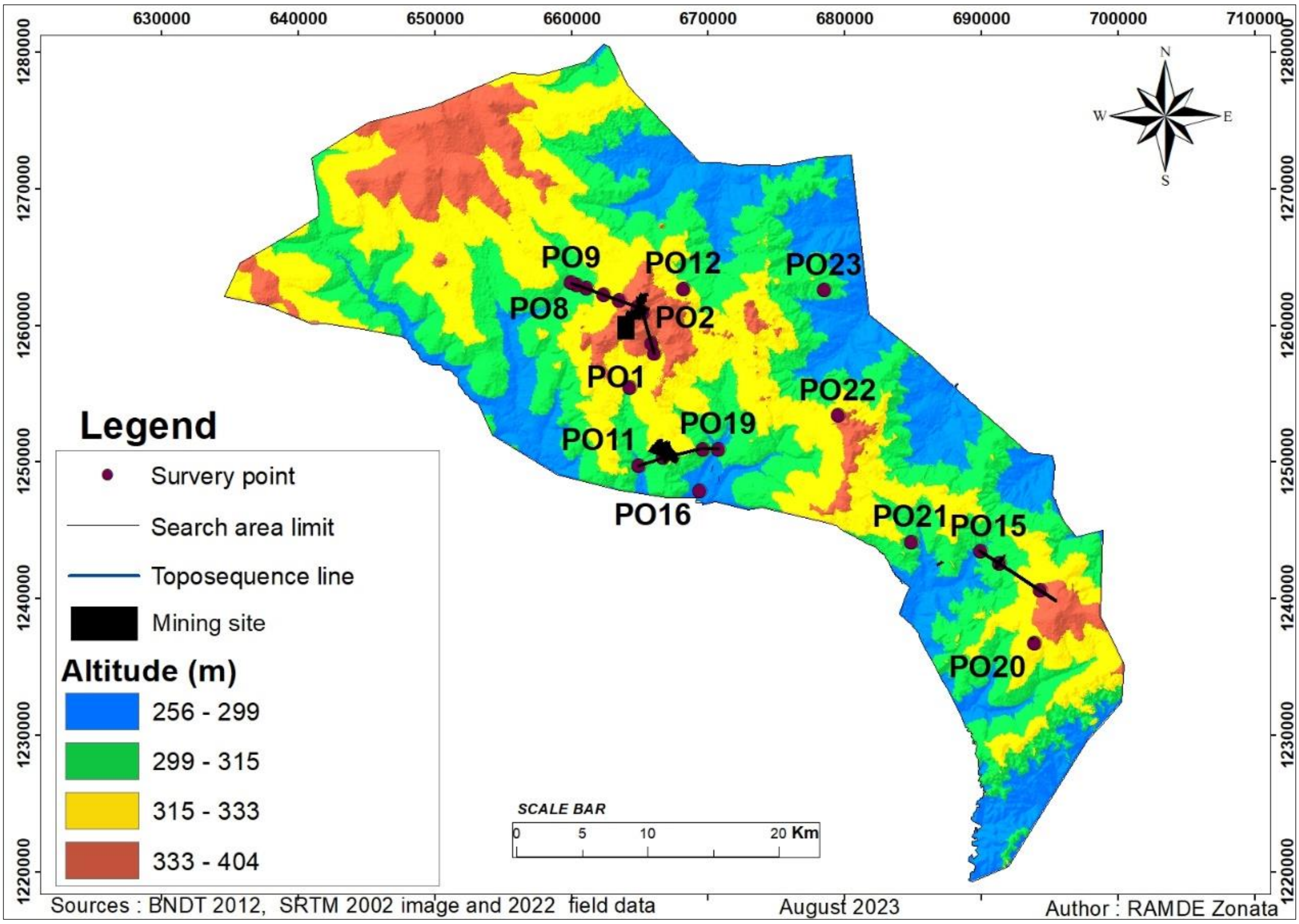

Figure 4. *Location of soil samples collected in the study area.*

2.5. Soil Description and Analysis

The soil profiles were described according to the guidelines of [11, 10, 3] and classified according to the French system "*Commission de Pédologie et de Cartographie des Sols* (Commission for Pedology and Soil Mapping)" [7, 13] adapted to the local conditions of Burkina Faso. The parameters determined in the laboratory on the samples were: organic matter, exchangeable base sums, water pH, total carbon and cation exchange capacity (CEC). Analyses were carried out according to international methods [2].

3. Results

3.1. Morpho-Pedological Characterization of Soils in the Study Area

A total of nine (09) mappable profiles, variously affected by mining effluents, were selected and described in a representative manner in order to conduct the morphopedological characterization of the environment.

1) *PO1 profile description*

0 - 30 cm: the color is grayish-brown (10YR 5/2) when wet; the texture is sandy-clay; the coarse content is nil; the structure is molten; the consistency is sticky; the biological activity is well-developed; the transition is gradual.

2) *PO2 profile description*

0 - 25 cm: the color is reddish yellow (7.5YR 6/6) when dry and strong brown (7.5YR 5/6) when wet; the texture is silty-clayey-sandy; the coarse element content is 25% and consists mainly of ferruginous gravel; the structure is polyhedral, sub-angular, and weakly developed in medium aggregates; the consistency is hard; the pores are numerous, ranging from fine, very fine, medium to large; the roots are sparse, very fine, and fine; the biological activity is well developed, the transition is abrupt.

> 25 cm: ferruginous armor.

3) *PO3 profile description*

0 - 30 cm: the color is reddish-yellow (7.5YR 6/6) when dry and strong brown (7.5YR 5/6) when wet; the texture is silty-clayey-sandy; the course content is 50% and consists mainly of ferruginous pebbles and gravel as well as quartz; the structure is polyhedral, subangular and weakly developed in fine and medium aggregates; the consistency is hard; the pores are numerous, fine, medium, and large; roots are numerous, fine, medium and large; biological activity is

well-developed; the transition is distinct.

4) *PO4 profile description*

0 - 30 cm: the color is dark yellowish-brown (10YR 4/4) in dry and wet state; the texture is clay-loamy; the coarse element content is 40%, consisting mainly of ferruginous gravel and quartz; the structure is polyhedral, subangular, moderately developed in fine and medium aggregates; the consistency is hard; the pores are numerous fine, medium, and large; the roots are numerous, very fine, and fine; the biological activity is well developed, the transition is abrupt.

5) *PO5 profile description*

0 - 20 cm: the color is dark yellowish-brown (10YR 4/4) when dry, and strong brown (10YR 3/3) when wet; the texture is silty-clayey-sandy; it consists of 15% of coarse elements composed of ferruginous gravel; the structure is weakly developed, polyhedral, and subangular in medium-coarse aggregate; the consistency is hard; the pores are fairly numerous, fine, and medium; the roots are numerous, very fine, and fine; the biological activity is well developed, the transition is gradual.

20-30 cm: the color is yellowish-brown (10YR5/6) when dry, and dark yellowish-brown when wet (10YR4/4); the texture is clay-loam; the structure is subangular, polyhedral, and weakly developed in medium and fine aggregates; the consistency is very hard; the pores are few, very fine, and fine; the roots are numerous, fine, medium, and large; the biological activity is well developed.

6) *PO6 profile description*

0 - 21 cm: the color is dark yellowish-brown (10YR 4/4) when dry state and wet (10YR 3/4); the texture is silty-clayey-sandy; the structure is weakly developed, subangular, and polyhedral in medium aggregate; the consistency is hard; the pores are numerous, fine, medium and large; the roots are numerous, fine, medium and very fine; the biological activity is well developed, the transition is gradual.

21-33 cm: the color is dark yellowish-brown (10YR4/6) when dry and moist (10YR 3/6); the texture is clay-loam; the structure is polyhedral, subangular, and weakly developed in medium and fine aggregates; the consistency is very hard; the pores are few, fine, and very fine; the roots are numerous, fine, medium, and very fine; the biological activity is well developed.

7) *Profile description PO7*

0 - 19 cm: the color is light yellowish-brown (10YR 6/4) when dry and dark yellowish-brown (10YR 4/4) when wet; the texture is silty-clayey-sandy; the structure is massive, it consists of 10% ferruginous gravel and quartz; the consistency is soft; the pores are few, fine, medium, and large; the roots are non-evident; the biological activity is well developed, the transition is gradual.

0 - 32 cm: the color is yellowish brown (10YR5/6) when dry and dark yellowish brown when wet (10YR 4/6); it is composed of 10% rusty spots (7.5YR6/8); the texture is clayey-loamy-sandy; it embodies some ferruginous concretions as coarse elements; the structure is polyhedral, sub-angular and weakly developed in coarse and medium aggregates; the consistency is hard; the pores are numerous, fine, very fine, medium, and large; the roots are rare and very fine; the biological activity is well developed.

8) *PO8 profile description*

0 - 18 cm: the color is yellowish-brown (10YR 5/4) when dry and dark yellowish-brown (10YR 4/4) when wet; the texture is silty-clayey-sandy; the structure is weakly developed, subangular, and polyhedral in medium and coarse aggregates; the consistency is not very hard; the pores are numerous, very fine, medium, and large; the roots are numerous, fine, medium, and large; the biological activity is well developed, the transition is distinct.

18 - 37 cm: the color is brownish-yellow (10YR6/8) when dry and yellowish-brown when wet (10YR 5/8); it is composed of 7% yellowish-brown hydromorphic stains (10YR5/4); the texture is clay-loam; it consists of 10% of iron concretions in coarse elements; the structure is polyhedral, subangular and weakly developed in coarse and medium aggregates; the consistency is very hard; the pores are numerous, very fine, medium, and large; the roots are numerous, fine, medium, and large; the biological activity is well developed.

9) *Profile description PO9*

0 - 30 cm: the color is light gray (10YR 7/1) when dry, and gray (10YR5/1) when wet; it has a few brownish-yellow rusty spots (10YR6/8) when dry; the texture is clay-loam; the structure is subangular, polyhedral, and weakly developed in coarse and very coarse aggregates; the consistency is very hard; the pores are numerous, very fine and fine; the roots are numerous, fine, and very fine; the biological activity is well developed, the transition is gradual.

3.2. Assessment of Land Degradation Risks in the Study Area

To assess the risk of biophysical soil degradation due to mining activities around the PONASI ecological complex, toposequences were created. A total of two (02) toposequences were distributed throughout the study area, taking into account the different types of occupation and land use. These toposequences enabled a morphopedological description of the environment, the development of soil profiles, and the collection of twenty-three soil samples for physico-chemical analysis in the laboratory. Figures 5 and 6 illustrate these toposequences.

They were used to assess the risk of mining effluent flowing down the slopes to low-land areas.

Figure 5 shows the first toposequence around the PONASI complex. It crosses the Balogho mining site in the municipality of Sapouy. It spans over a distance of around 8.5 km, with two average slopes of 2.3% and 1.9%, and includes an inselberg. The altitude of the first slope varies from 400 m upstream to 330 m downstream (the river's minor bed), with a south-southeast (SSE) and north-northwest (NNW) orientation. The second slope, on the other hand, varies from 400 m upstream to 295 m downstream (the river's minor bed), with a southeast (S-E) and northeast (NE) orientation. The average altitude is 365 m for the first slope, and 348 m for the second slope.

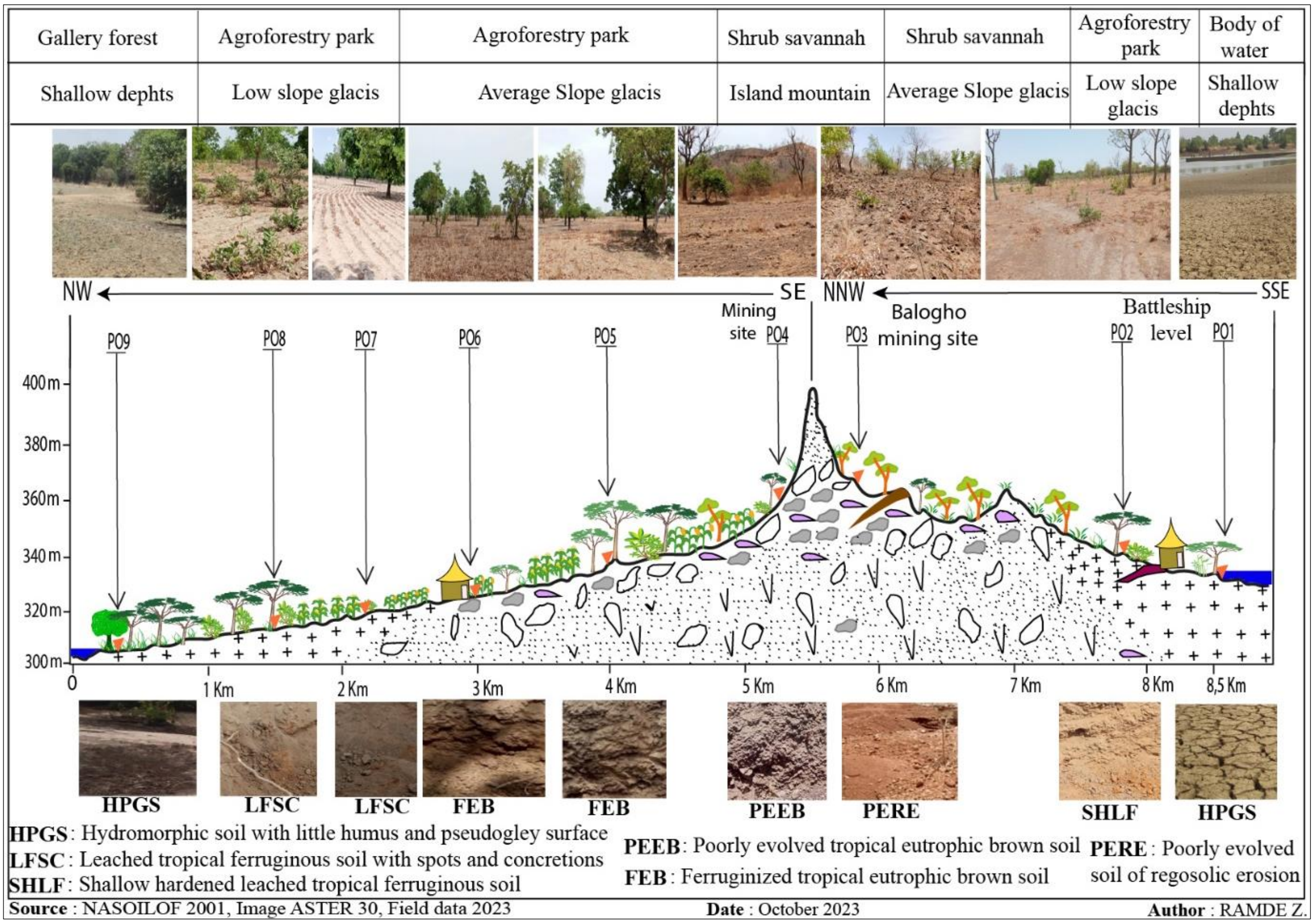

Figure 5. *Toposequence through the balogho mining sites in the complex.*

At the top of Figure 5 is a photographic plate illustrating the vegetation, topography (such as hills and valleys), and soil types found at each measuring point along the transect. This toposequence helps to understand how soil conditions and topography affect land use and biodiversity around the complex.

The observation of the toposequence reveals two juxtaposed slopes, separated by an inselberg with a tapered summit. The first slope, running from south-southeast to north-northwest, is less steep than the second one, which runs from southeast to northwest. Both slopes open onto shallow areas. The mining sites in this toposequence are each located on a hillside, on the upper slopes of the hillsides. There is, therefore, a risk of contamination of land use units, soils and animal species due to mining effluents. Fields, shrub savannahs, gallery forests and watercourses along the topographic profile are all at risk of contamination. This poses a risk to the health of local residents, as well as their livestock who regularly drink from the lowland streams. The entire ecosystem is threatened, as most of the toposequences flow into protected areas, as well as into central watercourses such as the Nazinga, Delwindé and Nazinon. The pastoral zone is also threatened by contamination from mining effluents. Consequently, there is a high probability of contamination of watercourses as a result of rainwater run-off along the slopes. Fauna and aquatic species in the PONASI complex are thus threatened with extinction. The issue of mining activities must therefore be taken into account in management and conservation strategies for the PONASI ecological complex. Morpho-pedological units are threatened by erosion due to rudimentary gold mining techniques. At the bottom of Figure 1, different soil types are indicated with their corresponding acronyms (HGPS, FLIPP, FLIP and BEER), as well as a brief description along the toposequence,

Figure 6 shows the second toposequence. It crosses the mining sites of the village of Koumbili, located in the municipality of Guiaro. This toposequence spans over a distance of approximately 6.2 km, with two average slopes of 0.8% and 1.4% and a tabular summit in the form of a cuirassed mound. The altitude the first slope varies from 320 m upstream to 302 m downstream, corresponding to the river's minor bed, with an east-west orientation. The second slope varies from 320 m upstream to 292 m downstream, also running east-west. The average altitude is 311 m the first slope, and 306 m for the second slope (Figure 6).

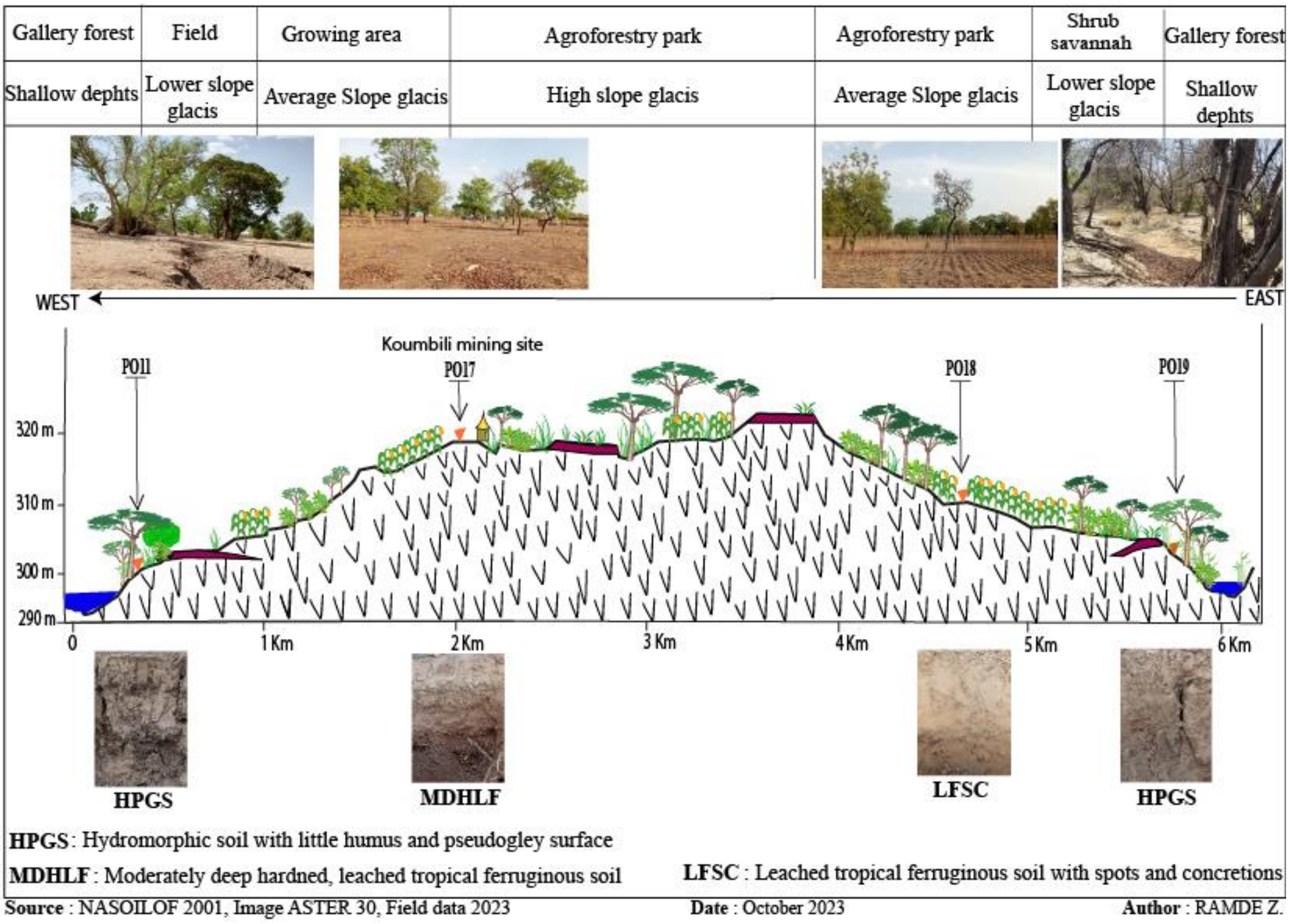

Figure 6. *Toposequence through the Koumbili mining site around the complex.*

Points P011 to P019 indicate specific locations along the transect where soil samples were taken. The profile also indicates the presence of a mining site at Koumbili. Due to the position of the site on the middle-slope glacis, there is a high probability of surface water flowing down to lowland level, suggesting that mining activities could have an impact on local ecology and soils.

The Koumbili mining sites, located on the middle glacis of the slope, indicate a high probability of mining effluent flowing down the slope to the lowland area to the west of the toposequence. Rainwater is then likely to carry these mining effluents down to the lowland areas, due to the effect of the slopes. The majority of plant and animal species as well as watercourses located along the toposequences are exposed to the risk of contamination due to mining effluents.

The types of hydromorphic soils with low-humus content and surface pseudogley found along the toposequence indicate excess surface moisture. There are also shallow indurated leached tropical ferruginous soils, and deep indurated leached tropical ferruginous soils, as well as poorly evolved brown soils of regsolic erosion, probably indicating a weak weathering and an erosion process of the parent rocks.

The photographs show the different ecological conditions along the transect, through gallery forest, fields, agroforestry parks, shrub savannah and floodplains in the lowlands. This shows the diversity of ecosystems found in the study area.

3.3. Assessment of Mining Effluent Dispersion in the Study Area

3.3.1. Dispersion of Cyanide (CN^-) in Soils Around the PONASI Complex

After laboratory analysis of the soil samples, it was found that a total of three of the 23 soil samples taken had free cyanide concentrations in excess with regard to the WHO standard for Burkina Faso, which is 0.5 mg/kg (Figure 7). The highest concentrations of free cyanide were 1.07 mg /Kg, 0.67 mg/kg and 0.57 mg/kg respectively at points PO20, PO17 and PO6, which are for all the mining sites. This can be explained by the fact that gold concentration and recovery activities continually generate cyanide and contribute to soil pollution on these sites [9, 18].

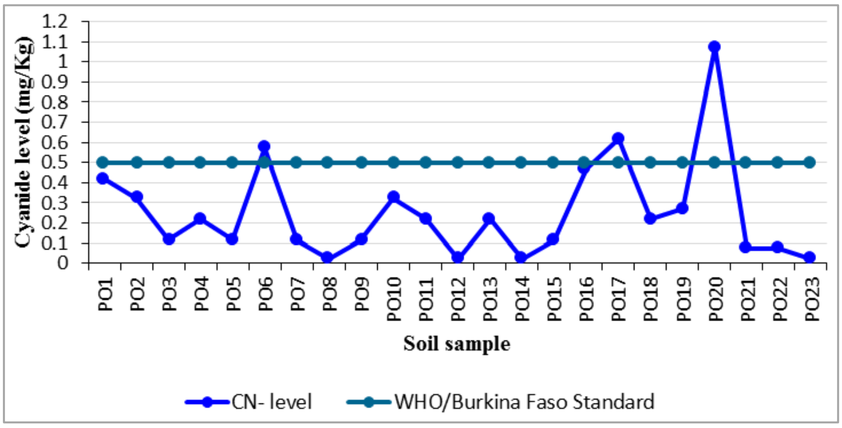

Figure 7. *Cyanide (CN^-) concentration in soil samples.*

The lowest levels of 0.02mg/kg and 0.07mg/kg respectively at PO12, PO21, PO22, PO23 correspond to lowland soils, shrub savannahs around secure areas, and sorghum and sesame fields under agroforestry parkland. These low concentrations of these points are probably due to dilution and leaching by rainwater when they are exported by runoff on slopes. In fact, some of these slopes are conducive to the transport of cyanide water from gold processing operations, which is carried by runoff to other locations where it can affect soil quality [21, 26]. A concentration peak is particularly noticeable at point PO20. This is due to the presence of an ore processing site at this location, where cyanide is often used in the gold extraction process, thus constituting a source of environmental pollution. Actions are needed to treat or monitor these specific areas in order to protect the health of local residents and the environment.

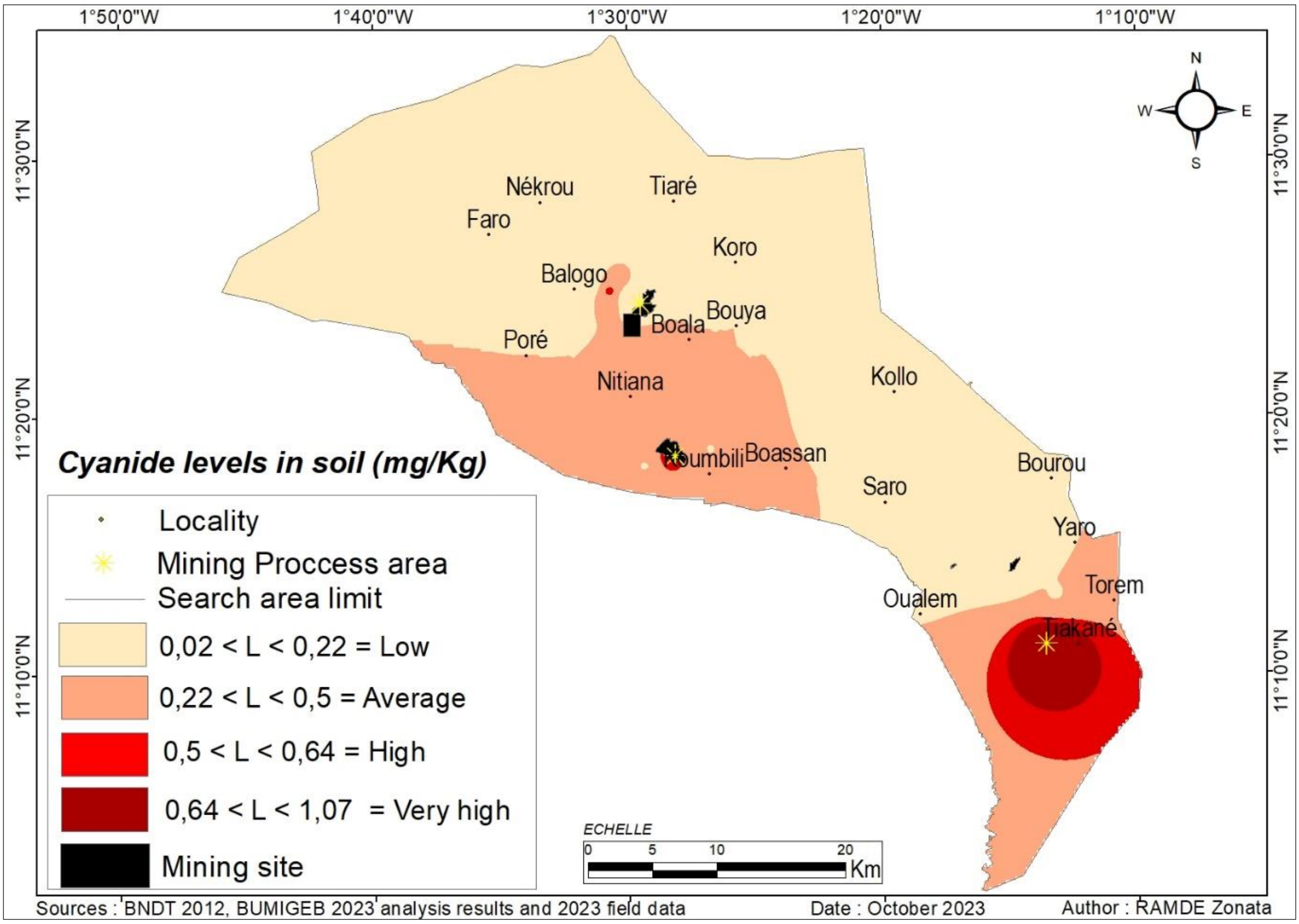

Figure 8. *Dispersion of cyanide (CN^-) in soils in the study area.*

Figure 8 shows that the areas most contaminated by cyanide are found around mining sites, particularly around Tiakané, where contamination is very high. This might suggest that mining activities are a major source of cyanide contamination in this part of the study area.

Figure 8 illustrates the importance of monitoring extraction activities, such as mining operations, which can release toxic substances into the complex environment.

3.3.2. Dispersion of Mercury (Hg^+) from Soils in the Study Area

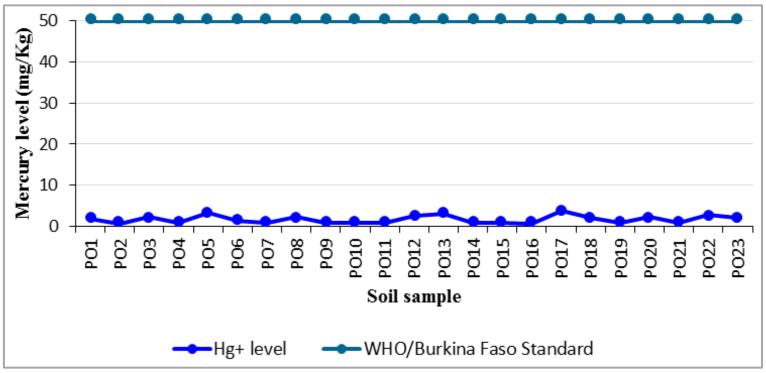

Figure 9. *Mercury concentration (Hg^+) in soils.*

Figure 9 above shows the concentration of mercury (Hg^+) in milligrams per kilogram of soil (mg/kg) in different soil samples, labelled P01 to P023.

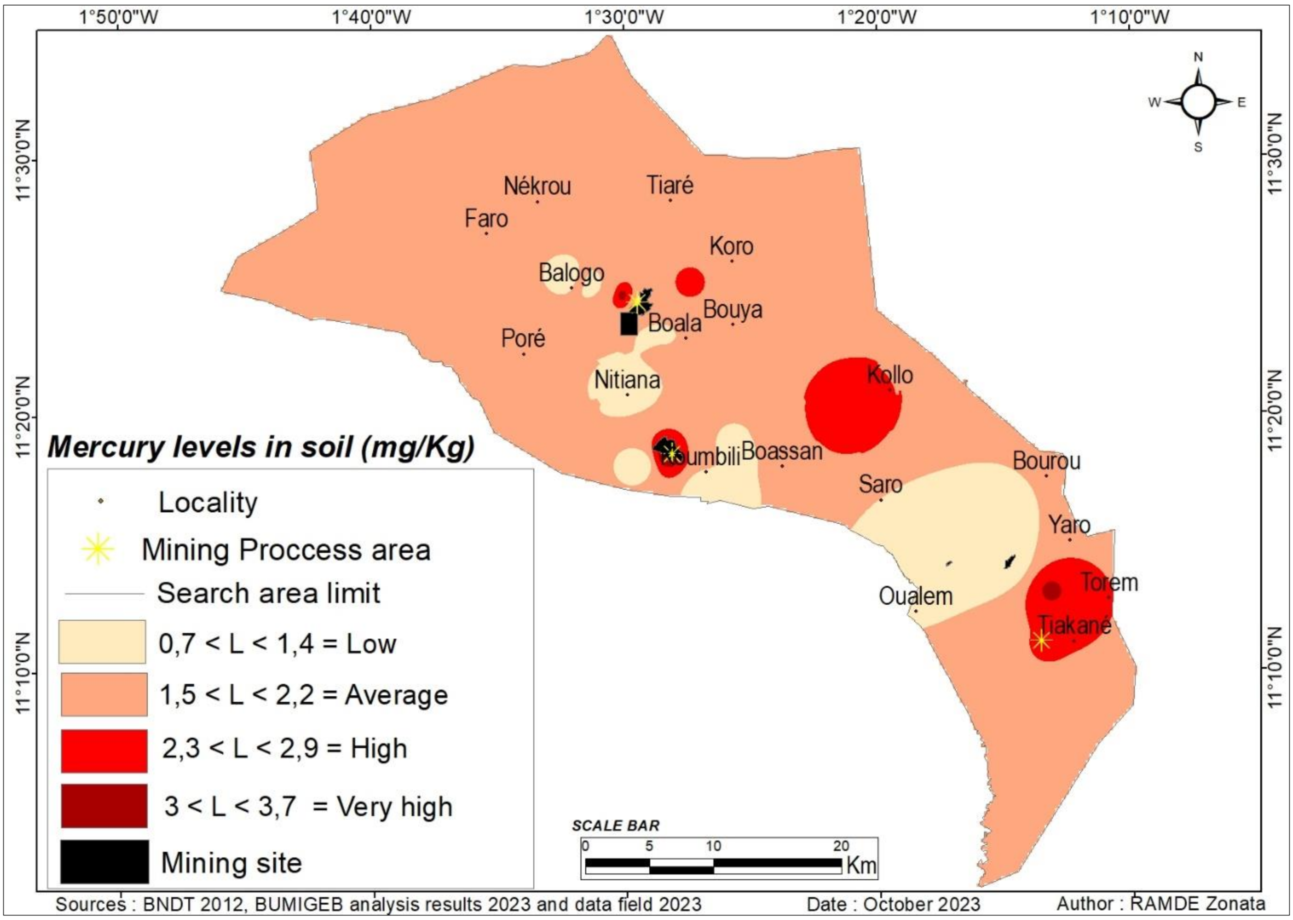

Figure 10. *Mercury dispersion (Hg^+) in soil samples.*

The blue line indicates the mercury levels measured in each soil sample. It can be seen that this line is relatively stable and well below the orange line, which represents the World Health Organization (WHO) standard in Burkina Faso for permissible levels of mercury in soil (50 mg/kg).

All soil samples show mercury concentrations well below this limit. This suggests that, for the samples tested, mercury contamination is not at a level that would exceed international and local safety guidelines. It is important to note that mercury is a toxic element that can have serious effects on human health and the environment, even at low concentrations.

The fact that these concentrations are below the standards is reassuring, but the presence of mercury must still be continuously monitored, especially in the vicinity of human activity sites that could emit mercury, such as mining or industrial sites. Figure 10 shows mercury contamination levels in the soil around the PONASI complex. The most heavily contaminated areas are shown in red and are located around mining sites, suggesting a correlation between mining activity and mercury contamination.

The most severe areas of contamination appear to be concentrated around the villages of Tiakané, Kollo, Koumbili and Boala, indicating significant contamination in these localities. This is probably related to the mining sites, and requires special attention to assess the risks to the health of local populations and the local environment. The presence of mercury contamination in this part of the area may have serious implications for public health, agriculture and biodiversity [35].

3.4. Direct Effects of Mining Effluents on Some Soil Fertility Parameters

3.4.1. Effects on the Evolution of Organic Matter (OM)

The percentage of organic matter in a soil sample is calculated from the carbon rate (multiplication by 1.72). Carbon is determined using the Walkley and Black method. The concentration ranges and interpretation standards are based on the range of organic matter percentages found in Burkina Faso soils, taking into account international standards [12]. The concentrations to be assessed relate to the first 40 cm of soil, i.e. The weighted average is calculated from the concentrations in the surface horizons [2]. Figure 11 illustrates the evaluation of organic matter in the study area.

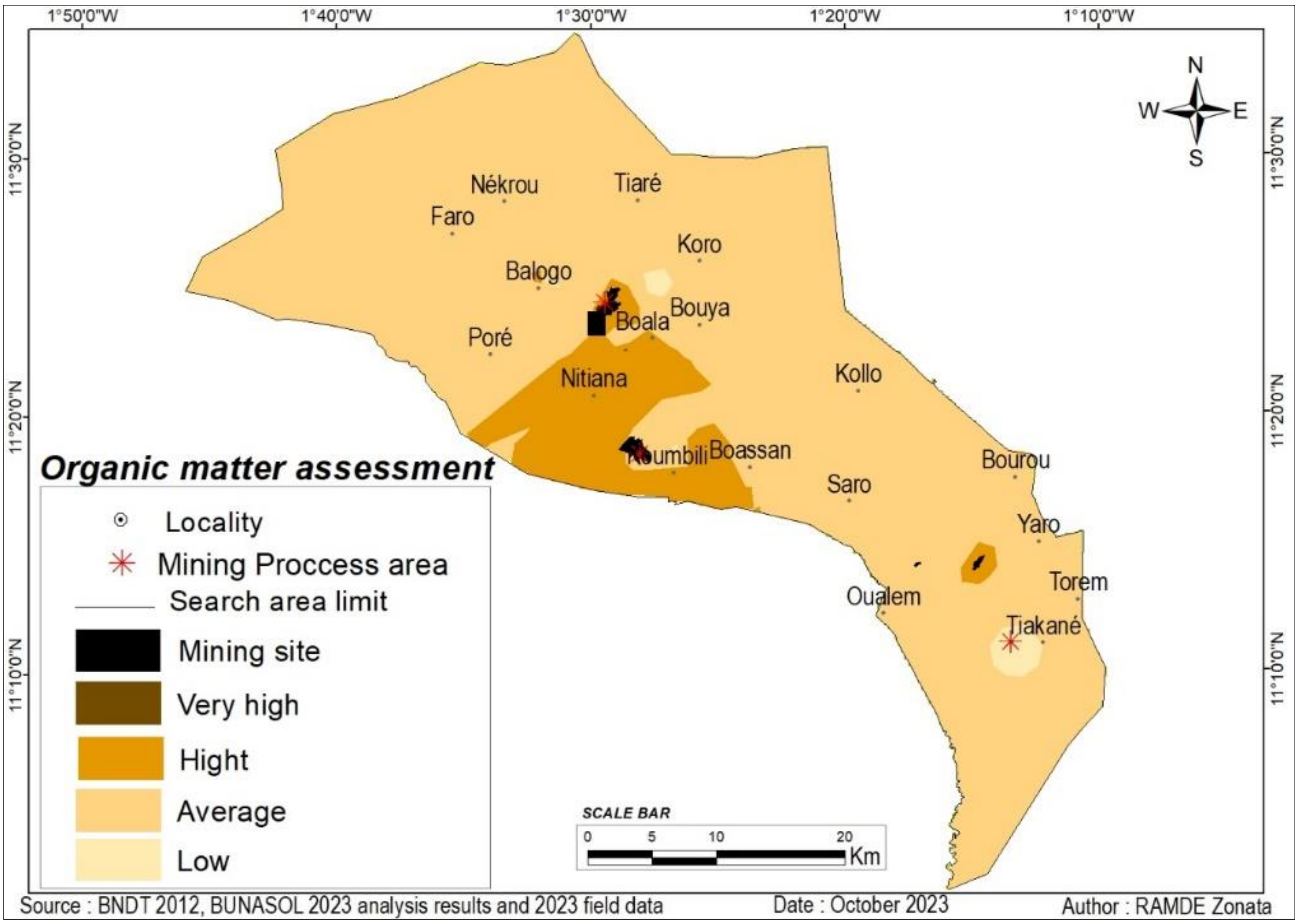

Figure 11. *Assessment of organic matter around the PONASI ecological complex.*

Areas with high levels of organic matter can indicate well-developed, healthy soils that are good for agriculture or conservation.

It is interesting to note that mining sites are mainly located in areas with moderately high levels of organic matter, indicating that mining activities occupy, among other things, potentially fertile soils. This may raise concerns about the impact of mining on soil quality.

To the south-east of the study area, in the village of Tiakané, there is an area with low levels of organic matter. This is an ore processing site that makes heavy use of mining effluents, including cyanide and mercury. This could imply a reduction in organic matter under the influence of mining effluents. Thus, we could conclude that on mining sites, organic matter is at a medium and high level, but on ore processing sites where mining effluents are used extensively, organic matter is at a low level. There could, therefore, be a relationship between organic matter and mining effluents, in a way that the latter would lead to a reduction in organic matter in the environment.

3.4.2. Effects on the Evolution of the Sum of Exchangeable Bases (SBE)

The sum of exchangeable bases has the advantage of being neutral with respect to the analytical method regarding CEC, and combines the influences of CEC and saturation on retention. Figure 12 shows the evaluation of the sum of exchangeable bases in the soil around the complex. Exchangeable bases are ions such as calcium (Ca^{2+}), magnesium (Mg^{2+}), potassium (K^+) and sodium (Na^+), which are essential for soil fertility as they are important for plant nutrition [4, 5].

The presence of areas with "very high" or "high" concentrations of exchangeable bases is generally positive for plant growth and agriculture. However, if concentrations are too high, this may also indicate imbalances in the soil that could affect the availability of other nutrients.

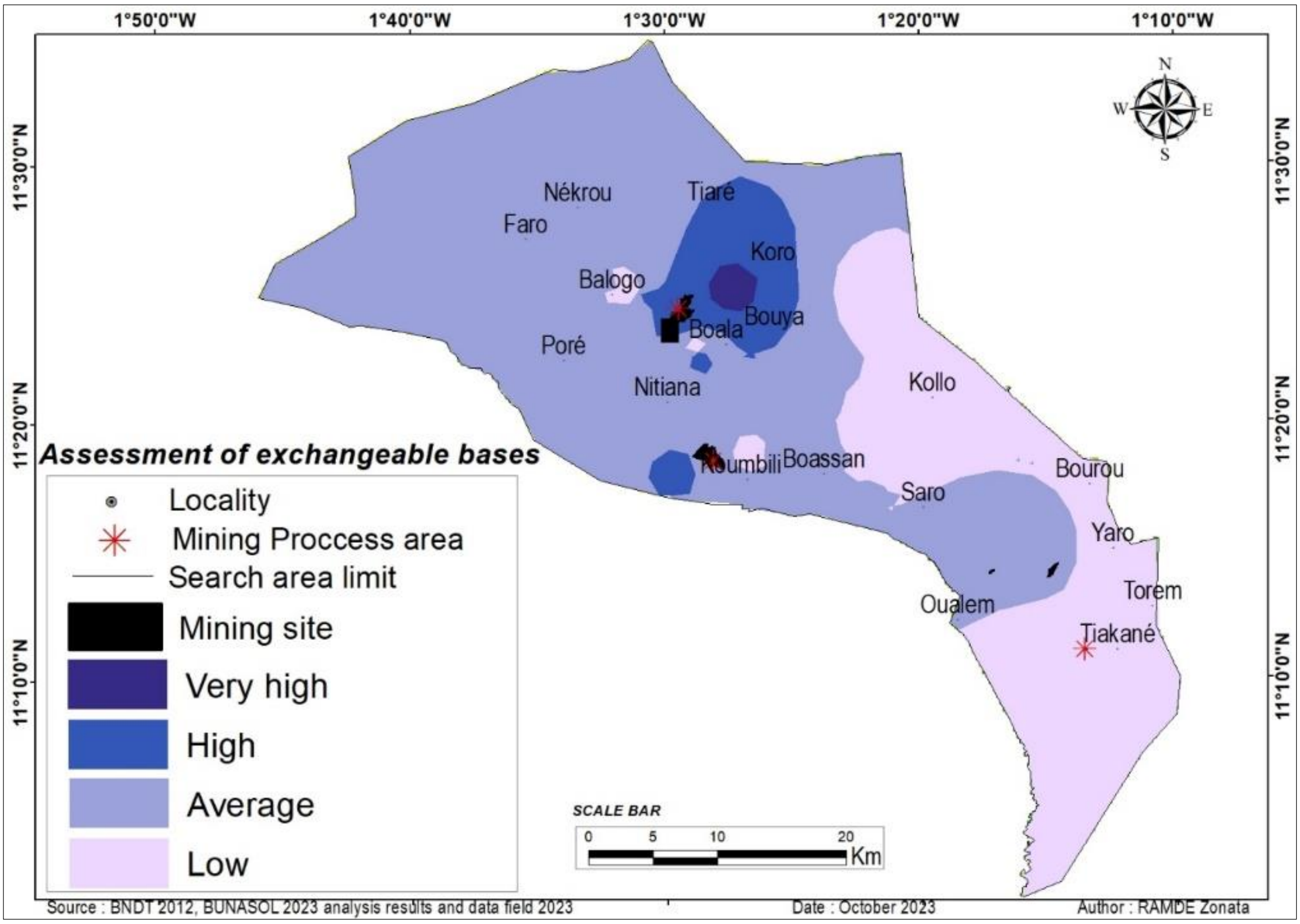

Figure 12. *Evaluation of exchangeable base sums around the PONASI complex.*

According to figure 12, mining sites are located in areas with varying levels of exchangeable bases, from "very high" to "medium". It is important to note that mining activities can influence levels of exchangeable bases in the soil, either through the addition of chemical substances, or through physical disturbance of the soil. At the mineral processing site in the village of Tiakané, a "low" level of exchangeable bases has been observed. This is certainly due to the significant presence of mining effluents during the treatment of tailings. The high concentration of mining effluents absorbs the exchangeable base, thus reducing soil quality.

3.4.3. Effects on the Evolution in the Hydrogen Potential (PH) of Soils in the Area

At BUNASOL, PH (water) is determined using an electrode after shaking a mixture of 20g Sol (sample) and 50 ml distilled water for 30 minutes.

PH (water) has a major influence on nutrient availability. However, crops differ in their ability to adapt to the concentrations of H^+ ions in the soil solution and to the effects of PH variations, and it is impossible to indicate an optimum PH range valid for all crops (figure 13).

Interpretation of the ranges given below is therefore based essentially on the varying availability, depending on PH, of most nutrients.

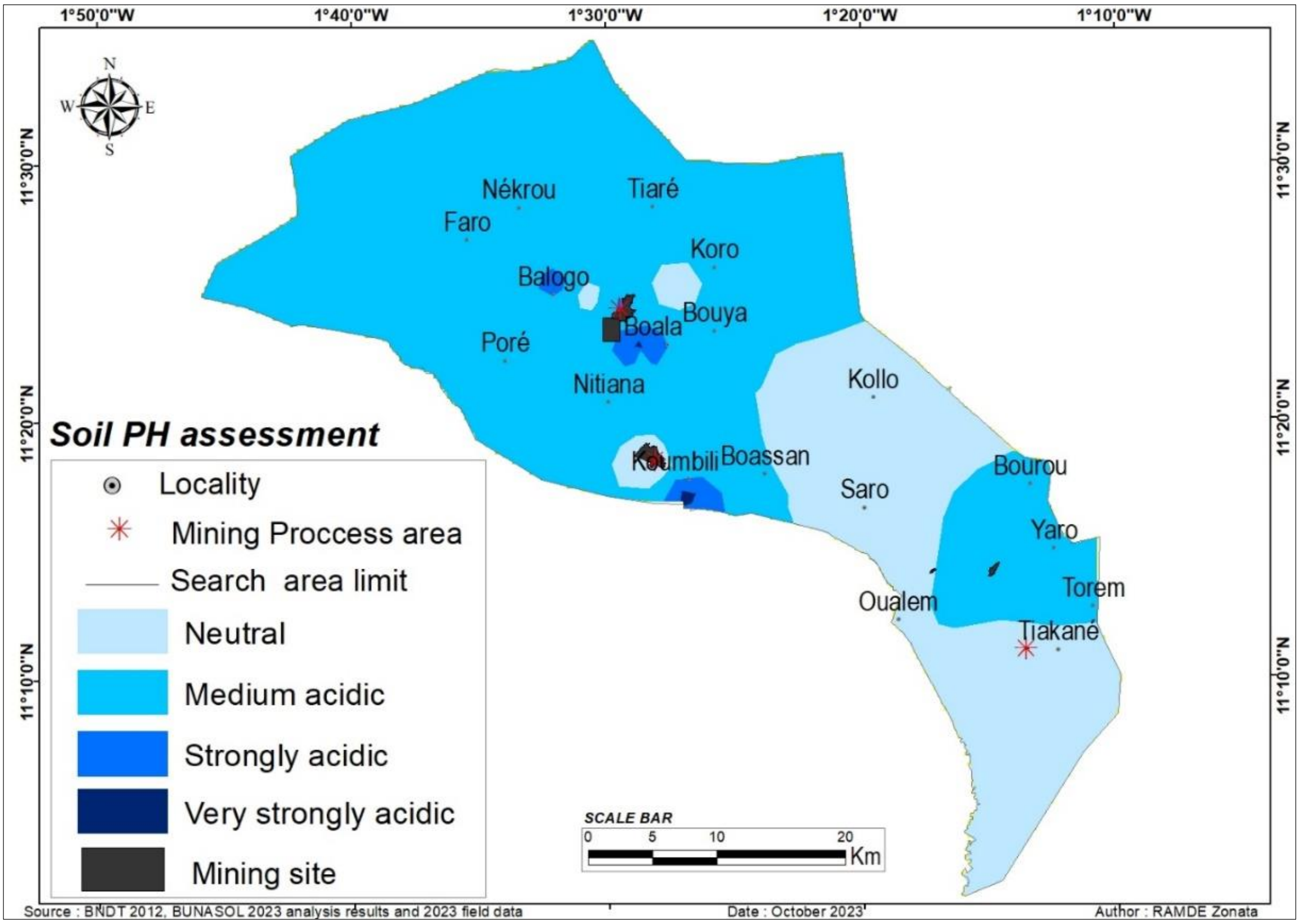

Figure 13. *Assessment of the Hydrogen Potentials (PH) of the soils around the PONASI complex.*

Figure 13 above shows an assessment of soil pH in the study area. pH is a measure of an acidity or alkalinity of a soil, an important factor affecting nutrient availability for plants and soil microbial life.

The presence of mining sites in areas where the soil is neutral or moderately acidic is notable. Mining activities can influence soil pH through the addition of substances such as ore tailings, which can be acidic. The assessment of the acidity around the complex shows that most of the area is of neutral to moderately acid pH, with more isolated areas of high and very high acidity. This could have implications for land use, as very acidic soils may require adjustment to be usable for agriculture or ecological restoration.

3.4.4. Effects on the Evolution of Soil Fertility Around the Ecological Complex

Mining activity can have a number of impacts on soil fertility, often negative, due to the disruptive nature of mineral extraction and processing.

In order to assess soil fertility in the study area, it was necessary to cross-reference different maps. These are the maps of the spatialization of exchangeable base sums (SBE), the maps of the spatialization of hydrogen potential (PH) in the soils of the study area, and the map of the evaluation of organic matter (OM) in the study area. This composition corresponds to the minimum range for soil fertility assessment [3]. Cross-referencing the different maps helped develop the soil fertility map (figure 14).

Figure 14 shows an assessment of soil fertility around the PONASI ecological complex. The green colors indicate different assessments of soil fertility, which is a key indicator for the ability of soils to support plant growth and agricultural productivity. This map shows that fertility varies across the area, with areas of high fertility scattered rather than concentrated. This may indicate variability in soil conditions, topography, or land management practices that affect fertility.

Analysis of this map shows that the mining sites are mainly located in areas of high and medium fertility. In fact, the PONASI complex area is quite fertile overall, due to favorable climatic conditions, except in rocky outcrop areas where there are a few pockets of low fertility. The opening up of mining sites takes place both in the fields and in the conservation areas, where the soils are fairly fertile. This is inherent to mining activities, which can be carried out in any environment, as gold comes from internal rocks and most often appears in quartz rocks. During site excavation, the fertility of surrounding soils can be affected by soil stripping and deforestation. Especially during cyanide or mercury ore processing, soil fertility appears to be severely affected. The evidence in this study is that on processing sites, soil fertility appears more reduced. It is therefore essential to monitor the impact of mining on the fertility of surrounding soils, as this could reduce the ability of soils to support plant life around the ecological complex.

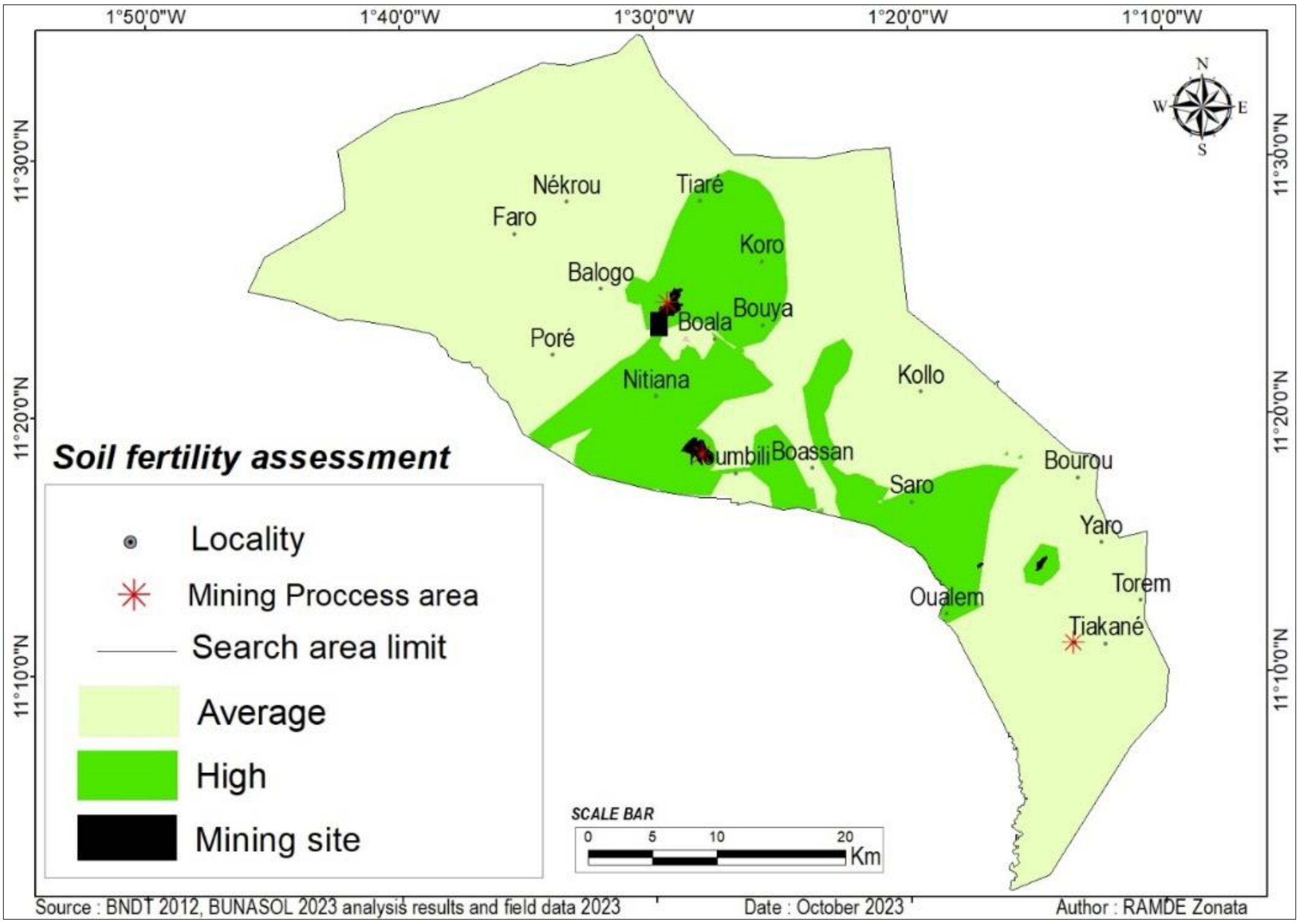

Figure 14. *Soil fertility assessment around the ecological PONASI complex.*

4. Discussion

The results of this study showed that mining has a negative biophysical impact on the soils around the complex, with a reduction in fertility, an increase in the acidity of cultivable soils and a gradual reduction in organic matter. These same results are confirmed by [1] in the Bomboré municipality, where gold panning has contributed to the pollution of groundwater with cyanide and mercury. Thus, the lack of control over this activity could prevent the development of certain ecological and biodiversity conservation activities, such as agroecology. This agricultural practice, strongly recommended by several authors [37] as a ray of hope for farmers living near the complex in view of the ecological, economic and social dimensions it combines, could be questioned if nothing is done to contain its harmful effects.

As part of this study, toposequences based on the geomorphology, morphopedology and topography of the environment were used to follow the trajectory of mining effluent flow from the upper slopes of the glacis to the shallows and watercourses of the complex. This made it possible to assess the risk of contamination of the natural resources of the complex. This technique, which yielded relevant results, was used by [33] to assess land degradation and soil erosion in the upper Sissili watershed, and by [30] to study the spatial organization of the Kangala municipality in the “Hauts- Basins” region of Burkina Faso. In fact, it is a technique commonly used by the National Office of Soils (BUNASOL) [3] to assess biophysical soil degradation and fertility.

A study of the soils in the study area revealed four morpho-pedological units: glacis, cuirassed levels, inselbergs and lowlands. Their morphological and physico-chemical characteristics indicate five distinct soil classes: low-humus hydromorphic soils with surface pseudogley, leached tropical ferruginous soils with stains and concretions, shallow indurated leached tropical ferruginous soils, low-leached eutrophic tropical brown soils, eutrophic tropical ferruginous brown soils, and those with little regosolic erosion. Gold mining in this agricultural zone has a direct negative impact on natural resources. It results in the loss of agricultural land [20, 23, 34], increased land pressure and growing difficulty in finding replacement land. In addition, stripping topsoil and sinking pits increases soil compaction, reducing its fertility and ability to support crops over the long term [8, 34, 31, 32].

5. Conclusion

This study showed that mining activities has significant direct impacts on land resources in the study area, namely: degradation of vegetation cover, soil erosion and loss of soil fertility. These impacts underline the importance of sustainable natural resource management and the need to reconcile extractive activities with the preservation of agricultural land essential for local food security and livelihoods [24]. The risks of land degradation are confirmed by laboratory analysis of soil samples. Direct impacts on soils due to mining effluents are of moderate importance. However, when cumulated with pre-existing impacts, their severity is high. These impacts will continue if nothing is done to reverse the trend.

Abbreviations

BDOT	Land Use Database
BEER	Brown Eutrophic Soil of Regosolic Erosion
BNDT	National Topographic Database
CEC	Cation Exchange Capacity
CN^-	Cyanide
CPCS	Commission for Pedology and Soil Mapping
FLIP	Deep Hardened Leached Tropical Ferruginous Soil
FLIPP	Shallow Indurated Tropical Ferruginous Soil
GPS	Global Positioning System
Hg^+	Mercury
HPGS	Hydromorphic Soil with Little Humus and Pseudogley Surface
MO	Organic Matter
NTFP	Non-Timber Forest Products
PH	Hydrogen Potential
PONASI	Pô-Nazinga-Sissili Ecological Complex
SBE	Sum of Exchangeable Bases
WHO	World Health Organization

Author Contributions

Zonata Ramdé is the sole author. The author read and approved the final manuscript.

Conflicts of Interest

The author declares no conflicts of interest.

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