CHARACTERIZATION OF THE EDAPHIC PROPERTIES IN A CHRONOSEQUENCE OF LAND REHABILITATION, CERREJON MINE, LA GUAJIRA, COLOMBIA

CARACTERIZACIÓN DE PROPIEDADES EDÁFICAS EN UNA CRONOSECUENCIA DE REHABILITACIÓN DE TIERRAS, EN LA MINA CERREJÓN, LA GUAJIRA, COLOMBIA

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ABSTRACT

Carbones del Cerrejon Limited, a coal mining company located in the department of La Guajira, Colombia for more than 25 years has implemented the process of rehabilitating land used for mining once the operations are concluded, closing the mining cycle. The main objective was to characterize the edaphic properties in a chronosequence of land rehabilitation (0, 5, 10, 15, 20 years) and the control. Soil sampling was performed at depths of 0-3, 8-11, 16-19 and 24-27cm; with the following physical properties (bulk density, fine granulometry) and chemical properties (pH, electric conductivity, organic carbon, cationic exchange capacity, Phosphorus, interchangeable cations), following the Agustin Codazzi Geographic Institute protocols. The results indicated that there are significant differences in the behavior of all edaphic parameters except Electric Conductivity. Additionally, it was found that most of the evaluated properties, after 20 years ago, presents conditions close to those of areas not intervened by the mining, giving indications of stability and new pedogénesis, that during the first years of rehabilitation was not possible to detect because of its high variability in the soil layer applied on the sterile rock dump (30cm). Based on this, we conclude that the properties of the rehabilitated soils under the model implemented, in semi-arid environmental conditions and without anthropic pressure, give indications of progressive evolution with similar quality to the undisturbed soils in the area.

Keywords: rehabilitation, pedogenesis, mining.

RESUMEN

Carbones del Cerrejón Limited, empresa de minería de carbón, ubicada en el departamento de La Guajira, Colombia, por más de 25 años, ha implementado el proceso de rehabilitación de tierras intervenidas por la minería, una vez finalizan las operaciones, cerrando el ciclo minero. Se planteó, como objetivo general, caracterizar las propiedades edáficas en una cronosecuencia de rehabilitación (0, 5, 10, 15, 20 años) y testigo. El muestreo de suelos, se realizó a profundidades de 0-3, 8-11, 16-19 y 24-27cm, con determinaciones de propiedades físicas (densidad aparente, granulometría fina) y químicas (pH, Conductividad Eléctrica, Carbono Orgánico, Capacidad de Intercambio Catiónico, Fósforo y bases intercambiables), siguiendo protocolos del Instituto Geográfico Agustín Codazzi. Los resultados indicaron que existen diferencias significativas en el comportamiento de todos los parámetros edáficos, excepto conductividad eléctrica. Adicionalmente, se encontró que la mayoría de las propiedades evaluadas transcurridos 20 años, presentan condiciones cercanas a las de zonas no intervenidas por la minería, dando

indicios de estabilidad que, en los primeros años, no fue posible detectar, por la alta variabilidad de las propiedades del material edáfico aplicado (30cm) sobre el estéril. Con base en lo anterior, se concluye que los suelos rehabilitados, bajo el modelo implementado, en condiciones ambientales semiáridas y sin presión antrópica, dan indicios de evolución progresiva con calidad similar a los suelos no intervenidos de la zona.

Palabras clave: restauración, pedogénesis, minería.

INTRODUCTION

Mining processes modify the environment and its interactions, which connects and reactivates through the functional rehabilitation. Among the impacts attributed to coal mining we can find the chemical and physical variation of the soil (Guerrero & Pineda, 2016), but the greatest impact has to do with the total transformation of the landscape and the loss of natural resources. There is an opportunity to mend the mistakes of the past, and provide post mining soils with the landscape's rehabilitation required sustainability. Altough the evaluation of proper alternative solutions is complicated, it requires the holistic inclusion of environmental, economic, and social impacts (Limaa *et al.* 2016). When there is not edaphic material reserved, the creation of renewable energy farming solutions called Tecnosoles is mostly considered as a cardinal way within the mining projects' rehabilitation techniques (Gómez-Ros *et al*. 2013). A situation that does not occur in the Cerrejon coal mine, located in La Guajira, Colombia, company managed by Carbones del Cerrejon Limited. (Gualdrón, 2011; Moscote & Castellanos, 2013).

The processes of land's rehabilitation that have been intervened by mining, requires a deep investigation of its physical, chemical, mineralogical and edaphic parameters (Díaz *et al*. 2013). The soil, as support of terrestrial ecosystems, have been the base to restore lands intervened by mining; although there are still successful cases of rehabilitation that did not need this resource (USC, 2014). Cerrejon has chosen to preserve the soils before mining processes, so when incorporating it to the rehabilitation process, its properties could be expressed again, which will make it suitable to support the vegetal communities.

In order to know these properties, every rehabilitation project must be under observation to control its evolution and to know if it has reached its goals (Pastorok *et al.* 1997; Mukhopadhyay *et al*. 2016); among the useful properties for observation we can find: hydrological availability, granulometry, organic carbon, electric conductivity, and others in semiarid conditions. The edaphoclimatic condition generates important tensioners in the soil. It is convenient that the applied rehabilitation reflects the dynamic and usefulness of the native soils in accordance with its characteristics. It is important this to evolve to soils with a reserve of water, nutrients, and properties that can be an optimum way of vegetation growth in the rehabilitation process areas (Moscote & Castellanos, 2013).

Soils intervened in mining areas could be located as Technosoles (IUSS-WRB, 2015) in a taxonomic way. It could also be located as soils with anthropic epipedon, which implies the variation and transportation of different origin material (USDA-NRCS, 2014) and the beginning of a pedogenesis with great anthropic influence that includes the use of mining material, edaphic substratum or a combination of both (Arranz-González, 2011).

The Cerrejon coal mine north zone has an extension of 69.364 hectares (Gualdrón, 2011), its coal production for 2016 was estimated in 32.4 million metric tons (Cerrejón, 2016). The land rehabilitation program started in 1990; it aims to restore the ecosystem in functional conditions, and leave it in a similar or better way. To achieve it, the company's rehabilitation model is based on the use of previously saved edaphic material, which comprises the following basic stages (Gualdrón, 2011): *(i)* **Land Reshaped,** it consists in preparing the ground built with mining waste and infertile material, to receive the soil that will be put on it. It begins when -after its final exploitation- mining operations cease and the area is released to start the rehabilitation. This implies reconfiguring the landscape, creating new flatland and hillsides homogenous and stable; plowing the base material to break the compaction and induce good physical condition in the area of contact. *(ii)* **Soil Stabilization (area grassed)**, it starts when applying a layer of soil on the sterile material (approx. 30cm of depth). That layer of soil derives from the mix of edaphic material that has been collected from the grounds, prior to mining; and it is submitted to the same way according to the mine protocol. It is protected against erosive processes through the seeding of *Cenchrus ciliaris* grasses, as a protective cover in all the rehabilitated areas. It is mainteined without additional anthropic intervention such as fertilization, management of phytosanitary problems and risk, in a range of 5 to 6 years; as well as the construccion of ebbs in the hillside to a secure and controlled conduction of superficial waters; Y *(iii)* **Revegetation or vegetal repopulation,** as a process of induced vegetal succession (approx. after 5 years), native species tress will be introduced in the rehabilitated areas. These trees will be replacing the herbaceous stratum, as it occurs in an ecological natural succession (Gualdrón, 2011).

With reference to the above, it was planned to provide soils that offer environmental services similar to the soils in the intervention areas; therefore, the goal was to characterize the rehabilitated soils in the Cerrejon mine chronosequence (0,

5, 10, 15, 20 years) to contrast it with the not intervened soils, analyze its changes and infer on its quality.

MATERIAL AND METHODS

The research took place in areas in process of rehabilitation at the Cerrejon mine, La Guajira, Colombia (Figure 1), within the following quadrant of coordinate: 11°02'56,9"N 72°44'29,3"W; 11°02'54,2"N; 72°34'36,5"W; 11°08'19,2"N; 72°33'28,9"W; 11°08'22"N; 72°43'21,9"W; located in an area classified as tropical dry forest (Bs-T), according to Holdridge's parameters (1978), the annual average precipitation is of 800 mm and an annual average ETP above 2.000mm. The temperature swings between 19.4° and 37.6°C, with an annual average value of 27°C; relative humidity swings between 70% and 80% in an annual average (Corpoguajira, 2012).

Speaking in a taxonomic context, most of the soils existing in this territory and before mining, corresponds to Aridic Haplustalf, with parental material consisting of highly altered tertiary sediments, low content of organic carbon, high content of interchangeable ions, with an Ochric and Argillic diagnostic horizon, with a superficial effective depth with limitations by clayey layer (30cm average) (Cerrejón PMA, 2001). In this sense, before the mining stage it is necessary to recognize the plots and to mark the extraction depth according to the description of the soil layer's conditions; if there are limitations to a specific depth, the extraction is carried out until that depth, therefore, the extraction's average depth is 30cm.

A sample design was used considering the time elapsed since the beginning of the operations in every area and plot
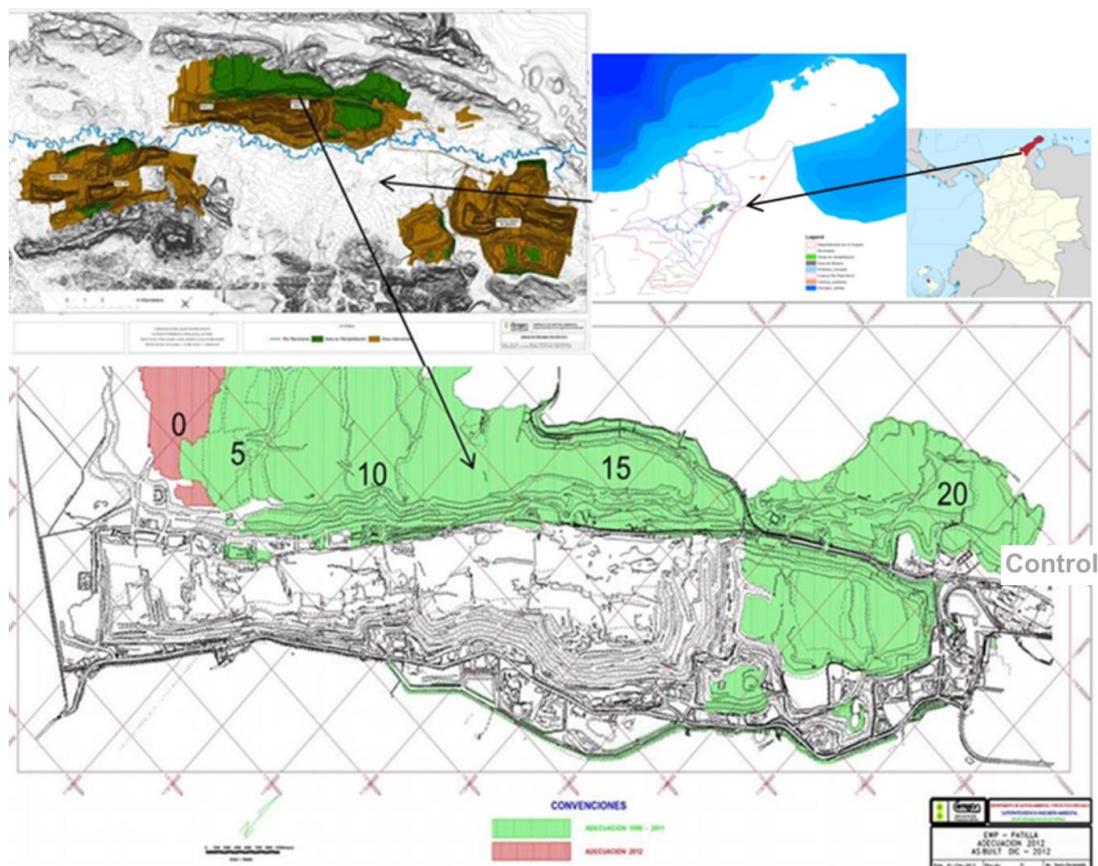
Figure 1. Location of the Cerrejon mine and area of study. (Source: Cerrejon, 2016)

in rehabilitation (treatment). The soils were submitted to the same standard management practice according to the protocol of Cerrejon Limited Company (Gualdrón, 2011), to study a chronosequence of lands rehabilitation (0, 5, 10, 15, 20 years). It was contrasted in relation to an area not-intervened by the mine company, called control. As it was previously explained, the plots evidence the changes of the vegetal succession in a spatial level; it was produced by the land rehabilitation strategy carried out by the company. In order to study the changes in the soil through the years, samples in 4 depth were taken: 0 - 3, 8 - 11, 16 - 19 and 24 - 27cm. In every plot of the chronosecuence 3 repetitions were taken, for a total of 72 samples with an approximate weight of 1.5kg per sample.

The studied edaphic properties were: a) bulk density by the ring or the nucleus method. b) total content percentage of sand, clay and silt, according to the measurement international system, by Bouyoucos method. c) pH, by potentiometric method. d) Electric conductivity (Ec), by the method of extract saturation plaster, and reading with a conductivity meter. e) Cation-exchange capacity (CEC), by the ammonium acetate method 1 N pH 7. f) Oxidize organic carbon (OC), by the method of Walkley & Black. G) Phosphorus (P), by the method of Olsen modified. H) Total interchangeable bases, Ca^{+2}, Mg^{+2}, Na^{+1}, K^{+1}, by the method of ammonium acetate 1 N a pH 7, reading by the optical spectrometer of atomic absorption. All these methods are present in IGAC (2006).

The information was analyzed comparing the data from the different plots in relation to the age, and the variation presented according to its development and rehabilitation time. This allowed to compare the soils non-intervened by mining. The age of the soils rehabilitation and the depth of the sample were considered as factors of analysis, which together were called as sample treatments. In order to establish if the data of the soils had a normal distribution, the Kolmogorov-Smirnov test was applied for the number of samples (n=72; p>0.05). Additionally, the Levene's variance homogeneity test was applied in order to corroborate the tendency to normality. According to the above, the results shows that the studied edaphic parameters do not follow a normal tendency; therefore, in order to compare the averages of the different studied variables the Kruskall-Wallis' non-parametric test was applied, and this way to be able to establish if there are differences in the plots according to the rehabilitation age and the depth of the sample. The IBM SPSS Stastics 22 (free) software was used.

Subsequently, it was carried out the analysis of the behavior of every edaphic property, considering the temporal (chronosecuence) and spatial (depth of the sample) factor. The programs Sigma Plot 12 (free) and Minitab 17(17.1.0) were used.

It was also conducted an analysis of the main components, in order to establish the tendency to similarity between the edaphic variables with potential of indicators about the quality of the rehabilitated soils in coal mining. The IBM SPSS Statics 22 (free) software was used.

RESULTS AND DISCUSSION

The Kruskall-Wallis non-parametric test was used to establish if there are differences in the different parameters of the soil, according to the treatments that combine rehabilitation age and depth. The results presented in table 1 shows that there

Table 1. Kruskal-Wallis Test applied to physical and chemical properties in a chronosequence in Cerrejon's rehabilitated soils (0, 5, 10, 15, 20 years, control) y 4 depth (N=72; si p<0,05 it is rejected Ho).

Properties	gl	Next. Asymptotic
pH	23	0.008
EC	23	0.114
OC	23	0.001
CEC	23	0.000
Ca	23	0.020
Mg	23	0.003
K	23	0.000
Na	23	0.004
AP	23	0.001
BD	23	0.004
Sand	23	0.000
Silt	23	0.000
Clay	23	0.036

are differences in every studied edaphic parameter, except for EC.

The distribution of mineral particles of the soil (sand%, clay%, silt%) influences the values of bulk density (Martín *et al*. 2017); therefore, knowing the texture of the soil allows to interpret with more accuracy the resultf of the bulk density. The mineral particles of the soil (sand, clay, silt) suffer processes of transportation and accumulation in a different way during the chronosecuence (Figure 2). No major changes were observed in the content of the sand and silt particles through the profile during the studied chronosequence. But in relation to the content of the clay, it is evident a percentage reduction in the surface after 20 years, compared to the beginning of the rehabilitation (0 years), which could be explained by migration processes to deeper layers dissolved in the water and moving between the pores of the soil that is reorganizing. It could also be explained by the growing of the roots of the

plants, elements that govern the neoformation of edaphic systems evident in the creation of structure (Macías *et al*. 1992). In that same direction, Ibáñez *et al*. (1988) indicates that the transportation of the particles through the profile of the soil (internal drainage) is part of its self-evolution.

This dynamic influences the bulk density (BD), which in figure 2 shows a great variability all along the new soil's profile (30cm), but in relation to the chronosecuence, a reduction of its value was observed, even regarding the control, which could be explained also by the vegetal dynamic and the processes activated by the incorporation of organic substance in the soils; and also the anthropic and animals low pressure, thanks to the isolation of rehabilitated areas in the mine. For this reason, the bulk density is considered as a dynamic property (Pla, 2013) to continue studying the stability and maturity of the soils in rehabilitation. The BD also has relationship with other physical properties of the
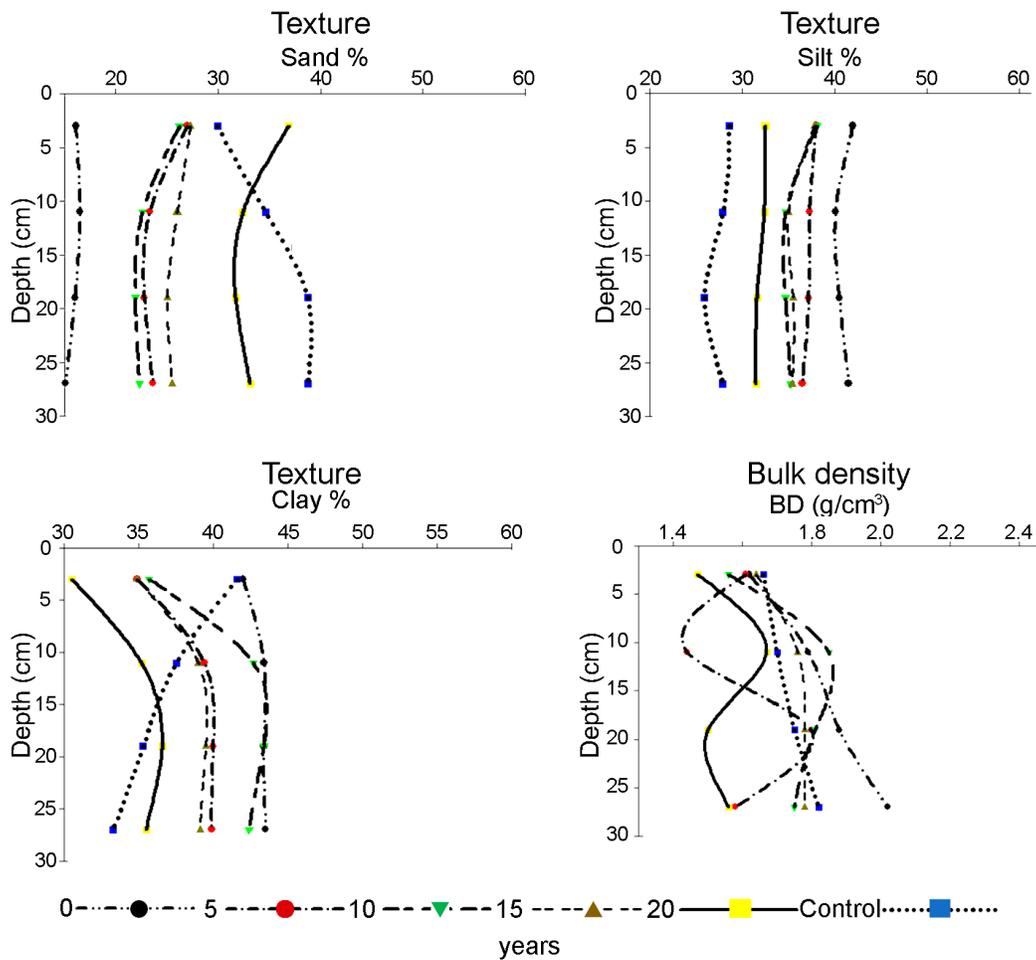
Figure 2. Variation of physical properties: soil's minerals percentage content (%SA, %SI, %CL), bulk density (g.cm⁻³), according to chronosequence (0, 5, 10, 15, 20 years and control) and depth (0-3; 8-11, 16-19, 24-27cm) in the Cerrejon mine.

soil such as structure, porosity and humidity tension (IGAC, 2014; Monroy *et al.* 2017) which will explain how to preserve soil's humidity and reduce its overflow and loss (Ghosha *et al.* 2015), allowing to design management strategies in a long term. In spite of the short time, the bulk density is showing signs of evolution of this new soil, getting close to the conditions of those that are in a dry forest without intervention (control), which is the purpose of the Cerrejon soil's rehabilitation program (Figure 2).

In connection with pH (Figure 3), its values are maintained in the typical ranges of alkaline soils of the area (IGAC, 2012; USDA- NRCS, 2014), the edaphic material used in the soil's rehabilitation program comes from the mix of the soils extracted before the mining stage who are taxonomic located in the Alfisols Order, as it was explained

In relation to the EC, the values observed (Figure 3) do not show a high salinity in the soluble phase (García, 2003), but differences were detected between the different plots by the age and the depth of the sample. It is lower in those who

have longer times of rehabilitation, even in relation to the Control plot.

As noted before, the creation of structure by the soil's mineral particles dynamic, in combination with the growth of the roots and the inclusion of organic substance (Macias *et al.* 1992; IGAC, 2014), allows the infiltration of good quality water (which comes from the rain) and the leaching of radicular zone salts (García, 2003), reducing the EC. It also helps that in rehabilitation's program practices, the superficial plowing of sterile material is applied before depositing the edaphic material, weeks before the beginning of the rains during the second semester every year for every plot (Gualdrón, 2011).

When referring to the cationic exchange capacity (CEC), its values are high (García, 2003) even in the control area (Figure 3), in accordance with the soils described by IGAC (2012) and Cerrejon company PMA (2001), which explains its mineralogy characteristics. The high variability in the first years could be explained also by the origin of the applied edaphic material layer, which comes from a mix of the soils of
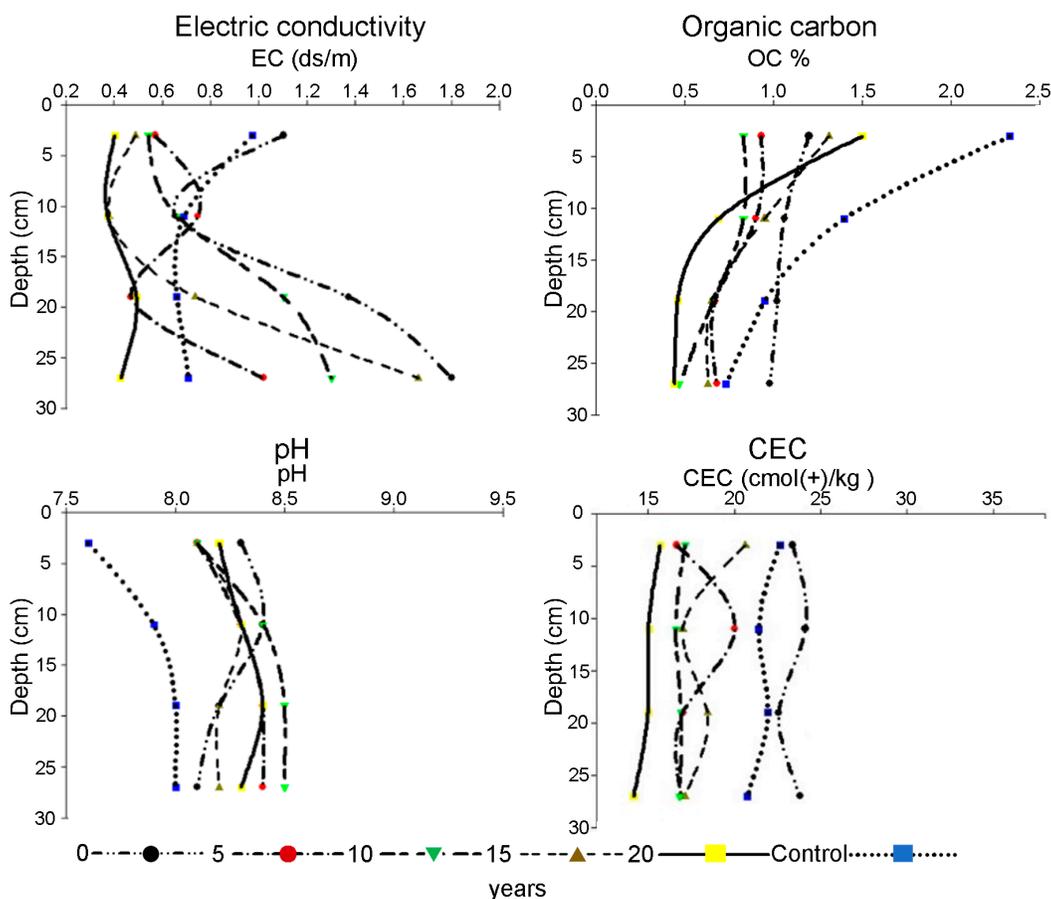
Figure 3. Variation of the soil's chemical properties: E.C.(dS.m^{-1}), O.C.(%), pH, CEC (cmol(+).kg^{-1}), according to chronosequence (0, 5, 10, 15, 20 years and control) and depth (0-3; 8-11, 16-19, 24-27 cm) in the Cerrejon mine.
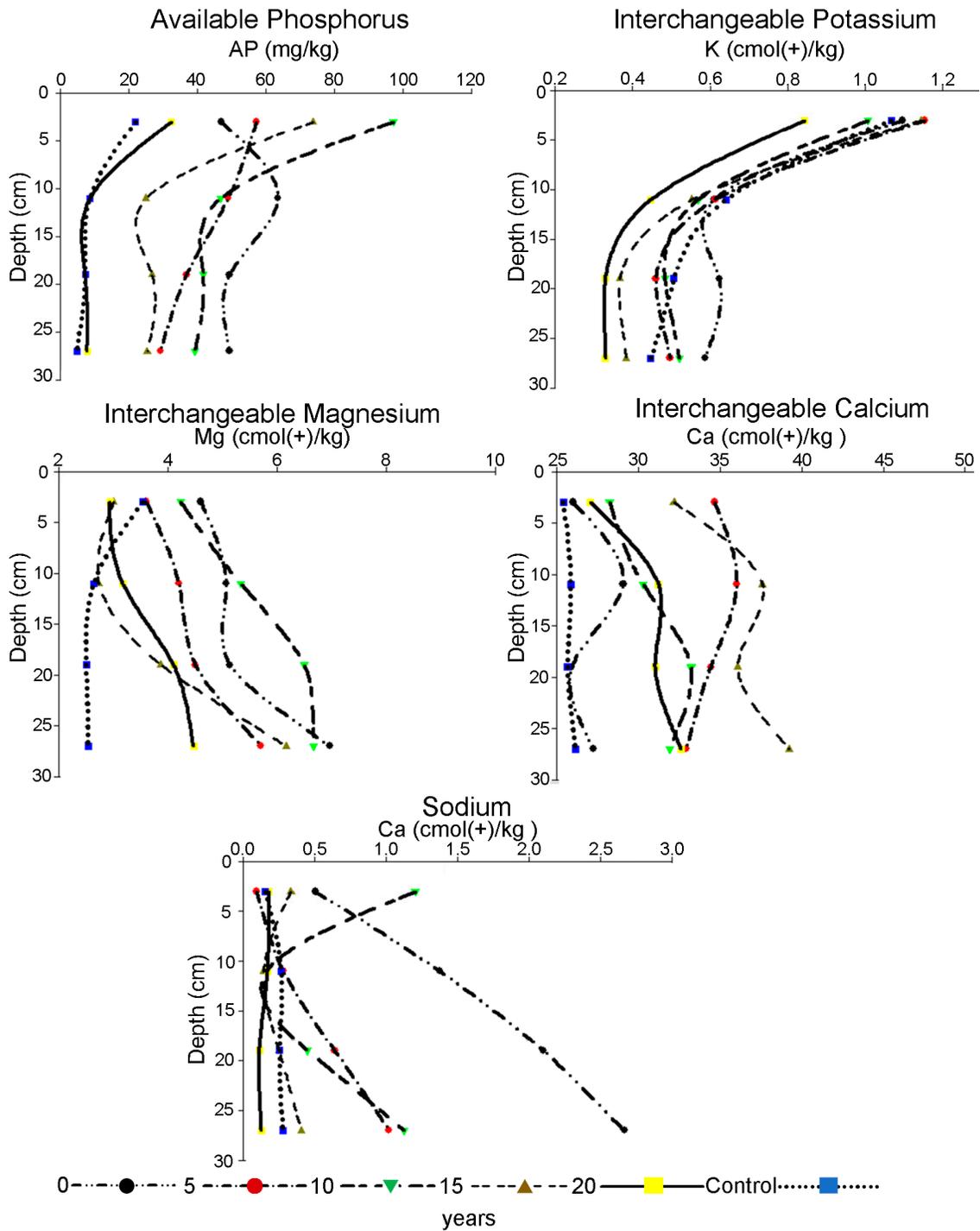
Figure 4. Variation of the content of soil's nutrients: available phosphorus (mg.kg⁻¹) and interchangeable bases (cmol (+).kg⁻¹), according to chronosequence (0, 5, 10, 15, 20 years and control) and (0-3; 8-11, 16-19, 24-27 cm) in the Cerrejon mine.

the area. While the soil is reorganizing and evolving, it starts to reduce. The CEC could be also affected by the content of the organic carbon (OC) (IGAC, 2014), which increases along the chronosequence in the surface, explained by the contributions of the vegetal cover established while the vegetal succession advance.

The increase of OC helps to reduce the BD, being more evident in the superficial layer of the ground (0-3cm), vegetal established coverage of the organic's substance deposit area, with benefits on the soil's properties, reported in many studies (Martínez et al. 2008, Moreno-Barriga et al. 2017; Kumar et al. 2018).

Figure 4 shows the interchangeable bases content variation Ca^{+2}, Mg^{+2}, K^{+1}, Na^{+1} in the rehabilitated soils chronosequence, influenced by the type and mix of the clay like particles, and the border of the edaphic material deposited with the sterile substance. According to the analyzed parameter, these soils could be described as saline (García, 2003; IGAC 2014), which due to the semiarid conditions in this land (Corpoguajira, 2012), forces to include practices that allows the adaptation to the drought, such as having tolerant species to the hydrological stress and

droguth, providing coverage in the soil, and managing rain water effectively, all are currently being applied in the mine (Moscote & Castellanos, 2013).

The edaphic materials used in the Cerrejon mine have high content of salts, called interchangeable by Ca^{+2}, which is mostly related with the mineral particles of the soil, sand, clay, silt (multivariate analysis through dendogram Figure 5), CEC and phosphorus (P), which is common in alkaline soils because of the formation of the apatite mineral (Besoain, 1985; Schoeneberger et al. 2012). The other interchangeable cations (Na^{+1}, Mg^{+2}, K^{+1}), are more related with dynamic parameters (Pla, 2013) such as OC, EC, pH, BD, more susceptible to the management of the soil.

With these elements, it is considered that the studied edaphic parameters (content of mineral particles of the soil BD, pH, EC, CEC, OC, pH, P, interchangeable bases) allowed to detect signs of stability and evolution of the soil, in a chronosequence of coal mining rehabilitation zones.

The content of the soil's mineral particles (sand, clay, silts), BD, EC, CEC, OC, pH are dynamic parameters that evidence the effects of the management practices in the
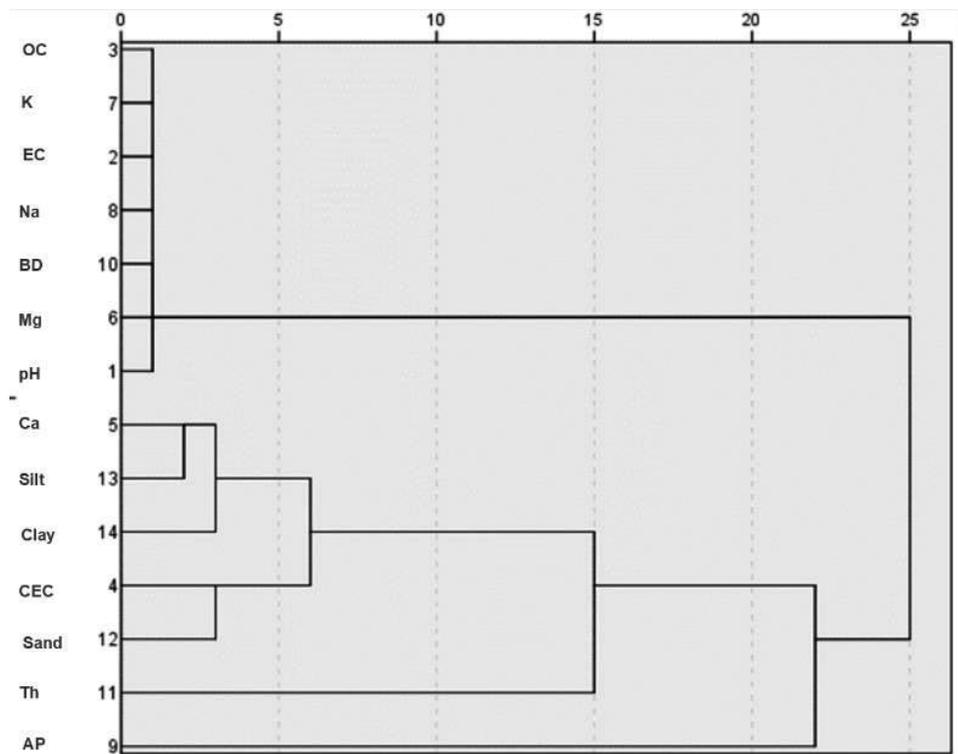
Figure 5. Relational dendrogram of edaphic properties of chronosequence in the Cerrejon mine rehabilitated soils.

soil's rehabilitation program; therefore, it is recommended to include it in this type of programs' monitoring activities.

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