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Temporary Effect of Mining on Breathing and on the Physicochemical Conditions of Soil

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Abstract: The physicochemical variables and the respiration of the soil were characterized in the areas of 5, 15 and 30 years of post-mining recovery and a reference forest. We used 15 plots of 200 m^2 (4 × 50), in each of the successional stages (area of early succession, forest of late succession and reference forest) for a total of 60 plots. The results showed that after the mining, the contents of OM, total N, Al and clay were increased; while, the concentrations of available P and sand decreased. The edaphic availabilities of Ca, K, Mg, CICE and silt increased during the intermediate stages of succession, and were reduced in the reference forest, while the variables indicating edaphic microorganism activity (H, CH_4 and CO_2) were high in all the scenarios evaluated. It was concluded that after 30 years of recovery the K, Ca and Mg have their greatest availability in the soil and that with the advance in plant succession the availability of total N and MO increases due to the recovery of the forest increases the accumulation of aerial and subterranean vegetation biomass, which increases the accumulation of OM of the soil, given the balance of income and expenses due to production and decomposition of organic waste (litter) of the forest. It is evident that with open-pit mining in tropical rainforests, pedogenesis and soil development begins again, with the attenuating of not favoring the natural ecological recovery.

Key words: soil, mining, breathing, physicochemical conditions

1. Introduction

Soils are fundamental components of tropical forest ecosystems [1]. Since, according to their physicochemical characteristics, they determine plant diversity, ecological succession, net primary productivity, nutrient recycling and the role of forests in mitigating global climate change [2-7]. However, these ecosystem components are strongly threatened by the destruction and degradation of habitats, which generate significant negative impacts on their ecological functioning [8]. In particular, open-pit mining is one of the main anthropogenic activities that causes losses and significant degradation of tropical soils. Open-pit mining of metals is a harmful process against tropical soils; since, in the exploitation process, the vegetation cover and the edaphic substrate covering the exploited mineral deposit are removed [9, 10]; As a result, soil aggregates are eroded, texture is changed, moisture content is reduced, nutrients are leached, the substrate is contaminated with toxic waste (mercury), vegetation is reduced and associated ecological processes are affected [9-11]. Also, after the mining activity the residual material is accumulated forming small mounds, characterized by having very low fertility and presenting, in the upper part, coarse textures (gravels and coarse sands), with very little

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moisture content and low proportions of silt, clays and organic matter (MO), due to the process of water dragging and deposition in the lower parts of the mound [12]. Therefore, a mosaic of soil substrates and plant communities are generated in different successional stages, differentiated according to the time and intensity of the disturbance [9].

When open-pit mining is carried out, the soil is totally exposed (without surface horizons, nor forest cover) and the nutrients are easily lost by leaching [10], this situation accentuates the infertility of the soil and hinders plant succession and recovery [12, 13]. Given that mining has strong impacts on the edaphic system, it is essential to develop restoration processes to recover the ecological functions developed by tropical soils [10, 12-14]. In particular, soil type, microbial activity, texture and availability of nutrients have a primary effect on the recovery of soils in degraded areas 12, 13, 15]; consequently, in order to effectively execute restoration programs it is necessary to know how the physicochemical properties of the soil change in successional ecosystems degraded by mining.

It has been hypothesized that in tropical soils, in initial successional stages, there is a limitation by nitrogen (N), which over time is mitigated due to the colonization of atmospheric N2 fixative plants [16]; in turn, this N fixation is limited by the availability of P and humidity. Therefore, as the succession progresses, this limitation is reduced [15, 17]. Unlike N, P levels in the soil tend to be high in the first successional stages, and over time it tends to decrease its availability, due to losses by leaching and immobilization in Fe and Al sesquioxides [18-20]. However, some studies that evaluate the edaphic parameters in different successional stages show that the nutrients present different dynamics that differ from the hypothesis proposed [21-23]; For example, Werner (1984) [21] showed that some minerals increase temporarily and then decrease (Fe, Al, H, MO, total N), some fluctuate (NH4-N, PO4-P) and others decrease (Ca, Mg, K, Mn). While, Li et al. (2013) [23] observed that with the passage of time in the succession there were no significant changes in total P and soil NH4-N. Which, evidences that each ecosystem presents different environmental conditions that condition the ecological succession and consequently the restoration of degraded areas; likewise, these investigations denote uncertainties and lack information in this regard.

The biogeographic Chocó region is considered one of the most biodiverse and endemic hotspots on the planet [24]. However, in these ecosystems, rural communities constantly conduct gold and platinum open-pit mining [25, 26]. According to the Ministry of Mines and Energy of Colombia, as of 2011, ≈ 268,821 hectares of forest have been granted for this activity [27, 28]; likewise, according to the IIAP (2001) [29] about 360 hectares of natural forest are destroyed each year as a result of this activity [29]. This produces soil degradation, pollution and considerable losses of diversity [30]. Given this situation, and with the purpose of evaluating the hypotheses about the dynamics of nutrients in tropical successions [21, 23, 31], we set out to evaluate the physicochemical properties of soil in successional ecosystems degraded by mining in forests of the biogeographical Chocó.

2. Materials and Methods

2.1 Study Area

The present study was conducted in the San Juan mining district, in the Jigualito corregimiento, belonging to the municipality of Condoto, in the department of Chocó, Colombia. The town of Jigualito is located at an altitude of 74 masl; it limits to the North with Guarapito by the highway that leads to Chiquichoqui, to the South with Novita by the watershed between the rivers Tamaná and Opogodó, to the East with Opogodó, to the West with the Tigre by the streams El Tigre and Luis (City Hall of Condoto 2004). The average annual rainfall of the area is 8000 mm per year, the relative humidity is 90%, the soils are mostly Ultisols, and the life zone corresponds to tropical rain forest [32, 33]. According to Valoyes

(2017) [34], the area presents a landscape contrast because it still contains areas with a dense vegetation cover without anthropic intervention, where variables such as topography and climate converge, which model the landscape between 100-250 m of altitude. On the well-drained slopes there are species such as Brosimum utile (HBK) Pittier, Huberodendron patinoi Cuatrec, Campnosperma panamensis Standl, Oenocarpus minor Mart, Mauritiella macroclada (Burret) Burret, Carapa guianensis Aubl., Cespedesia spathulata (Ruiz and Pav.) Planch, Euterpe precatoria Mart, Vismia macrophylla Kunth, Saccoglotis procera (Little) Cuatrec, Iriartea deltoidea Ruiz and Pav, palmares of Wettinia quinaria (OFCook and Doyle) Burret, mixed with Welfia regia H.Wendl., Socratea exorrhiza (Mart.) H. Wendl., And Oenocarpus bataua (Mart.) At the level of the arboreal stratum, and Geonoma cuneata H. Wendl. ex Spruce, at the level of the shrub layer among other species [35].

2.2 Selection of Sampling Sites

With information from the people of the community of Jigualito who were exclusively dedicated to mining in the area; In addition, with the support of the Community Councils of Condoto, Rio Iró (COCOMACOIRO), and the town of Jigualito, and finally with the support of the Mayor's Office of Condoto, three areas were defined with different stages (or elapsed times) and/or post-intervention chronosequences by gold and platinum open-pit mining. In this sense, an area with recent disturbance was defined (Area of early succession with 5 years of recovery), another area with an intermediate time of recovery (Area of late succession with 30 years), and finally a secondary Forest. In each of these areas, the physicochemical characteristics of the soil were measured to observe and quantify the changes that occur in edaphic systems after mining activity.

2.3 Area of Early Succession (5 Years)

Located at coordinates 1043965 N, 1047797 W, corresponds to a forest recently intervened by mining activity, with a soil devoid of organic matter, without defined horizons, composed mainly of gravel, with a micro topography with intermediate undulations, surrounded by artificial lagoons (channels resulting from mining activity). The area has little vegetation, a process of primary succession was observed where the dominant flora is composed of herbaceous species consisting mainly of Gramineae (Andropogon bicornis L., Cyperus luzulae (L.) Rottb.), Legumes (Mimosa pudica Mill.) , Rubiáceas (Borreria latifolia (Aubl.) K. Schum) and Melastomatáceas (Aciotis sp, Nepsera aquatica (Aubl.) Naud) among others and some species of woody plants in seedling and juvenile state, which are dispersed and close to the matrix [34, 35].

2.4 Forest of Late Succession (> 30 Years).

Located at coordinates 07641582 N and 0502416 W; corresponds to a forest of late succession, presents a moderate micro topography with undulations in the terrain. The soil lacks a defined structure, it is composed of gravel left by the mining activity, which is nourished by the litter product of the biomass that the trees present in the area contain. The vegetation is dominated by Cespedesia spathulata, accompanied by other pioneering species such as Cecropia peltata, Cecropia sp, Conostegia micrantha (with variable heights that exceed 15 m and DAP ≥10 cm) [34, 35].

2.5 Reference Forest

It is located at coordinates 7641063 N, 0501424 W, corresponds to an area of intervened forest, with advanced succession process where mining activity has not been practiced; it presents soils with a homogenous topography, poorly drained, with a defined structure and a defined organic layer; The vegetation of the area is made up of varied species whose composition and structure is dominated by tree species, some of them from intervened areas, but dominate species of the original composition [34, 35].

2.6 Establishment of Plots

We used 15 temporary research plots of 200 m^2 (4 × 50) each, in each of the successional stages (Area of Early Succession, Forest of Late Succession and Secondary Forest Reference); for a total of 45 sampling plots. These plots were established between 2013 and 2016; and in turn, they were divided into five squares of 4 × 10 m (40 m^2) considered as registration units; in which soil samples were taken for this study.

2.7 Soil Analysis

To evaluate the fertility of areas degraded by mining, composite soil samples were used, taken at the four corners and in the center of the grid (4 × 10 m), and then unified, collected at 20 cm depth, previously removing the leaf litter and organic material thereof; In each of the three successional stages, 15 composite samples of soils will be taken, giving a total of 45 samples; Samples were analyzed for the texture, pH, MO content and nutrient content (N, P, K, Ca, Mg), in the Biogeochemistry laboratory of the National University of Colombia Medellin Headquarters, using the techniques that are referenced then: the texture with the Bouyoucos technique, the pH in water (1: 2) with Potentiometer, the MO content with the Walkley and Black technique, the total N with the Micro-Kjeldahl technique, the P was extracted by the method of Bray II and determined with ascorbic acid in UV-VIS spectrophotometer, the nutrients Ca, Mg, and K were extracted with 1M ammonium acetate, neutral, and determined by atomic absorption [36].

2.8 Statistic Analysis

Measures of central tendency and dispersion of the data were calculated. To compare the soil fertility (texture, MO, pH, Al, N, P, Ca, K, Mg, CICE) of the three successional stages in areas degraded by mining, the nonparametric tests of Kruskal Wallis were used because they were not they fulfilled the assumptions of normality and homogeneity of variances of the data, evaluated with the Bartlett's and Hartley's tests. By means of principal component analysis (PCA), the physicochemical variables (acidity, MO, nutrient content and texture) of the soil in each one of the scenarios or successional stages were related multilineally. The analyzes were carried out with the Statgraphics Centurion XV [37] and The R Project for Statistical Computing programs (www.r-project.org/).

3. Results

3.1 Soil Fertility

In the areas degraded by open-pit mining, it was observed that the soils show extreme acidity in different stages of ecological succession (5, 15 and 30 years), with greater acidity in the reference area. Aluminum concentrations were low in the early stages of recovery of degraded areas, but in the reference forest, their content was significantly high, reaching values close to toxicity (2.41 cmolc kg^{-1}) (

Table 1). The contents of Ca, K, Mg and CICE were low in the first years after mining (5 and 15 years), then increased significantly with the passage of time, until reaching intermediate and high values (30 years); finally, concentrations in the reference forest tend to be low again. On the other hand, the available soil content is very high in the mines, but decreases drastically with the passage of time, to such an extent that in the reference forests its content is very low. The contents of total N and organic matter are low in the areas degraded by mining, but show considerable increases with the passage of time after mining, with the highest values in the reference forest. A similar trend shows the percentages of silt and clay in the soil, which are very low in the intervened areas, but increase their concentration in the reference forest. The sand content was high in the areas of 5, 15 and 30 years, and shows a reduction in the reference forest (

Table 1). In summary, it was observed that after the mining, the contents of OM, total N, Al and clay increased; while, the concentrations of available P and sand decreased. On the other hand, the edaphic availabilities of Ca, K, Mg, CICE and silt, increased during the intermediate stages of succession, and then decreased in the reference forest (

Table 1).

When evaluating the changes in the physicochemical characteristics of the soils after the degradation by mining, it was observed that the edaphic concentrations of total MO and N were limited during the first 30 years of recovery. Contrary to this, the amount of available P was high in the initial stages (5 and 15 years) after mining, and decreased significantly with the succession. The concentrations of Ca, K and Mg were very low in the initial stages, after 30 years they increased their availability considerably, while in the reference forest the edaphic quantities were smaller. The observed trends in nutrient availability (Ca, K and Mg) were also evidenced in the pH, the CICE and the percentage of soil silt. Finally, the edaphic concentrations of Al and clay increased significantly with the recovery of the ecosystem; while, the sand content decreased.

The PCA showed an underlying gradient determined by age after abandonment, where elements such as organic matter and nitrogen showed a marginal increase with the age of abandonment among the mines, but a drastic increase between them and the reference forest (Fig.). In summary, the soil variables measured in the areas of 5, 15, 30 years and the reference area varied among themselves, and indicated that the areas intervened together have sandy soils and are poorer in nutrients when compared with the soil in the reference forest. Specifically, variables such as phosphorus, pH, magnesium and calcium were related to each other and were higher in the areas of 5, 15 and 30 years than in the reference forest, while nitrogen and organic matter presented positive relationships and were manifested with greater magnitude in the reference forest. The rest of the measured variables did not vary significantly between successional environments (

Table 1).

Table 1 Physical and chemical characteristics of the soil in sampling plots in mines of 5, 15 and 30 years after the abandonment and reference forest in Condoto, Chocó, Colombia.

Variable	Escenario																Kruskal-Wallis	
	5 años				15 años				30 años				Bosque referencia					
	Media	Min	Max	DE	Media	Min	Max	DE	Media	Min	Max	DE	Media	Min	Max	DE	H	*P*
A	69.6	56.0	84.0	10.8	57.5	57.0	58.0	0.71	46.8	28.0	58.0	11.4	64.4	28.0	90.0	20.6	0.70	0.12
L	19.6	10.0	34.0	9.1	18.5	18.0	19.0	0.71	36.0	28.0	42.0	5.10	21.2	8.00	38.0	9.67	8.74	**0.03**
Ar	10.8	6.0	16.0	3.6	24.0	24.0	24.0	0.01	17.2	12.00	30.0	7.56	14.4	2.00	34.0	11.3	3.98	0.26
pH	4.4	4.0	4.7	0.3	4.8	4.7	4.8	0.07	4.60	4.20	5.40	0.48	4.06	3.80	4.30	0.18	11.6	**0.008**
N	0.2	0.1	0.3	0.1	0.2	0.2	0.2	0.05	0.20	0.06	0.27	0.09	0.64	0.36	1.05	0.25	15.9	**0.001**
MO	0.8	0.1	1.5	0.6	1.8	1.7	1.8	0.07	6.82	3.70	9.00	2.20	12.8	4.40	23.8	7.78	14.6	**0.002**
Al	1.4	0.6	2.1	0.6	1.5	1.4	1.5	0.07	1.38	0.34	2.16	0.69	2.12	1.05	3.43	0.75	4.74	0.19
Ca	0.4	0.2	1.0	0.3	0.3	0.3	0.3	0.01	3.22	0.80	5.50	1.92	0.13	0.08	0.27	0.06	16.3	**0.001**
Mg	0.3	0.1	0.4	0.1	0.4	0.4	0.4	0.01	1.63	0.34	3.20	1.13	0.24	0.12	0.47	0.11	10.9	**0.01**
K	0.05	0.03	0.1	0.03	0.3	0.3	0.3	0.01	0.18	0.07	0.28	0.08	0.14	0.06	0.31	0.07	13.1	**0.004**
CIC	2.2	1.5	2.9	0.7	2.3	2.2	2.4	0.14	6.40	2.40	9.50	2.78	2.65	1.40	3.90	0.83	7.47	0.06
P	29.2	19.0	44.0	9.7	17.0	16.0	18.0	1.41	18.2	7.00	37.00	12.2	2.10	1.00	3.00	0.74	17.1	**0.001**

3.2 Biological Activity of the Soil

The variables indicating the biological activity of the soil (H, CH_4 and CO_2) showed statistically significant differences between the sampling scenarios, in this sense, in general terms the activity was higher in the reference forest and in the area with 15 years of recovery (Table 2). However, from the biological point of view, it is important to note that the biological activity of the soil is high from early stages of succession, in particular, all the variables that indicate activity of edaphic microorganisms were high in all the scenarios evaluated (Table 2, Fig.). The previous trend was maintained even throughout the entire measurement time of the indicator variables (Fig.).

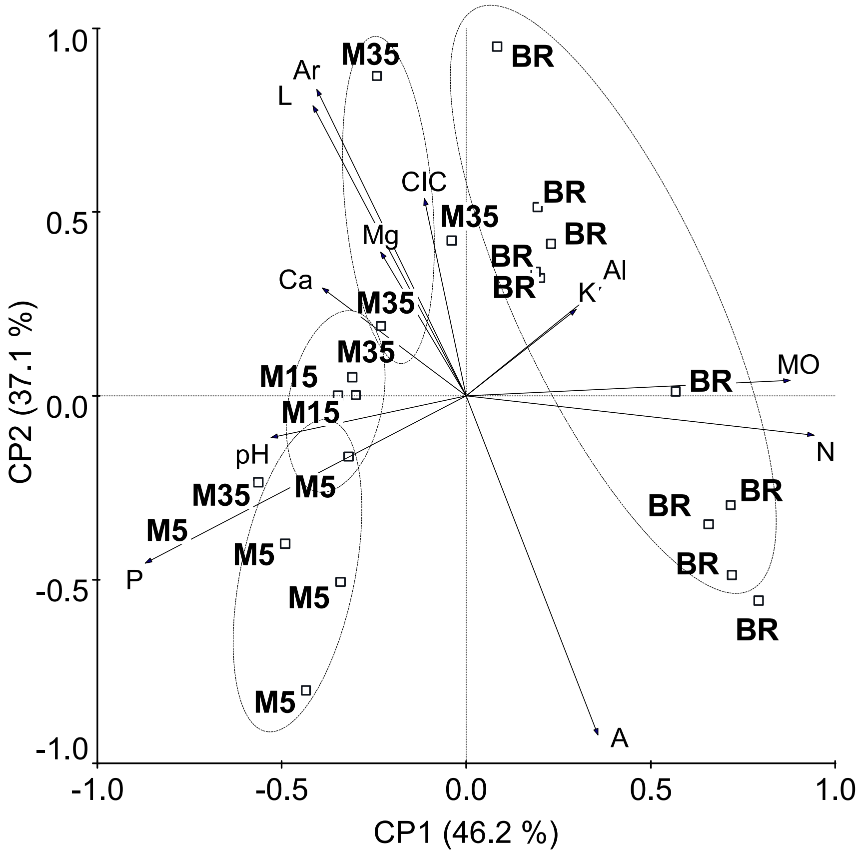

Fig. 1 Principal components analysis (PCA): physical and chemical characteristics of the soil in sampling plots in mines of 5, 15 and 30 years after abandonment and reference forest in Condoto, Chocó, Colombia.

Table 2 Indicator variables of biological activity in the soil of mines and reference forest in Condoto, Chocó, Colombia.

Escenarios	Variables		
	H	CH_4	CO_2
5 años	567.5±37.7	479.7±29.6	394.3±28.2
15 años	698.9±27.6	604.0±33.4	558.8±36.6
30 años	543.3±31.9	505.4±35.9	400.2±37.1
BR	686.7±21.8	564.6±14.3	497.1±10.8
$F_{3,11364}$	19831.9	10351.1	19842.5
P	< 0.0001	< 0.0001	< 0.0001

4. Discussion

Changes in soil acidity in areas degraded by mining: Areas degraded by open-pit mining with different recovery times in Jigualito, Condoto (Chocó), presented extremely acid soils (Table 1, Fig.). This corroborates the extreme acidity previously recorded in tropical rain forests in the localities of Bajo Calima, Opogodó, Pacurita and Salero, in the Chocó Biogeográfico [33, 38]. Furthermore, these observations confirm the tendency of acid soils mentioned in several studies carried out in tropical humid forests [2, 32, 39-41].

The extreme acidity in tropical soils is mainly generated by the leaching of basic cations (Ca, Mg, K and Na) and the accumulation of acid cations (Al and H) due to environmental factors such as high precipitation [42, 43]; likewise, due to the influence of other factors such as the high content of MO that releases carbonic acids that acidify the soil, and the symbiotic fixation of N_2 that liberates H + ions that increase soil acidity [43]. Therefore, it can be stated that, in areas degraded by mining in the biogeographic Chocó, variations in the concentration of cations, MO and total N, possibly explain in greater proportion the changes in soil acidity levels. In the successional stage that presented lower acidity (after 30 years of recovery), the highest availability of cations (K, Ca and Mg) was also registered.

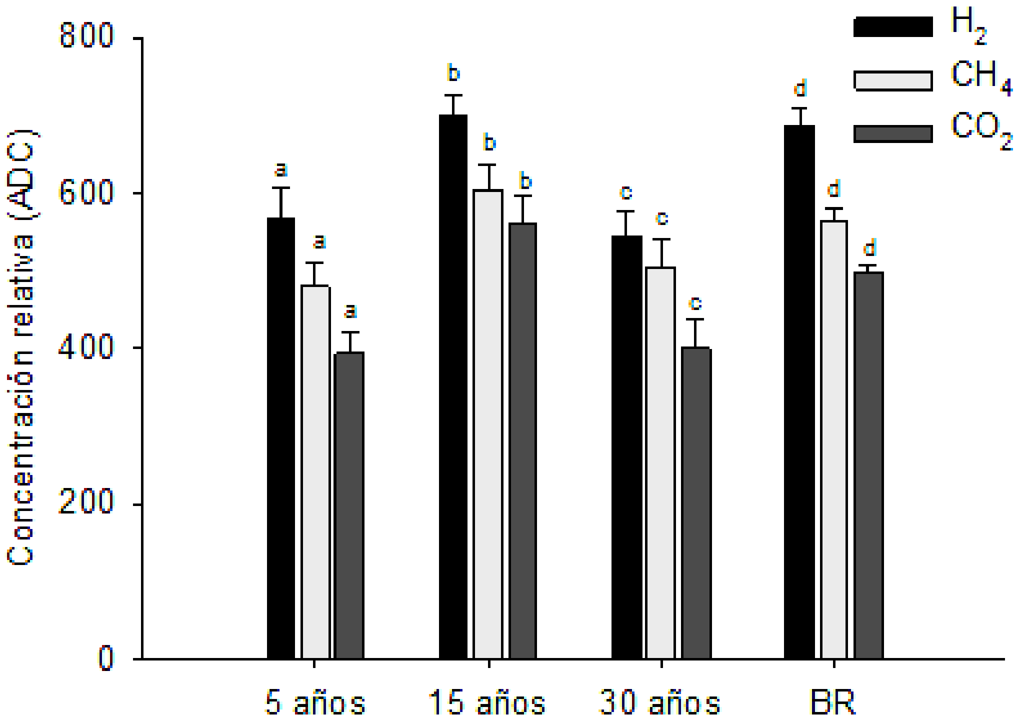

Fig. 2 Biological activity of soil in mines and reference forest in Condoto, Chocó, Colombia.

However, the trends in soil acidity of areas degraded by mining were different from those recorded by Li et al. (2013) [23] who observed greater edaphic acidity in successional stages characterized by having soils rich in OM and minerals (K, Zn, Cu, Fe) in tropical forests of China [23]. Also, the results of the present study were different to those mentioned by Werner (1984), who observed that pH levels remained relatively constant through plant sequences following deforestation processes in tropical forests of Costa Rica. These differences in edaphic acidity with plant succession after anthropic interventions of different tropical rainforests [4], show that pH levels are very sensitive to local edaphic conditions (nutrients, MO, humidity, etc.); and that, in addition, due to its sensitivity it would not be a good edaphic predictor in terms of restoration of degraded ecosystems, especially those degraded by open-pit mining.

Changes in the content of Aluminum, Calcium, Potassium and Magnesium in the soil in areas degraded by mining: The reference forest presented the highest concentration of Al soil (Table 1, Fig.), which, evidences a possible toxicity that is frequent in these geographical zones, which are similar with the high mineral levels registered in the soils of localities like Bajo Calima, Salero and Pacurita, in the biogeographical Chocó [38, 44]. The reason why it increases the Al soil with the succession in areas degraded by mining, is surely because when open-pit mining is carried out, the mechanical action of the backhoes on the ground and subsoil, expose fragments of igneous and metamorphic rocks that by weathering processes they gradually release minerals (Al, Fe, S, P, Mg, K, etc.) to the residual soil [9, 10, 12]. A large part of these minerals, released to the ground by weathering, are rapidly leached by intense rains [36, 45, 46]; However, the concentration of Al tends to increase, possibly due to the fact that its leaching rate is lower than that of the other minerals [36]. In addition, the Al may be in soluble forms in the soil solution, interchangeably absorbed on the surface of the negatively charged clays, complexed by the OM of the soil, and/or precipitated as a secondary mineral in the form of oxide and hydroxide in the soil, which explains its high availability in extremely weathered soils such as Ultisols and Oxisols [36]; similar to what occurs in clay soils with high aluminum content in the Chocó Biogeographic [47].

In tropical areas that have suffered anthropogenic disturbances, soil nutrients increase their availability during the initial and intermediate stages of succession; but later, they reduce their concentration in the advanced stages of ecosystem development [4, 21, 31, 48]. Particularly, in areas degraded by mining in Jigualito, after 30 years of recovery, K, Ca and Mg presented their greatest availability in the soil (Fig.); However, when comparing the content of these minerals in the ground of the reference forest, a decrease in their concentration is noted. Possibly, by the absorption and immobilization of cations in the vegetable biomass of the forest, which represents one of the main mechanisms of conservation of limiting nutrients [4, 49, 50]. These patterns of increases and reductions in the concentration of nutrients in areas degraded by mining are similar to those registered in soil development processes (pedogenesis) and primary succession, in which the availability of nutrients and soil fertility increase in the first stages of pedogenesis; but at the end of the succession, when a dynamic equilibrium is reached in the ecosystem, the concentration of nutrients decreases [31, 48]. Consequently, it can be concluded that, with open-pit mining in tropical rainforests of the biogeographic Chocó, an "edaphic rejuvenation" is generated.

Changes in the concentration of organic matter, total nitrogen and soil phosphorus in areas degraded by mining: it was evidenced that, with the advance in plant succession after mining, the availability of total N and OM in the soil increases. Particularly, the OM presented very high values and increased with the natural recovery time of the system. This increase is possibly due to the fact that the recovery of the forest increases the accumulation of aerial and subterranean vegetation biomass [23, 51], which increases the accumulation of OM of the soil, given that it is the result of the balance of income and expenses for the production and decomposition of organic waste (leaf litter) from the forest [44]. The high values of OM observed in areas degraded by mining have also been previously recorded in other tropical rainforests of the biogeographic Chocó [38, 52, 53]; which is probably due to the effect of high rainfall on the functioning of tropical forests; since, the high rainfall generates decrease in the foliar concentrations of N, P, Ca and Mg [45, 46, 52, 54], decreases the decomposer activity of microorganisms due to lack of oxygen [54, 55], it reduces the decomposition rate of organic matter [56], and therefore reduces the edaphic availability of nutrients [57]; as a result of the above, the content and time of replacement of the organic matter of the soil is increased [52], and explains the high contents of OM in areas degraded by mining after 30 years.

Finally, changes in soil concentrations of total N and P available in areas degraded by mining, showed increases and reductions, respectively. These trends corroborate the hypothesis that in tropical soils, in initial successional stages, there is a limitation by nitrogen (N), which over time is mitigated due to the colonization of atmospheric N_2 fixative plants [16]; in turn, this N fixation is limited by the availability of P and humidity. Therefore, as the succession progresses, the total N of the soil increases and its limitation for the ecosystem is reduced [15, 17]. In addition, this hypothesis states that, unlike N, P levels in the soil tend to be high in the first successional stages, and over time tends to decrease their availability, due to losses by leaching and immobilization in Fe and Al sesquioxides [18-20]. In summary, it is evident that with open-pit mining in tropical rainforests of the biogeographic Chocó, pedogenesis and soil development begins again, with the attenuating of conditioning the natural ecological recovery.

Biological activity of soil in areas degraded by mining. The variables indicating the biological activity of the soil (H, CH_4 and CO_2) showed that in all the evaluated scenarios the microbial activity is high (Table 2), even in the mines poor in nutrients (Fig.). These results are possibly due to the fact that the activity of soil microorganisms is determined by various environmental variables such as temperature, humidity, acidity, clay content, soil alterations, quality and quantity of organic material, and characteristics of the microbial community, among others [58], which determine considerably processes like microbial respiration in edaphic ecosystems like those of the biogeographic Chocó. Specifically, the soils of the biogeographic Chocó evaluated in this study are characterized by high temperatures and humidity [32, 33], high contents of organic matter and acid soils (Table 2 and Fig.); which, favors microbial activity in these areas.

According to Mendiara (2012) [58], the main edaphic processes that influence the process of soil respiration are leaching, fragmentation and chemical alteration. In particular, soil fragmentation is a preponderant process in areas degraded by mining, and would explain to a large extent the high microbial activity in these edaphic ecosystems; since, with mining, accumulated residual material is generated forming small mounds; characterized by having coarse textures (gravels and coarse sands) in the upper part [9, 12]. In short, mining increases the amount of rock fragments and soils; consequently, such fragmentation of the soil creates new surfaces for microbial colonization and increases the proportion of the amount of residues that are accessible to the attack of microorganisms [58]; which would partially explain the high microbial activity of areas degraded by mining.

However, the highest microbial activity occurred in the reference forest and in the mines with 15 years of recovery (Table 2); which, possibly, is due to the combination of environmental factors (high humidity, temperature, organic matter) favorable for the activity of microorganisms [58]. Specifically, high humidity (90%) is produced in 15 year old mines due to the constant and heavy rains of the region, which favor microbial activity; likewise, high temperatures are a constant in these ecosystems, which are devoid of dense forest cover, the product of deforestation by mining, with which solar radiation is direct, which increases the temperature and favors the activity of microorganisms. This assertion is based on the point raised by Raich and Schlesinger (1992) [59], who consider that, on a global scale, soil respiration is influenced by average annual temperatures and precipitation, and the interaction between these two variables [59]. In addition, explain that soil temperature is one of the factors that has greater importance on the growth and survival of edaphic microorganisms. Since, as the temperature rises, chemical and enzymatic reactions are accelerated, so that the growth, metabolism, biomass and rate of microbial respiration increase considerably in the soil [58-60]. In addition to the above, these mines presented accumulations of organic matter (1.8%) as a result of the colonizing vegetation; which, favors the microbial activity. In short, the joint action of the high humidity (product of precipitation), the temperature (generated by direct solar radiation) and the accumulation of organic matter, is responsible for the high microbial activity recorded in the areas of early stages of succession (15 years); which may be similar to that recorded in the neighboring reference forests.

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