Original Article

Forest Carbon, Soil Nutrients, and Heavy Metal Status after 15 years of Small-scale Gold Mining in Guyana

Devon George[1,2*] Amnat Chidthaisong[1,2*]

[1]The Joint Graduate School of Energy and Environment, King Mongkut's University of Technology Thonburi, Thailand
[2]Center for Energy Technology and Environment, Ministry of Education, Bangkok, Thailand
*Corresponding author: devongeorge04@gmail.com; amnat.chi@kmutt.ac.th

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ABSTRACT

This study evaluated the impacts of small-scale gold mining on forest regeneration, soil nutrients, and the accumulation of heavy metals over a chronosequence of 1-15 years after mining activities in Mahdia, Guyana. Thirteen 50m x 50m plots were established across twelve mined-out sites, with three plots each in areas abandoned after 1, 5, 10, and 15 years, along with a control plot. Soil samples were taken from each mining plot, along with collection of tree data, including species composition, height, and diameter at breast height (DBH) for trees >4 cm in diameter. Small trees (DBH 1-4 cm) were measured within subplots of size 10m x 10m, and saplings were counted in 4m x 4m plots. The control plot was dominated by four species: *Mora gonggrijpii, Chlorocardium rodiei, Mora excelsa*, and *Catostemma commune*, which contributed more than 60% of the overall species sampled, with biomass and carbon content measured at 665 ton/ha and 313 tonC/ha, respectively. In contrast, tree regeneration in mined-out areas was significantly slower, with only 1-2 tree species present after 15 years and the maximum biomass and carbon content estimated between 1.3-1.5 tonC/ha. Heavy metal levels generally returned to levels similar to that of the control, except for mercury and lead, which were two-fold and four-fold higher, respectively. Additionally, nitrogen and phosphorus levels were considerably lower, likely contributing to the limited accumulated biomass through regrowth and altered species composition in the mined-out soils.

Keywords: Small-scale gold mining; Heavy metal; Soil nutrient; Forest regeneration; Guyana

INTRODUCTION

The global demand for gold and its increasing price has led to significant growth in legal and illegal global mining activities. These activities have resulted in substantial degradation of forested areas and soil toxicity through heavy metals (Román-Dañobeytia *et al*., 2015). It has been reported that small-scale gold mining has primarily contributed to mercury and heavy metal pollution globally (Aquino *et al*., 2022), playing an important role in the economies of several developing countries, including Guyana. It provides employment opportunities in rural areas with limited economic activity and serves as a major source of foreign exchange (Cortines and Valcarcel, 2009; Karthikeyan *et al*., 2021; Akoto *et al*., 2023). However, the use of harmful chemicals, particularly mercury, in the extraction of gold has contributed to soil degradation and heavy metal contamination, a common issue in mining areas. Studies have consistently reported that gold mining significantly increases the concentrations of heavy metals like arsenic, chromium, iron, lead, zinc, and mercury in the soil (Bempah *et al*., 2013; Tóth *et al*., 2016; Akoto *et al*., 2023). The global demand for gold and its increasing price has led to significant growth in legal and illegal global mining activities. These activities have resulted in substantial degradation of forested areas and soil toxicity through heavy metals (Román-Dañobeytia *et al*., 2015). It has been reported that small-scale gold mining has primarily contributed to mercury and heavy metal pollution globally (Aquino *et al*., 2022), playing an important role in the economies of several developing countries, including Guyana. It provides employment opportunities in rural areas with limited economic activity and serves as a major source of foreign exchange (Cortines and Valcarcel, 2009; Karthikeyan *et al*., 2021; Akoto *et al*., 2023). However, the use of harmful chemicals, particularly mercury, in the extraction of gold has contributed to soil degradation and heavy metal contamination, a common issue in mining areas. Studies have consistently reported that gold mining significantly increases the concentrations of heavy metals l.

The degradation of soil quality due to mining can have severe consequences for land use and recovery, including the natural regeneration of forests. In extreme cases, plant growth may be hampered on mined-out lands due to poor soil physical properties, insufficient nutrients, and high toxicity levels from heavy metals (Román-Dañobeytia *et al*., 2015). The diversity and abundance of plants, particularly woody tree species, are critical indicators of the success of remediation efforts in areas contaminated with mercury and heavy metals (Román-Dañobeytia *et al*., 2015). Studies have documented a relatively lower number of woody species in regenerating post-mining sites. For example, Peterson and Heemskerk (2001) observed a reduction in tree diversity growing on abandoned mining plots in Suriname compared to control plots. Similarly, Nyenda *et al*. (2021) reported that it could take up to 100 years for soil macronutrients to return to pre-mining levels in a survey of sites in Zimbabwe. Waste rock dumps from post-mining activities also pose long-term environmental challenges unless reabilitated through vegetation (Lewis *et al*., 2022).

In Guyana, artisanal and small-scale gold mining (ASGM) has expanded significantly over the past 25 years, with 374,739 hectares of land under gold mining as of April 2021. By the end of 2023, there were 2,422 licensed small-scale gold mining operations were recorded in the country (Mcpherson *et al*., 2021). Gold mining is a leading export industry in Guyana, driving economic growth (Laing, 2019). However, many mined-out lands have been rendered degraded and nutrient-poor due to the lack of backfilling and a high concentration of toxic heavy metals in the soil, posing significant challenges for forest regeneration. Despite the scale of mining activities, very few studies have monitored changes in heavy metal distribution, soil nutrient levels, and forest succession in these abandoned mining areas in Guyana. Therefore, the objective of this study was to investigate the concentrations of heavy metals and soil nutrients in post-mining areas and to estimate the regrowth of native forests and their carbon sequestration capacity. The results of this study are expected to provide foundational knowledge related to the future management and ecological recovery of lands impacted by small-scale gold mining activities.

MATERIAL AND METHODS

Site location and description

The study was conducted in the Mahdia Region 8 (Potaro-Siparuni) of Guyana, which hosts a significant number of the country's gold mines. This region is geographically bound by the Potaro River, Ebini Mountain Range, and Konawaruk Mountain Range, covering an area of 22,330 km² at an altitude of 415 meters. The climate is characterized by an average temperature of 24.5°C and an annual rainfall of 2,269 mm. Mahdia is part of the pre-Dambrian Shield of Guyana, and the Potaro Mahdia alluvium is composed of three main sedimentary layers geomorphologically, clay, clayey sand, and gravel (Mcpherson *et al*., 2021). Figure 1 shows a visual representation of Mahdia's location within region 8.

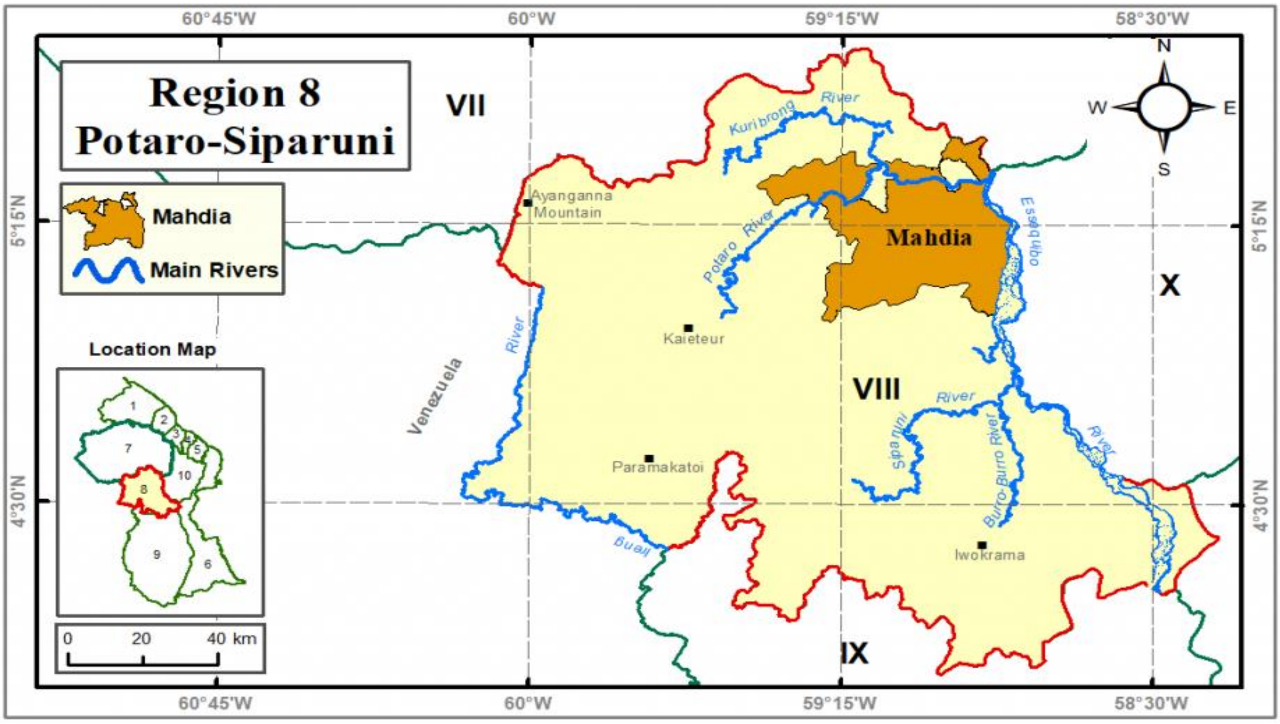


Figure 1 The location of Mahdia in the Potaro Mining District, Guyana (*Guyana Lands and Surveys Commission*, n.d.).

Enrichment Factor (EF) was used to quantify the number of times an item is enriched compared to the reference material. The reference material is considered as being unpolluted.

$$EF = \frac{[Metal]_{sample}}{[Metal]_{background}}$$

Tree characteristics and carbon storage in the biomass

Sampling plots were established at each mined-out area to assess the forest condition, carbon stock, and changes in stock over time. Twelve 50 m x 50 m plots were established along a chronosequence of 1, 5, 10, and 15 years after the stoppage of mining activities, with an additional control plot (no mining activity) used as a reference. Within each plot, tree characteristics were recorded to evaluate the tree density, species composition, growth rate, and carbon sequestration. Trees with a diameter at breast height (DBH) greater than 4 cm were measured for height and DBH, while three 10 m x 10 m subplots were established in each plot to measure trees with a DBH between 1-4 cm. Additionally, within each 10 m x 10 m subplot, three 4 m x 4 m plots were established to count the number of saplings. Species were identified with DBH greater than 1 cm. Plot measurements were made using a standard 50 m tape and the plots were strategically placed to encompass overburdens, tailing ponds, and mining pits wherever possible. Figure 2 illustrates the layout of the sampling plots.

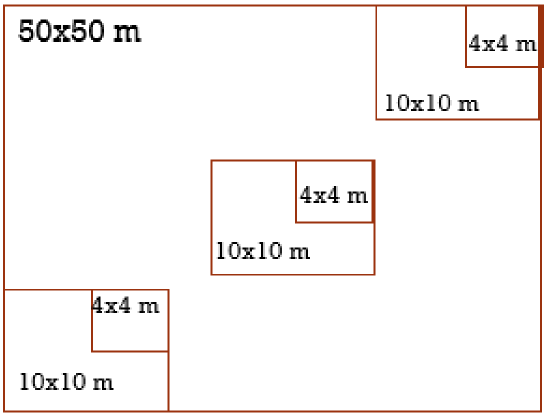


Figure 2 Layout of each plot established in the mined-out areas

Soil sampling and analysis

Fieldwork and soil sampling were conducted in October 2023. Soil samples were collected from three distinct locations within each mined-out site: (i) overburdens, (ii) tailing ponds, and (iii) mining pits, to provide a comprehensive representation of the mining area. Thirteen plots were sampled in total, with three plots for each chronosequence (1, 5, 10, and 15 years post-mining) and one control plot from the undisturbed primary forest. Soil samples were taken from the topsoil layer (depth between 0-20 cm), where most of the tree roots are found and obtain the most essential nutrients (Khadka, 2016). For each sample, at least 1,000g of soil was collected using a spade, which was cleaned between samples to prevent contamination. The soil samples were placed in olefin bags and air-dried on-site. The three samples (overburden, tailing pond, and mining pit) from each mined-out site were labeled, dried, and mixed thoroughly in a polytene bag to form a composite sample. Approximately 1,000g of the composite sample was then placed in a newly labeled olefin bag to represent the site. These samples were sent to Actlabs Inc., which is a certified laboratory specializing in soil testing and analysis in Guyana.

All the minerals were analyzed using aqua regia digestion (concentrated HNO_3 and HCl) at elevated temperatures, following ISO standards as outlined in Tóth *et al*. (2016). The samples were subsequently analyzed for the levels of phosphorus and potassium using Inductively Coupled Plasma - Optical Emission Spectrometry (ICP-OES), while lead, iron, copper, mercury, arsenic, and chromium accumulation was measured using Inductively Coupled Plasma - Mass Spectrometry (ICP-MS). The total nitrogen (N) content was determined using elementary exceed instrumentation, which measures the total nitrogen through combustion.

Data analysis

Allometric equations used for estimating the aboveground biomass in the tropical moist forest was based on the work of Brown *et al.* (1989), and can be mathematically written as:

$$AGB = \exp(-2.4090 + 0.9522 * \ln(D^2 * H * \rho)),$$

where: AGB is above ground biomass of a tree (kg), D is DBH is diameter at breast height in cm, H is the tree height in meters, and ρ is the wood density (g/cm^3).

The belowground biomass was calculated using the default values listed in Table 4.4 of the 2006 IPCC Guidelines (IPCC, 2006). The ratio of belowground to aboveground biomass in a tropical rainforest (0.37), and the carbon fraction of biomass (0.47) were also taken from Table 4.3 of the IPCC Guidelines. Figure 3 below shows the location of each sample point.

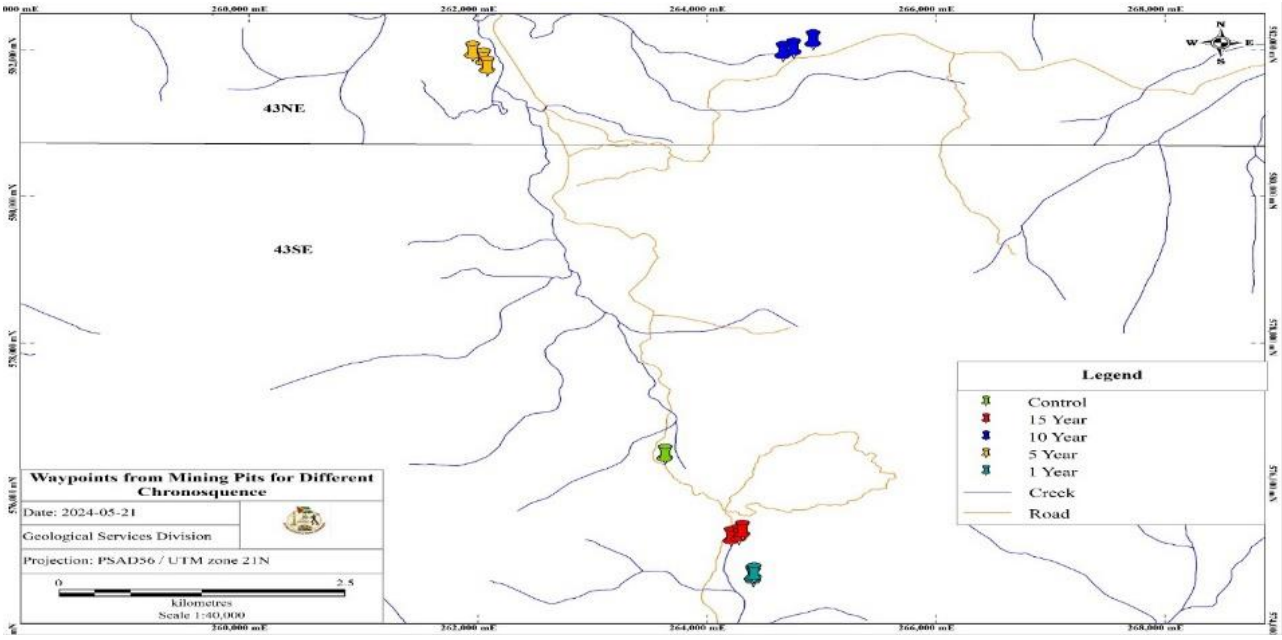


Figure 3 The location of sample points over the chronosequence of 1-15 years after mining
***Remark*:** This map was produced for the authors by the Guyana Geology and Mines Commission (2024).

Statistical analysis

A two-tailed F-test and two-tailed T-test was used to determine any significant differences between the means of measured variables. All the statistical analysis was performed using XLSTAT 2013 at a significance level of 95%.

RESULTS AND DISCUSSION

Forest characteristics

Primary forest (no mining activity)

The primary forest used as the control plot was characterized by dense forest cover with a diverse range of tree species, varying in both height and DBH. A total of 13 tree species were identified within the plot, with a density of 1,056 trees/ha exceeding 4 cm DBH documented in the 50 m x 50 m plot. Four dominant species, *Mora gonggrijpii*, *Chlorocardium rodiei*, *Mora excelsa*, and *Catostemma commune*, constituted over 60% of the total tree species (Figure 4-5, Table 1). The tallest tree in the plot was from the species *Chlorocardium rodiei* reaching a height of over 31 meters, while the largest measured DBH was 65 cm for a tree belonging to the *Mora gonggrijpii* species. In the smaller 10 m x 10 m plots, 368 trees ha^{-1} with a DBH between 1-4 cm were recorded, with species composition similar to the larger trees. Additionally, within the 4 m x 4 m plots, 1,580 saplings/ha under 1 cm in DBH were identified, although their species identification was not done for these smaller plants. The soil samples collected from the control plot were darker in color compared to those from the mined-out areas and had a thicker layer of organic matter, containing more leaves and small roots. The soil texture was classified as silty clay loam.

Figure 4 Visualized forest conditions of the control plot

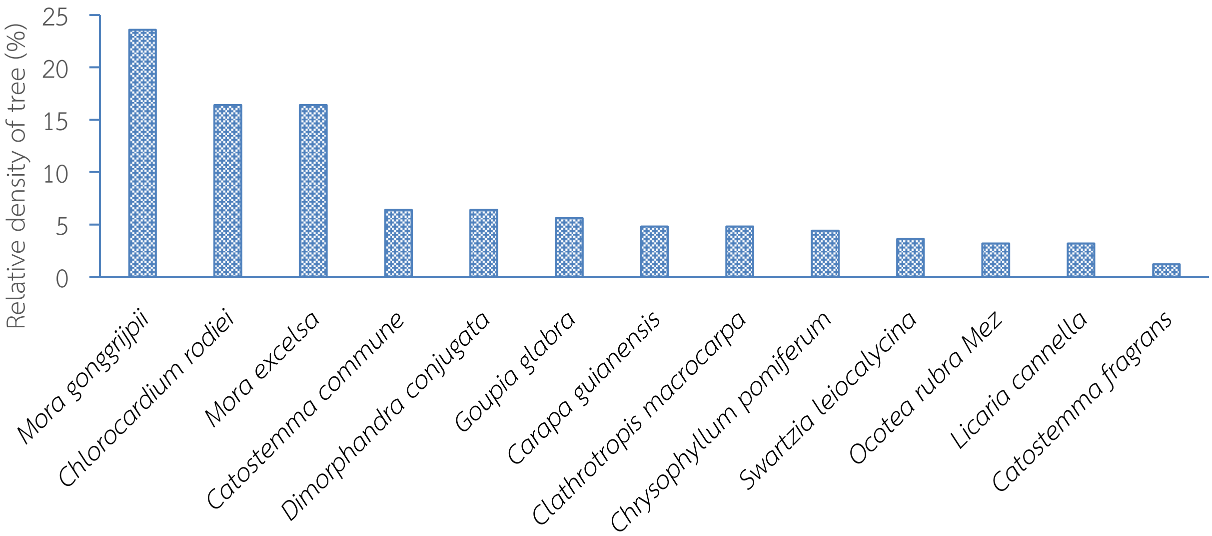


Figure 5 Species composition of the control plot

Mined-out areas

We investigated the forest conditions in abandoned mining areas over a chronosequence of 1, 5, 10, and 15 years. Visually, it was evident that the pit areas had almost no tree cover. Figure 6 depicts the visual comparison of plots abandoned for 1, 5, 10, and 15 years. After one year post-mining, the area exhibited minimal regrowth, with no presence of forest species. The perimeter of mining area was primarily covered with grass species that were all less than 0.5 meters tall. A few trees from the Cecropia peltata and Vismia guianensis species were found, predominantly in the overburdens. The height of the tallest tree recorded in this area was 5.2 meters, with the largest DBH recorded at 8 cm. No vegetation, either trees or grasses, was found in the tailings pond or the mining pit. Soil samples from this area had a slightly darker color relative to other samples across the chronosequence, except for the control plot. The soil texture varied from sandy clay loam to clay loam.

Plots abandoned after five years had a slightly higher biomass than the one-year plots, though the soil conditions were below optimum to support robust plant growth five years post-mining. These plots were dominated by grasses, with various species reaching heights of up to 1.5 meters in some areas. Thin grass cover was also present in the mining pits and tailings pond. A small creek running near the plots may have contributed to the presence of grasses, as the area is prone to flooding during the rainy season. This periodic flooding would have likely promoted grass growth while also potentially preventing the establishment of trees. The soil in these plots was classified as clay loam to loam, with more coarse particles compared to the other mined-out plots. This coarser texture is likely a result of the creek's floodwaters, which may wash away finer particles, leaving heavier, coarse material behind.

The abandoned mining areas after ten years had a higher biomass accumulation compared to the earlier stages in the chronosequence. However, tree growth remained confined to the areas outside of the mining pits and tailings ponds, indicating that toxic heavy metals and a lack of nutrients were still hindering the vegetation regrowth within these zones. These plots had a lower grass cover compared to those abandoned for shorter periods, although the overburden was densely populated with pioneer species such as *Cecropia peltata* and *Vismia guianensis*. The tailings pond had very little grass cover, but small amounts of organic matter, such as dead leaves from the overburden, were found in both the mining pits and tailings pond. The soil particles in these plots were finer than those sampled from the earlier stages, with textures ranging from clay to sandy clay. Despite the higher biomass, no forest species had been able to re-establish in these areas, suggesting that forest regeneration was still limited by the site's degraded soil conditions.

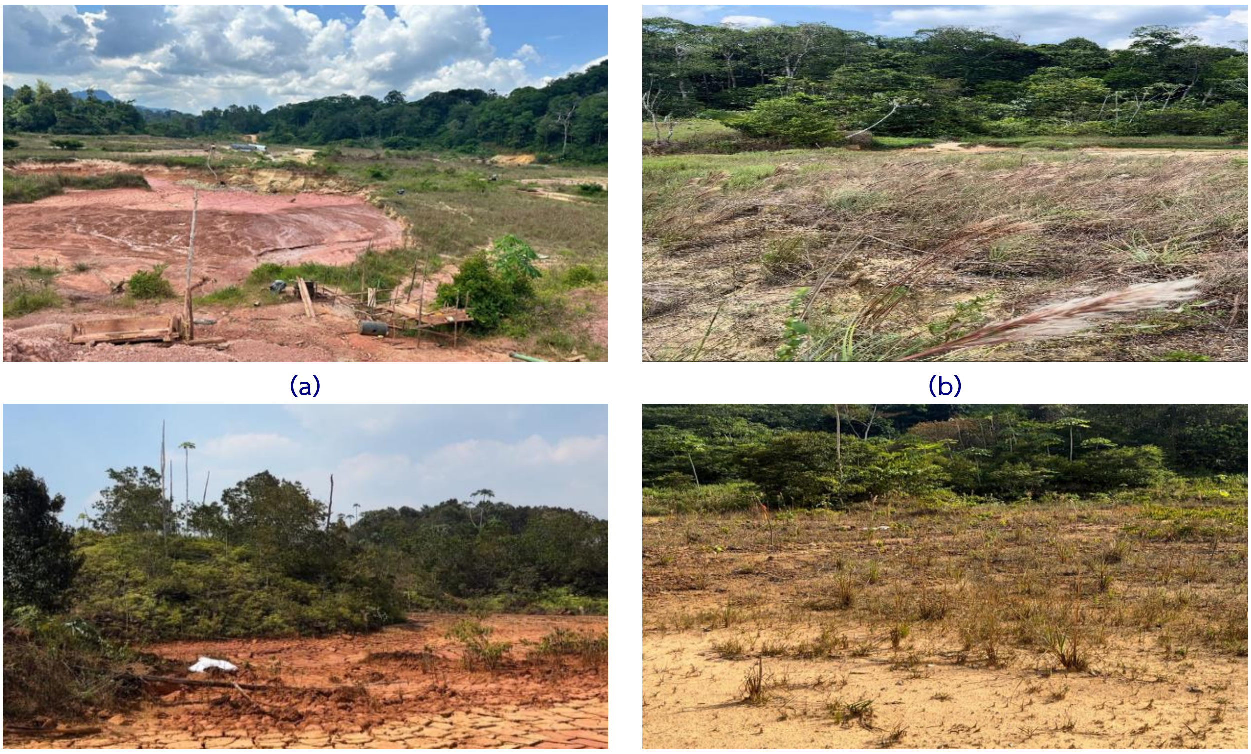
The area in plots abandoned for 15 years had similar condition as that of the 10-year plots, indicating that, without human intervention, natural recovery in mined-out areas can be exceedingly slow, even after 15 years (Figure 6). Notably, a few trees were observed growing in the tailing ponds and mining pits, although these were not forest species but rather the same pioneer species, *Cecropia peltata*. The general area remained largely covered with grasses, some of which appeared dead, likely due to a lack of water availability. The overburden and perimeter of the tailing ponds and mining pits were dominated by *Cecropia peltata* and *Vismia guianensis*, similar to previous stages. The soil texture in these plots was classified as clay loam, with a light brown color similar to that observed in the 5-year plots.

Based on the information described, it is clear that 15 years after the mines were abandoned, the areas did not fully recover. All the forest parameters investigated—such as total number of individuals, tree height, DBH, and species diversity—remained significantly lower than those in the control or nearby primary forest plots. Extreme soil conditions resulting from gold mining, including altered physical properties, nutrient depletion, and higher levels of heavy metal toxicity, appeared to have severely hindered plant regrowth. Notably, certain parts of the mining areas, particularly the mining pits and tailings ponds, had little to no growth. The removal of topsoil, rich in organic matter and essential nutrients like nitrogen and phosphorus, played a major role in the lack of vegetation regrowth (Arcand *et al*., 2010; Khadka, 2016). Additionally, heavy metal contamination further inhibited plant regeneration (see sections below), making these areas less conducive to recovery.

Despite these harsh conditions, large grass cover was observed in the 5- and 15-year abandoned areas, with grasses reaching up to 1.5 meters in height in the 5-year areas and 1 meter in the 15-year areas. While the total basal areas increased over time in the abandoned plots, they remained well below the levels in the control plots. Only two tree species, Cecropia peltata and Vismia guianensis, were identified in the mined-out areas. These species are low-density, short-lived pioneer species that typically colonize disturbed areas after strong disturbance to the local ecosystem.

Table 1 Forest characteristics of the control plot and of the plots after 1-15 years of mining termination

Plots	Total number of Trees per ha DBH >4 cm	Number species	Average height (m)	Average DBH (cm)	Total basal area (m^2/ ha)
Control	1056	13	10.0	13.8	1,376.1
1	48±8	2±1	4.2±1.0	6.4±1.0	12.2±3.0
5	52±9	1±0	5.7±1.0	7.1±1.0	16.4±3.0
10	220±32	2±1	5.8±2.0	7.9±2.0	95.5±7.0
15	192±28	2±1	5.2±2.0	7.9±2.0	87.3±9.0



(a) (b) (c) (d)

Figure 6 Mined out area after (a) one year (b) after five years (c) after ten years and (d) after fifteen years

Biomass and carbon storage

The results indicate that even 15 years after the cessation of mining activities, the total biomass in the area was less than 1% of that in the control plot. The biomass estimated in the control plot was 665 tons ha^{-1}, while the biomass in the 15-year post-mining area was only 2-3 tons ha^{-1}, with an average biomass increase of approximately 0.2 tons per year. At this rate, it would take over 200 years for the forest to recover naturally to a level comparable to that of the primary forest, making natural recovery without intervention highly unlikely. Similar recovery time scales were reported by Nyenda *et al*. (2021) in mining areas.

Human intervention, therefore, is necessary for successful regeneration and remediation in these mined-out areas. The first step should involve modifying the terrain to restore to its original state, primarily by replacing the nutrient-rich topsoil removed during mining. This process would not only help reduce erosion but also replenish essential soil nutrients (Lewis *et al*., 2022). Additionally, successful reclamation efforts, such as the planting of *Acacia mangium* Willd., have been shown to accelerate the recovery of mined out sites (Lewis *et al*., 2020).

In terms of carbon storage in vegetation biomass, the total carbon storage is directly proportional to the total biomass. The control plot stored 313 tons of carbon per hectare (ton C ha^{-1}), compared to just 0.12, 0.19, 1.30, and 1.15 ton C ha^{-1} after one, five, ten, and fifteen years after mine abandonment, respectively (Figure 7). These findings highlight that the slow regeneration of species in mined-out areas can significantly reduce the carbon storage capacity of these ecosystems.

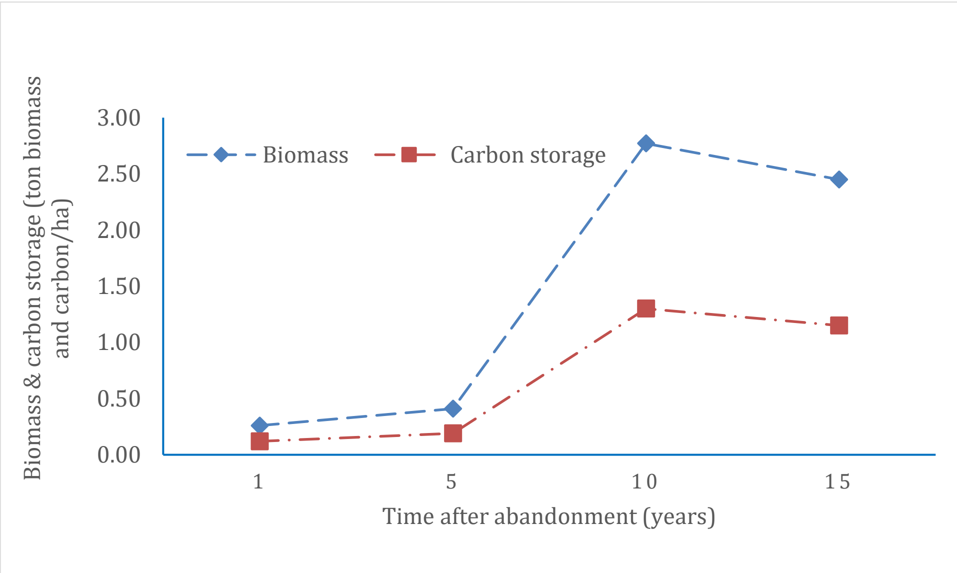


Figure 7 Biomass and carbon storage in aboveground and belowground biomass after 1-15 years of mining activity.

Heavy metals

Gold mining activities often lead to heavy metal contamination of the environment (Fashola et al., 2016). The primary sources of this contamination are the wastes generated during mining, mineral processing, and metallurgical extraction. In gold mining, more than 99% of the extracted ore is typically discarded as waste (Fashola *et al*., 2016). In small-scale mining, mercury is frequently used to separate gold from other materials (Stoffersen *et al*., 2018). In this study, the concentrations of arsenic, chromium, mercury, lead, iron, and copper were measured (see Figures 8, Table 2) and are discussed below.

Arsenic (As)

Arsenic (As) is naturally present in the Earth's crust and found in significant quantities in air, water, and soil. In its inorganic form, As is highly toxic (WHO, 2022a). Studies by Harmanescu *et al*. (2011) and Durães *et al*. (2021) have shown a strong correlation between arsenic concentrations in the environment and gold mining activities. For instance, Bempah *et al*. (2013) reported as concentrations as high as 1,752 mg/kg in gold mine tailings compared to the permissible level of As in soil of 20 mg/kg (Mercado and Aribal, 2020). The results from this study, as shown in Figure 9, indicate a significant increase (p < 0.05) in arsenic levels relative to the control plot

(2 mg kg^{-1}) to 279 mg/kg in mining pits abandoned for one year. These findings are consistent with previous studies, which also found elevated as levels in mining pits one year after mining activities (Bempah *et al*., 2013; Tóth *et al*., 2016; Akoto *et al*., 2023). However, the results show a decrease in concentrations over time, with reduction to nearly the same levels as the control (3 mg kg^{-1}) after 15 years of abandonment. The Enrichment Factor (EF) analysis indicates that as levels were extremely severe after one year but decreased to moderately severe in years five and ten, and to minor enrichment by year fifteen. This substantial decrease suggests that arsenic leached from the topsoil into deeper layers or nearby waterways over time.

Chromium (Cr)

Chromium (Cr) is found naturally in the rocky soils and is classified as a carcinogen. Cr is highly soluble and poses a significant hazard by contaminating the groundwater and entering the food chain. Its presence adversely affects plant growth by impairing essential metabolic processes and promoting the production of reactive oxygen species (ROS), leading to oxidative stress in plants (Sharma *et al*., 2020). Léopold *et al*. (2016) found that Cr levels in mined-out soils (57.53 mg kg^{-1}) were significantly higher than in non-mined areas (24.53 mg kg^{-1}). In this study, Cr concentrations fluctuated throughout the chronosequence. Cr levels increased from 155 mg kg^{-1} in the control plot to 188 mg/kg in plots abandoned after one year, that decreased to 110 mg/kg after five years. Interestingly, a significant increase ($p < 0.05$) was observed in plots abandoned for ten years, with Cr levels reaching 798 mg kg^{-1}. The reason for this observation is unclear, but it may be due to the sampling of a hotspot area. After fifteen years, Cr levels decreased significantly to 42 mg kg^{-1}, which was lower than the control plot levels. The EF analysis indicated no enrichment in samples from years five and fifteen, with minor to moderately severe enrichment observed in years one and ten, respectively. It is to be noted that the permissible level of Cr in soil is 100 mg kg^{-1}, a threshold exceeded by all samples except those from plots abandoned for fifteen years (Mercado and Aribal, 2020).

Mercury (Hg)

Mercury (Hg) is naturally present in the Earth's crust and is released into the environment through natural processes such as weathering of rocks and volcanic activity, as well as human activities. The primary sources of Hg pollution from human activity include coal-fired power plants, household coal burning, industrial processes, waste incineration, and mining operations, particularly mercury, gold, and other metal mining. As Hg cannot be destroyed, it can be recycled and repurposed, reducing the need for further mercury mining. The use of Hg is particularly hazardous in artisanal and small-scale gold mining, where it poses serious health risks to vulnerable communities (World Health Organization [WHO], 2017). Globally, artisanal and small-scale gold mining is responsible for around 37% of mercury emissions into the air and water (WHO, 2013).

The results from this study showed minimal changes in Hg concentrations throughout the chronosequence. Interestingly, there was a significant decrease ($p<0.05$) in Hg levels after one year (0.10 mg kg^{-1}) compared to the control plot (0.16 mg kg^{-1}). Previously, Kalamandeen *et al*. (2020) had also noted that mercury leached quickly from mining areas, with Hg levels in pits abandoned for six months to three years being two orders of magnitude lower than in active pits. After five years, Hg concentrations slightly increased to 0.19 mg kg^{-1}, and in pits abandoned for ten years, there was a significant increase ($p<0.05$) to 0.28 mg kg^{-1}compared to the control. By year fifteen, Hg levels had slightly decreased to 0.27 mg kg^{-1}. Notably, all Hg concentrations across the chronosequence remained below the WHO/FAO permissible limits for soils (0.3 mg kg^{-1}; Ssenku *et al*., 2023). The EF analysis indicated minor Hg enrichment in plots abandoned for five to fifteen years.

Lead (Pb)

Lead (Pb) is a naturally occurring toxic element found in the Earth's crust. Its widespread use has led to significant environmental contamination, human exposure, and major public health concerns. Globally, exposure to Pb-contaminated soil and dust from mining activities has resulted in widespread Pb poisoning and several child fatalities (WHO, 2023).

Léopold *et al*. (2016) found that Pb concentrations in exploited areas (19.02 mg kg^{-1}) were higher than in non-exploited areas (15.77 mg kg^{-1}). Similarly, Akoto *et al*. (2023) reported that Pb levels were up to 15-fold higher in areas where gold-bearing rocks were being excavated, processed, and where mine tailings were dumped, compared to control areas.

The results from this study confirm that Pb levels in soil increased following the stoppage of mining activities. A significant positive correlation between Pb and as was observed by Akoto *et al*. (2023), indicating that similar anthropogenic activities may influence both metals. The findings of this study are consistent with those of Léopold *et al*. (2016) and Akoto *et al*. (2023), demonstrating a significant increase (p<0.05) in Pb levels one year post-mining, with concentrations increasing to 8.32 mg kg^{-1} compared to the control. However, no significant changes were observed after five and ten years, with Pb levels measured at 2.84 mg kg^{-1}and 4.09 mg/kg, respectively. Interestingly, after 15 years, Pb levels increased significantly to 13.42 mg kg^{-1}. The findings indicate that Pb levels generally increase following gold mining activities and that these levels do not reduce significantly even after 15 years. Importantly, the measured Pb levels in this study were below the permissible limit of 50 mg kg^{-1} for soils (Mercado and Aribal, 2021).

Copper (Cu)

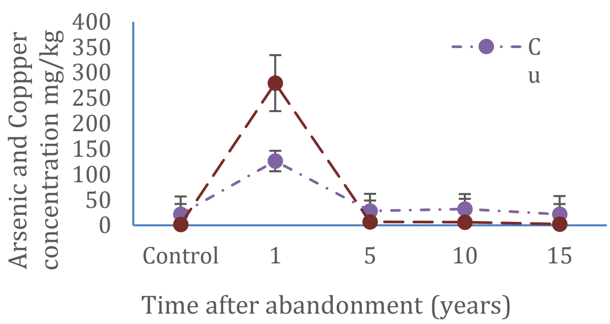
Copper (Cu) is both a pollutant in drinking water and an essential nutrient, with excessive levels in the body leading to organ damage and malfunction. Copper is widely used in alloys, coatings, and in the production of pipes, valves, and fittings (Abdul-Wahab and Marikar, 2011; WHO, 2022b). Cu is a high-density chemical element that can accumulate during the gravimetric concentration procedures at gold mining sites, leading to geochemical anomalies and contamination hotspots (Cesar *et al*., 2011). Tun *et al*. (2020) observed an increase in the heavy metals associated with gold mining, including copper, after mining activities, posing environmental and health risks to humans and animals.

In the present study, Cu concentrations significantly increased (p<0.05) to 126 mg kg^{-1}one year after mining, compared to 22 mg kg^{-1}in the control site. However, over time, the concentration of Cu in the soil decreased and returned to levels similar to the control site after 15 years. The EF analysis indicated that the soil was moderately severely enriched with Cu one year after mining, but the enrichment was classified as minor to negligible for years five, ten, and fifteen. This suggests that copper may leach out from the soil over time or be washed into nearby streams. It is important to note that the permissible level of copper in soils is 100 mg kg^{-1}, with all the measured levels in this study beling below this limit, except for the samples from the one-year plots (Mercado and Aribal, 2020).

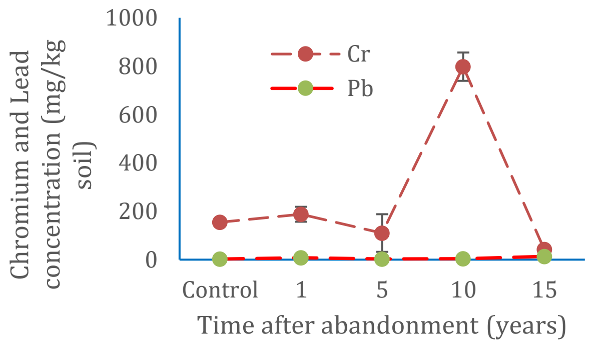
Iron (Fe)

Iron (Fe) concentrations in soils generally range between 20,000 and 550,000 mg kg^{-1}. Due to the specific characteristics of the soil and external factors, native Fe concentrations can vary significantly, even at smaller distances. In a study by Léopold *et al*. (2016), contrasting results were found in soils exploited by gold mining in Cameroon. In one area, exploited soils had a mean of 65,926 mg kg^{-1} (ranging from 40,976 to 120,926 mg kg^{-1}) compared to non-exploited soils with a mean of 35,039 mg kg^{-1} (ranging from 22,497 to 45,278 mg kg^{-1}). In another area, the mean Fe concentration in exploited soils was 41,197 mg kg^{-1} (ranging from 17,226 to 77,358 mg kg^{-1}), while non-exploited soils had a mean of 47,015 mg kg^{-1} (ranging from 41,416 to 52,159 mg kg^{-1}). These findings indicate that iron levels may depend largely on the soil's natural composition rather than mining activities alone.

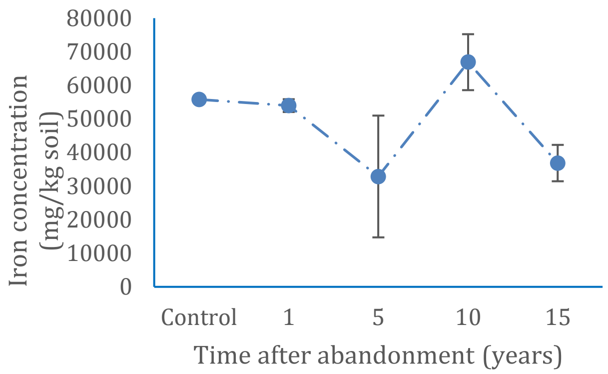
The results of the present study showed fluctuations in Fe concentrations across the chronosequence, though none were found to be statistically significant (p<0.05). One year after the mining, there was a slight decrease in Fe concentration (53,966 mg kg^{-1}) compared to the control (55,783 mg kg^{-1}). After five years, the concentration further decreased to 32,862 mg kg^{-1}, followed by an increase to 66,902 mg kg^{-1} after ten years. Finally, after 15 years, the concentration returned to levels similar to the five-year mark (36,857 mg kg^{-1}). These results do not indicate to any clear trends in the Fe concentrations over time, supporting Léopold *et al*. (2016) findings that iron levels can vary considerably, even within the same area. Notably, the permissible levels of iron in soil is 50,000 mg/kg, and only the samples from the five- and fifteen-year plots were below this threshold (Mercado and Aribal, 2020).



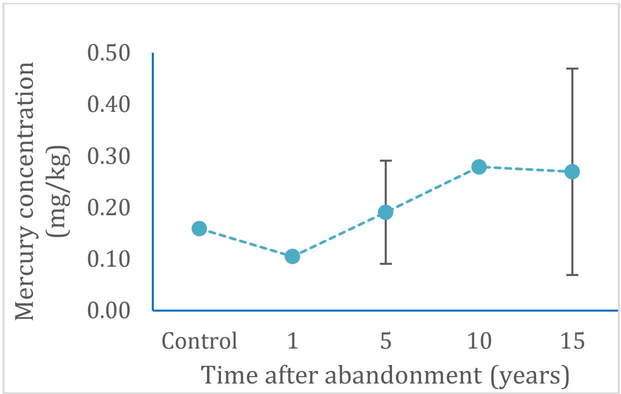
(a)



(b)



(c)



(d)

Figure 8 Changes in (a) Arsenic (As) and copper (Cu) concentrations over the chronosequence (b) Chromium (Cr) and Lead (Pb) concentrations over the chronosequence (c) Iron (Fe) concentrations over the chronosequence and (d) Mercury (Hg) concentrations over the chronosequence.

Table 2 Changes in heavy metal content in the soil from the mined-out areas (means ± S.D. of 3 replications). Values with the symbol (*) indicate a significant difference from control at $p<0.05$

Years after mine	Heavy metal content (mg/kg)					
Abandonment	Pb	Fe	Cu	Hg	As	Cr
Control	3.0±0.1	55,783±119	22±1	0.2±0.1	2.0±0.8	155.0±3.4
1	8.0±0.1*	53,966±1,911	126±21*	0.1±0.1*	279.0±28.0*	188.0±30.9
5	3.0±0.1	32,862±18,131	29±8	0.2±0.1	7.0±7.7	110.0±77.8
10	4.0±1.5	66,902±8,332	32±4	0.3±0.1*	6.0±3.2	798.0±58.6*
15	13.0±1.4*	36,857±5,414*	22±5	0.3±0.2	3.0±0.4	42.0±14.3*

Nutrients

In this study, the total nitrogen, phosphorus, and potassium content were measured and are plotted in Figure 9. Kalamandeen *et al*. (2020) noted that nutrient depletion, particularly nitrogen loss due to mining, may have a greater impact on forest regeneration than mercury contamination, as nutrient-poor soils hinder plant growth. Román-Dañobeytia *et al*. (2015) also pointed out that mining-related topsoil excavation depletes soils of essential nutrients and organic matter, significantly slowing the forest recovery compared to other land uses. Similarly, Khadka (2016) found a significant positive correlation between soil organic matter and total nitrogen levels, emphasizing the importance of maintaining high organic matter content to balance the macronutrient concentrations. The results of this study indicated to a significant decrease (p<0.05) in nitrogen content from 1,691 mg kg^{-1} in the control plot to 720 mg kg^{-1} one year after mining. This reduction is likely due to the absence of litter and organic matter on the topsoil, where nitrogen is typically stored. The mining pits and tailings pond areas, which had little to no vegetation, further exacerbated this decline. While nitrogen levels slightly increased over time, they remained significantly below the levels observed in the control plot. Nitrogen concentrations after five, ten, and fifteen years were estimated at 847 mg kg^{-1}, 923 mg kg^{-1}, and 863 mg kg^{-1}, respectively, suggesting that a lack of forest cover and organic matter continued to inhibit the recovery of nitrogen.

In comparison to nitrogen, phosphorus and potassium were not exhibit a pronounced change relative to the control plot. The removal of topsoil to access gold ore can lead to the loss of phosphorus. Nyenda *et al*. (2021) observed a gradual increase in phosphorus content over time in mine tailings, spanning from 10 to 110 years. However, the results of this study showed an overall significant decrease (p<0.05) in phosphorus across the chronosequence, except for the one-year pits. After one year, the total phosphorus was 321 mg kg^{-1}, a slight increase from the control plot's 287 mg kg^{-1}. By year five, the phosphorus levels ad dropped significantly to 155 mg kg^{-1}. In years ten and fifteen, phosphorus levels were recorded at 179 mg kg^{-1} and 152 mg kg^{-1}, respectively, both significantly lower than the control plot. The removal of topsoil, rich in organic matter, appears to have had a major impact on the phosphorus levels in the soil, contributing to the observed depletion over time.

We did not find any significant correspondence between potassium levels and gold mining activities, suggesting that other factors may have influenced its concentration. In the control plot, potassium levels were recorded at 311 mg kg^{-1}. After one year, potassium levels significantly increased (p<0.05) to 723 mg kg^{-1}. In the pits abandoned for five years, the mean levels dropped to 263 mg kg^{-1}, and after ten years, they decreased further to 100 mg/kg. Interestingly, after 15 years, potassium levels increased to 795 mg kg^{-1}. These variations throughout the chronosequence indicate that mining activities did not significantly affect the potassium levels, indicating to the likelihood that other environmental or soil-related factors influenced the potassium concentrations (Figure 9).

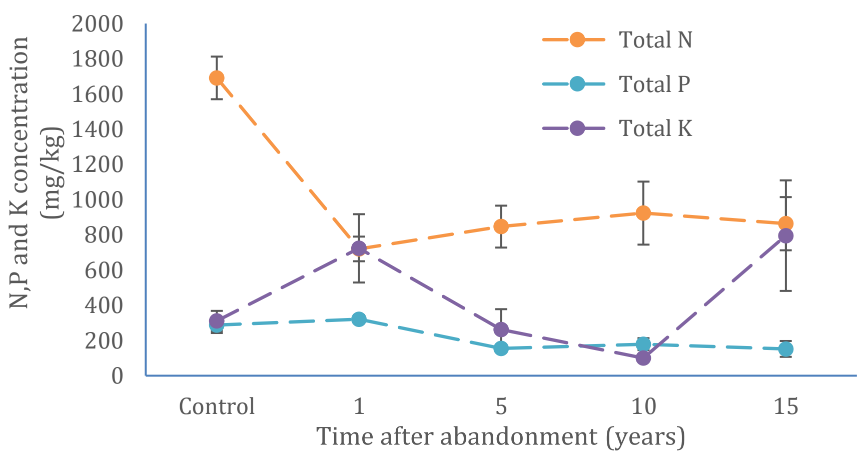


Figure 9 Changes in total nitrogen, phosphorus and potassium in the control and mined-out areas

The pH of the control soil was measured at 4.95, which is typical for regions with high rainfall. Following one year of mining, the pH increased to 5.22, and peaked at 5.59 after five years, with both increases being statistically significant (p<0.05). However, after ten years, the pH sharply declined to 5.17, followed by a further reduction to 5.14 after 15 years. The general trend shows a significant increase in soil pH during the first five years post-mining, followed by a gradual decline over time, as illustrated in Figure 10.

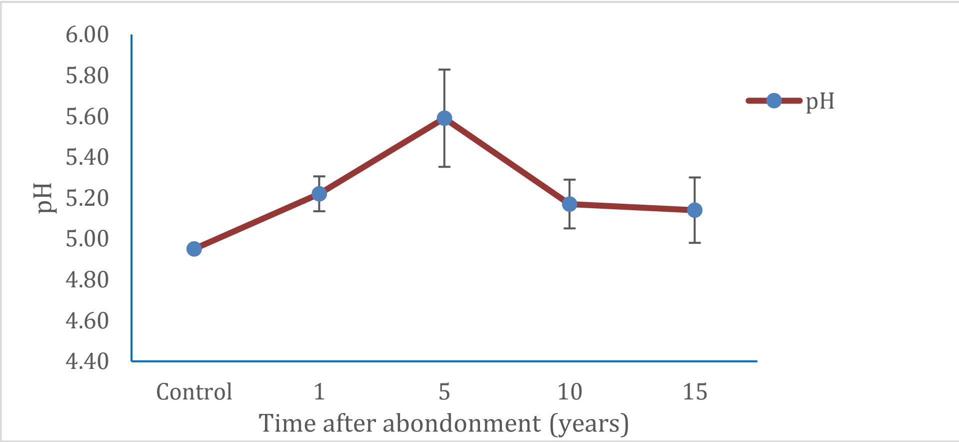


Figure 10 Changes in pH levels over the chronosequence

CONCLUSIONS

The results indicate that essential plant nutrients, particularly nitrogen and phosphorus, significantly diminished following mining activities, likely contributing to the limited biomass recovery observed throughout the chronosequence. Heavy metals such as copper, arsenic, and chromium significantly increased one year after mining, peaking at different times compared to the control. However, most heavy metal concentrations returned to levels similar to the reference levels after 15 years, except for lead and mercury. These two metals remained elevated even after 15 years, suggesting that they persisted in the soil at high concentrations and did not readily leach out.

Biomass recovery over the 15-year period was notably low, potentially due to the nutrient depletion and sustained high levels of mercury and lead, both of which negatively affect plant germination and natural ecological processes. This study established a baseline for the natural conditions observed after 15 years, highlighting that natural regeneration is highly challenging without intervention. Effective remediation, including backfilling and soil nutrient management, is essential for promoting plant growth and biomass recovery, underscoring the need for human intervention to reclaim and restore these lands.

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