

Challenges and potential approaches for soil recovery in iron open pit mines and waste piles

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Abstract

The revegetation of areas impacted by iron mining may be hampered by a series of chemical and physical impediments exhibited by those areas. Physical problems, such as penetration resistance and steep slopes, may outweigh the chemical problems, such that both should be considered for soil recovery. This study aimed to evaluate the main soil attributes that are directly related to plant growth on areas affected by iron mining activities discussing possible solutions. For this purpose, chemical and physical attributes including penetration resistance on open pit mines, waste piles and native forest in Carajás Mineral Province were analysed. The results show that the open pits had low to medium levels of P and low levels of organic matter and of the micronutrients B, Zn and Cu. In the waste piles, the chemical parameters were less hindering than in the open pits. Soil penetration resistance in open pits was higher than in the waste piles and the forest; however, there was a reduction of up to 69% in soil resistance in open pits in the rainy season. The principal chemical problems observed in mine pits can be easily corrected, although the inclination of open pit slopes in combination with elevated soil density increase the risks of losses of fertilizers and seeds by runoff. Penetration resistance is the most serious problem for the development of plants in mine pits, although the use of irrigation water can help to maintain tolerable levels of resistance in soil for proper root growth of native species.

Introduction

Mining, although essential to human development, is an activity that causes major changes in the environment and landscape due to vegetation suppression and excavations for mineral extraction (Gomes et al. 2019). To minimize the environmental impact, mineral exploitation activities in Brazil are accompanied by a recovery plan for degraded areas (Gastauer et al. 2019). However, the recovery of these areas may be less effective than expected, for example, due to the difficulty in managing and amending the soil and survival of the species used during the revegetation process.

The main difficulties for soil recovery in mining environments include chemical limitations such as acidity, low organic matter (OM) content, low cation exchange capacity, low levels of available nutrients and, in some cases, the presence of potentially toxic elements at levels above those tolerated by the soil biota and plants (Martins et al. 2018; Feng et al. 2019). In addition, there may be physical problems such as high bulk density, high stoniness, low porosity and low water retention, in addition to high penetration resistance (Asensio et al. 2013; Mohieddinne et al. 2019). These factors may impede the development of the plants used for revegetation of the impacted areas, as they hinder root development and prevent the access of plants to water at greater depths, which is key for their survival during periods of low rainfall (Colombi et al. 2018).

Iron ore is exploited in many parts of the world and therefore the recovery of areas impacted by mining is a challenge to be overcome globally (Lamb et al. 2017). In the region of Belgorod, Russia, Treschevskaya et al. (2019), evaluating the recovery process of an abandoned iron mine, they highlighted that this process is extremely complex and strongly affected by the degree of slope of the areas (which affects the

retention of organic substances), the texture of the substrate to be recovered and the selection of species that favor the retention of nutrients in the soil as leguminous.

Some countries, such as Australia, China, the United States and Brazil are looking for ways to recover these areas, however there are still few studies that show the progress of the recovery process in the mined environments. In the United States there are more than 550,000 abandoned mine sites (Soucek et al. 2000), while in Canada, Japan and United Kingdom 5,000–10,000 abandoned metalliferous mine sites are estimated (Mayes et al. 2009; Lamb et al. 2017) and in Australia there are approximately 50,000 abandoned mine sites, approximately 430 operating (Geoscience-Australia 2016).

In the Carajás mineral province, Eastern Amazon, where the largest high-grade Fe ore deposits in the world are located, mining occurs in open-cast mines, forming large pits and waste piles (IBRAM 2013). Open pit mines are mining areas characterized by the excavation and removal of large volumes of mining waste and ore, and the mining process results in the formation of slopes or benches with varying inclinations, and difficulty to revegetate increases with inclination (Mukhopadhyay et al. 2019). Waste piles are formed by the deposition of overburden from the excavations, which can form tall piles containing several slopes (Haldar 2013). Both the slopes of open pits and waste piles can be revegetated but have different characteristics and difficulty levels of recovery; for example, the slopes on waste piles may have a lower bulk density due to the presence of disaggregated materials, whereas the slopes on open pits may have a lower porosity and water holding capacity and a lower chemical quality of the soil (Haldar 2013; Sinha et al. 2017).

Therefore, there are many challenges for the recovery of areas impacted by Fe mining, especially slopes of open pits, for which research is still insipient. In this context, it is essential to better understand the physical and chemical parameters of the slopes of mining areas to enable the development of more effective recovery plans. For that purpose, this study aimed to compare the chemical and physical properties of soils found in native forests and on slopes of open pits and on waste piles at the Carajás Fe ore complex discussing potential approaches to solving observed problems. We hypothesize that compared with the slopes of waste piles, the slopes of open pits have a greater number of physical and chemical properties that are unfavourable to plant growth. It is expected that the results obtained may contribute to better management and effectiveness in the revegetation of the slopes of open pits and waste piles.

Materials And Methods

Study sites

The study was conducted in the Carajás mineral province, state of Pará, Brazil, in an open pit mine (N4 and N5 mining complex) comprising several pits in addition to waste piles. The open pit N5, on the west side (N5W), is located at the coordinates 50° 9'10.73"W and 6° 5'8.54"S and 2 slopes with 15 m height and extension of 950 and 550 m were evaluated, where 49 samples were collected for chemical analysis and 15 sites were established to proceed physical analysis such as moisture, density and penetration

resistance. The open pit N4, on the east side (N4E), is located at the coordinates 50°10'48.11"W and 6° 3'55.27"S, and 3 slopes with dimensions of 450, 350 and 250 m in extension and 15 m in height were evaluated, where 29 samples were collected and 15 points evaluated in physical analysis.

The sampling also was performed in waste piles formed by the deposit of waste from excavation processes to remove ore (WP_W and WP_S4). The Western Waste Pile (WP_W) is located at the coordinates 50°10'39.80"W and 6° 3'7.82"S, while South-4 Waste Pile (WP_S4) is located at the coordinates 50° 9'45.00"W and 6° 4'37.20"S. In both areas, 50 samples were collected to evaluate 3 slopes with dimensions of approximately 200 m in extension and 15 m in height and 12 points evaluated in physical analysis, which were in the initial, intermediate and advanced stages of revegetation. The initial stage is characterized by the presence of herbaceous vegetation and age 1-3 years, while the slope in intermediate stage there is a predominance of herbaceous and shrub vegetation at the age of 4 to 7 years. In the advanced revegetation stage, shrub and woody species are observed mainly and age older than 8 years. In the revegetation process a hydroseeder was used for the application of fertilizers and sowing using a seed mix of native and non-native species such as *Cajanus cajan*, *Crotalaria spectabilis*, *Avena strigose*, *Pilocarpus microphyllus*, *Cecropia distachya*, *Senegalia polyphylla*, *Solanum crinitum*, *Cassia reticulata*, *Rhynchospora barbata*, *Mesosphaerum suaveolens*, *Apeiba equinatha* and *Byrsonima spicata* which include leguminous species. Approximately 2 Mg ha⁻¹ of commercial organic compost, 600 kg ha⁻¹ of NPK 4-14-08, 10 kg ha⁻¹ of micronutrients via FRITAS_BR12 were applied, and topdressing fertilization was conducted 60 days after planting by applying 100 kg ha⁻¹ of NPK 20-00-20. A forest area close to the open pits and waste piles areas was evaluated as a references area in this study, where 5 samples were collected and 9 point evaluated in physical analysis. An overview of the environment in waste piles and open Fe ore pits and location of the study are shown in Fig. 1.

Analysis of soil fertility and mineralogy

The preparation of the samples for chemical analyses included air drying and sieving using 2-mm mesh sieves. Analyses were performed according to Embrapa (2017): Soil pH was determined in water and 10 g soil (1:2.5 soil:water ratio); available K and P were extracted in Mehlich-1 solution (0.05 M HCl and 0.0125 M H₂SO₄) (Mehlich 1953), after which K was determined by flame photometry and P was determined by colorimetry in ammonium molybdate solution at 660 nm; exchangeable Ca²⁺, Mg²⁺ and Al³⁺ were extracted with 1 M KCl, where Ca²⁺ and Mg²⁺ were determined by atomic absorption spectrometry and Al³⁺ was determined by titration in 0.1 M NaOH solution; and potential acidity (H+Al) was determined via extraction with 0.5 M calcium acetate and quantified by titration in 0.025 M NaOH. Available Fe, Cu, Zn and Mn were extracted in DTPA solution at pH 7.3 and determined by atomic absorption spectrometry; B was extracted using a hot 5 mM BaCl₂ solution (Camargo et al. 2009). Total N was extracted by the Kjeldahl method concentrated sulphuric acid, and S-SO₄⁻² was extracted in Ca(H₂PO₄)₂.H₂O solution in 2 M acetic acid containing 500 mg kg⁻¹ of P and determined by turbidimetry (Camargo et al. 2009). The cation exchange capacity (CEC) was calculated as Ca²⁺ + Mg²⁺ + K⁺ + H + Al³⁺, and base saturation (BS) as (Ca²⁺ + Mg²⁺ + K⁺) x 100/CEC. The organic matter content (OM) was estimated based on the soil

organic carbon concentration determined by wet combustion in 0.0667 M $K_2Cr_2O_7$ (Embrapa 2017). For mineralogical analysis, the samples of 1g were grounded and analysed by powder x-ray diffraction using a PANalytical X'Pert Pro MPD (PW 3040/60) diffractometer equipped with an X-ray ceramic anode Cu ($K\alpha_1=1.540598 \text{ \AA}$) and Ni $K\beta$ filter. The samples were scanned from 4° to 95° 2θ with a speed 0.02° 2θ every 30 s. The minerals identification was performed by software X'Pert HighScore Plus (PANalytical) The mineralogical data are presented in Table S2.

Analysis of physical soil attributes and inclination

For penetration resistance analysis, soil layers from 0 to 10 cm were evaluated in native forest, slopes of waste piles and slopes of open pits in 2 periods: the dry season (June 2019) and the rainy season (November 2019). In both season, dry and rainy, 30, 12, and 9 sampling points were analysed on the slopes of open pits, on waste piles and in the forest, respectively, with a minimum distance of 10 m and maximum of 50 m between each sampling point.

Penetration resistance was evaluated using an impact penetrometer according to the method described by Stolf et al. (1983), where the number of impacts is related to depth reached to calculate resistance force of the soil The cone-tipped penetrometer expresses results based in equation (1) of Stolf (1991), considering the characteristics of the equipment used, which is equipped with a fixed weight of 1.5 kg, which must be released from the same pre-established height of 40 cm, with measurements of the number of impact necessary to penetrate the ground.

$$PR = 2.37 + 3.7(N) \quad (1)$$

where PR is the soil penetration resistance in kgf cm^{-2} and N is the number of impacts of the metal weight. The results obtained in kgf cm^{-2} were multiplied by the constant 0.0980665 for conversion into MPa. At each penetration resistance evaluation site, undisturbed samples were collected for bulk density and gravimetric moisture analysis according to Embrapa (2017).

The average inclination in the open pits and waste piles was obtained through defined transects after processing remote sensor data. The technology used was LIDAR (Light Detection and Ranging), that is, a sensor on board a manned platform or a UAV (*Unmanned Aerial Vehicle*) that emits beams of light (laser) in the spectral range of the near infrared modeling the surface of the terrain three-dimensionally. From the Digital Terrain Model, the slope was obtained in the Arcmap software using the "Slope" tool in the Spatial Analyst toolbox. The results of this processing generate the inclination values of the terrain in degrees.

Statistical analyses

All chemical parameters were analysed using Fisher's LSD test when the data showed homogeneity of variance; otherwise, Dunnett's T3 test was applied to detect significant differences between the study sites. For analysing penetration resistance, the dispersion of the data was evaluated by the standard error, considering each observed depth. For these analyses, a confidence level of 95% was adopted, and the R

language, version 3.5.1 for Windows, was used (R Core Team 2018). SigmaPlot software version 12.0 was used to build the plots.

To detect differences in fertility among the 3 environments analysed in this study (forests, open pits and waste piles), we used mixed effect models, modelling the chemical parameters as a function of the environments, considering the study site as a fixed factor to correct for nested sampling design (more than one sample within the same study site). The mixed models were constructed using the 'nlmer' function of the 'nlme' package (Pinheiro et al. 2020). Significance levels among the different environments were detected using the 'lmerTest' package (Kuznetsova et al. 2017).

Results

Chemical parameters

The pH of the soil in the open pits and in the waste piles ranged from 5.5 to 6.2 (Fig. 2), a range considered ideal for the availability of macro- and micronutrients. These values were higher than those observed for forest soils (Fig. S1).

All study sites had available P levels below 12 mg kg⁻¹ (Fig. 2). On the slopes of the N5W mine, the available P levels amount only 25% of the recommended levels in soils for the growth of plants in the region (Table S1). However, the levels found on the slopes of the N4E mine were 20% higher than the reference levels (Fig. 3). The K concentrations in the pits did not exceed 11 mg kg⁻¹, and the highest values were found in forest areas; when compared to the levels recommended for soils in the region, these levels were lower by up to 91% on the slopes of pits and 80% lower on waste piles. Similarly, Ca and Mg levels were low in both open pits and waste piles and were 82 to 97% and 30 and 60%, respectively, below the recommended values. Other elements, such as Al, which was within the tolerable limits for plants, and S and Mn, which exceeded the recommended levels, did not represent a limitation for the revegetation process of these areas.

The OM content on the slopes of open pits and on waste piles was lower than that found in the forest areas (Fig. S1), at levels 60 to 80% lower, respectively, than the recommended levels (Fig. 3). This trend was also observed for the total N levels in the evaluated slopes. In addition, CEC and available Fe were higher in the forest than in the mining environments (Fig. S1).

In general, the levels of available micronutrients B, Cu, Zn, and Fe on the slopes of the open pits were much lower than the recommended levels adopted in this study (Fig. 3). In addition, the highest levels of these nutrients were observed in native forest soil (Fig. 2).

Density and penetration resistance

Analyses revealed low density values in the native forest area (1.1 g cm⁻³) (Table 1). The waste piles had soil bulk density values that ranged from 1.3 to 1.6 g cm⁻³, while in N4E, the soil bulk density (1.92 g cm⁻³)

was considered a hindering factor for the revegetation and restoration processes in the area. However, in the N5W pit, the data showed that soil density (1.54 g cm^{-3}) may not be the main physical problem for plant root development. In addition, the inclination of the slopes from open pits and waste piles ranged between 25.4 and 67.2 %, with the highest values observed on the pits.

The slopes of open pit mines also exhibited high root penetration resistance (Fig. 4), especially in the dry season and especially for pit N4E, which showed high penetration resistance (mean of 28 MPa). On the other hand, in the rainy season, there was a 69% reduction in penetration resistance in this pit in the top 5 cm. For this site, it was only possible to evaluate to 5 cm of depth due to the abundance of rocky material in the slopes. In contrast, lower penetration resistance values were observed on the waste piles, which were close to those found in the forest, in both the dry and rainy seasons.

Discussion

Chemical parameters

In the present study, the evaluated areas showed no limitations regarding soil acidity, which varied within the ideal range for the availability of most macro- and micronutrients (Alvarez et al. 1999). These pH values were higher than those observed in the native forest environment. However, it is important to highlight that in a forest, even with acid soil, various factors may have contributed to nutrient availability, such as higher OM, microbial activity, and root exudates, in addition to other factors such as a microclimate adequate for the development of native species (Fujita et al. 2019; Jing et al. 2020). In this environment, litter decomposition associated with high temperature and moisture is responsible for providing nutrients to the soil, allowing the development of vegetation without symptoms of nutritional deficiency, in a naturally poor soil (Quesada et al. 2011). According to Touceda-González et al. (2017), soil pH is one of the most important parameters for recovery of degraded areas and may be an aggravating factor because it causes low nutrient availability.

Phosphorus availability in mined areas ranges from low to high (Cravo et al. 2010), indicating the need for supplementation of this nutrient at sites with lower P availability to reach the reference value in some environments. Guedes et al. (2020) evaluated the P availability in Fe minelands and also reported low and high levels, which according to the authors depends directly on the OM accumulation in the soil. Although ferriferous formations may contain phosphate minerals (Upadhyay et al. 2011), P availability may be extremely low because this element may be associated with the crystalline structure of minerals or, when released by weathering into the soil solution, it can be adsorbed by Fe and Al oxides and hydroxides (Fink et al. 2016). For this reason, a possibility to increase soil P utilization efficiency may be the application of organic compounds that delay the retention of phosphates applied to the soil via fertilization, as well as the use of slow-release sources (Fertahi et al. 2019).

Low Ca and Mg levels were found on the slopes of open pits and waste piles (Cravo et al. 2010), especially in the pits, where a greater difference was found relative to the reference values. These low

amounts found on the slopes are due to the parent material, which gives rise to soils naturally poor in Ca and Mg, a fact that is confirmed in most soils of the Amazon region (Quesada et al. 2011). The Fe ore mines in Carajás are located in the Carajás Basin, where there are meta-volcano-sedimentary rocks composed mainly of metabasalt, metarhyolite and metadacite (Vasquez and Rosa-Costa 2008); however, despite containing Ca and Mg in the mineral structure, those elements are not available to plants. According to Sarkar et al. (2017), in general, the nutrient contents in mined areas are extremely low to plant growth, and this reinforces the need to supply Ca and Mg, especially using less soluble sources because both open pit and waste pile areas are inclined, which can favour erosion and nutrient loss by surface runoff and leaching. These practices must be applied together with immediate soil coverage, which can be promoted with the use of grasses to favor the initial accumulation of OM (Banerjee et al. 2018). In addition, it is possible to use topsoil to stimulate biological activity, to introduce native seeds in the soil and allow greater accumulation of nutrients and OM (Hu et al. 2020).

Unlike open pits, waste piles are more manageable areas (easier to plant, fertilize and maintain plants), and therefore, nutrient values are closer to the reference values. The waste piles had higher Ca and Mg levels due to liming performed at the beginning of the revegetation process. These results demonstrate that liming efficiently increased the values of these elements in these areas, matching the values observed in forest areas. In general, the slopes on the waste piles are less steep, favouring soil amendment operations. In contrast, some slopes on open pits can reach higher than 80%, representing a challenge for soil preparation practices, causing great losses, not only of fertilizers but also of seeds and seedlings. To minimize revegetation losses in very steep areas, Zhao et al. (2018) planted seedlings using a technique called “container seedling” and observed significant increases in the soil cover of road slopes, increasing the water and fertilizer utilization efficiencies. The use of this technique allows greater root development, and gains in the hydraulic conductance of the roots of plants used for reforestation were observed even when the plants were planted in arid conditions (Chirino et al. 2008).

The low K levels in the soils from open pits and waste piles may be explained by low contents of K in the geological substrates of the Carajás Basin, which are characterized by a low occurrence of granitic or granitoid rocks such as trachytes and trachytes of alkali feldspars (Vasquez and Rosa-Costa 2008). These values are lower than those observed in a coal open pit mine with long-term soil recovery, which plant coverage and diversity may have improved the soil environment (Lei et al. 2016). However, even when applied to the soil, K levels tend to be low due to the high mobility of the element in the soil, which is weakly retained in the soil by electrostatic adsorption (Eick et al. 1990; Abbaslou et al. 2018). This hinders fertilization management, requiring fractionated applications, taking into account not only the possibility of losses of the element but also the physiological needs of the plant and the balance with other nutrients (Das et al. 2019).

Both open pits and waste piles accumulated less OM than the evaluated forest areas. This occurred because there are few sources of OM in the mined areas, especially on the steep slopes of open pits, which is in agreement with data observed by Domínguez-Haydar et al. (2019). These authors reported that even in areas at an advanced stage of recovery the levels of OM are generally lower than those

observed in forests. Additionally, forest areas had higher levels of soil N as well as a higher CEC and higher available B and Fe, confirming the importance of OM for nutrient supply and micronutrient availability. According to Dunalska et al. (2012), OM is directly related to soil N levels and may be the main source of this nutrient in undisturbed environments, especially under high temperature conditions. Similarly, OM may have a large effect on soil CEC due to the high number of free surface charges on its structure (Zhao et al. 2019).

In summary, for the soil chemical properties, the slopes on the waste piles and, especially, on the open pits presented limitations for revegetation, such as low Ca, Mg, OM, and micronutrients; these limitations are associated with the steepness of the areas, which increases the operational difficulties for digging and planting, and risks of erosion make the recovery of slopes within open pits a great challenge. For this, Wijesekara et al. (2017) recommend the use of biowaste as a way to consolidate OM in the environment to be recovered, which favors the progress of other processes of physical and biological chemical improvement of the soil. A few published studies report success in the revegetation of steep open pit mines (e.g., Pinto et al., 2011; Zhao et al., 2018), in which planting in holes increased the use efficiency of fertilizers and avoided losses of plants due to flooding. Liu et al. (2016) observed an increase of vegetation coverage in a coal open mine after 25 years of rehabilitation process. Furthermore, hydrogel application is one method of increasing water utilization efficiency and facilitating root growth (Miller and Naeth 2019). For the slopes on waste piles, studies provide solutions for the recovery of this environment, such as fertilization and sowing by hydroseeding, the immediate protection of the soil with the application of various combinations of mulches, and the application of fibres for the fixation of seeds and fertilizers in the soil (Fields-Johnson et al. 2012; Liu et al. 2019).

Physical Attributes

The higher soil density values in waste piles than in the forest may be associated with the formation process of waste piles, which are formed by disaggregated material, which is compacted by machines during pilling; this material, over time, tends to rearrange, leading to increased density (Veiga et al. 2007). Despite this, the soil density on the slopes of waste piles does not seem to compromise revegetation because herbaceous species, shrubs and trees are part of the native vegetation and are easily found covering the soil in these areas. On the slopes of the open pits, where the highest soil density values were observed, it is possible that physical impediment is one of the causes of lower root development of plants, and consequently, this may negatively affect the revegetation process. According to Reinert et al. (2008), a soil density greater than 1.85 g cm^{-3} can cause severe restrictions on root growth and reductions in the development of several species. To date, there are no quick and effective ways to reduce soil density in very steep areas; however, it is expected that with the advancement of the recovery process, root development, increased microbial activity and the incorporation of OM will favor a reduction in soil density (Asensio et al. 2013). In these cases, the bioturbation caused by root development is a key factor (Colombi and Keller 2019).

Soil density in a forest area may be influenced by the greater amount of soil organic matter (SOM) and possibly by the higher microbial activity, which is essential for the soil structure and aggregation, in this environment, (Qin et al. 2017; Dultz et al. 2018). Thus, the low OM content found on the slopes of the open pits and waste piles can be considered a problem. Open pit areas are excavated environments that usually have low OM levels; however, waste piles are formed by different materials, which are mixed, facilitating the oxidation of OM (Ondrasek et al. 2019). Therefore, it is essential that the recovery of these areas includes the addition/incorporation of OM as a way to improve not only the chemical but also the physical conditioning of the soil. However, due to the inclination of the slopes in open pits and the difficulty of fixation and establishing plants in these areas, increasing the OM content can be a great challenge.

The penetration resistance of the open pits reached values above 10 MPa, which is considered extremely high for soils (Arshad et al. 1996). Thus, under dry soil or low moisture conditions in open pits, for example, starting at 1 cm depth, there is a strong impediment to root development, and at 5 cm depth, penetration resistance possibly precludes the growth of most species used currently in revegetation activities. According to Colombi et al. (2018), starting at 3 MPa, there may be severe root growth restriction, causing morphological changes and forcing root surface development in the soil, consequently limiting the absorption of water and nutrients on the soil surface and increasing the susceptibility to a water deficit. However, with the increase in soil moisture with the beginning of the rainy season in the region, a reduction in penetration resistance was observed on the slopes of the open pits, which approached the values observed in forest soil in the dry season. In addition to factors such as clay content, OM content and mineralogy, soil moisture is identified as another factor that affects soil penetration resistance, as it alters the cohesion between soil particles, such that the proximity of particles hinders its separation by external forces when the soil is dry or have low water content (Beltrame et al. 1981). Thus, with the increase in water content, the action of cohesion forces between soil particles and internal friction decreases, resulting in reduced shear strength and penetration resistance (Duncan et al. 2014). The results found in the present study suggest that there is a need to maintain adequate moisture levels in these areas so that revegetation practices are more successful, considering the physical impediment that exists at the site. This hypothesis confirms Souza et al. (2021), which reinforced the importance of rain cycles for the establishment and growth of roots, especially in the early stages of development.

The lower penetration resistance observed on the slopes of waste piles than in the pits is partly due to the poorly structured soil (still in the consolidation phase). Soil structure is also considered a determining factor for soil resistance, and in the case of poorly structured and poorly cohesive materials, there is a tendency for this resistance to be low (Gülser and Candemir 2012). Nevertheless, soil resistance starting at 5 cm depth is considered high (Arshad et al. 1996), which does not necessarily represent a problem for native species because these values are observed at similar levels in native forest areas. Furthermore, the high resistance in the waste piles may be related to the strong presence of small rocky fragments, which may not affect root growth, given the ability of the roots to go around these resistance points and alter their root architecture (Chen et al. 2014).

In general, physical problems are not easily manageable on the slopes of open pits, mainly due to their inclination. In addition, it is necessary to consider that the slopes present a high risk for revegetation activities, for example, digging and applying agricultural inputs, seeds and seedlings. However, with moisture control, it is possible to reduce the soil penetration resistance, minimizing the effects of density, which may facilitate the development of species for revegetation in open pits. For this, the implementation of irrigation systems may be a viable alternative not only for water supply to plants but also to reduce soil resistance. The availability of water to plants allows greater root development and access to deeper soil regions (Colombi et al. 2018) so that it can ensure greater soil cover, soil stability and, in dry seasons, a higher survival rate of the species planted.

Conclusions

The problems of chemical nature such as deficiency of nutrient observed both in open pits and in waste piles can be amended with fertilization; however, the arrangement and inclination of slopes, especially steep slopes in mine pits, can hinder the application of soil amendment techniques, such as liming and fertilization or even planting. The open pits had low levels of OM, macronutrients such as Ca, Mg, K and N, and micronutrients such as B, Zn and Cu. These nutrients can be applied to the soil during planting and seeding, To further enhance fixation of revegetation inputs, favour plant development and reduce soil losses by surface runoff, it may be necessary to develop additional soil stabilizing mechanisms beyond revegetation. For this, a system of planting in holes or containers can also be efficient in steep areas.

Despite the high resistance values in waste piles, no significant negative effects on the root development of native species used for management in these areas are expected. However, open pits have a high density and high root penetration resistance, which may be the main barriers to the revegetation of these areas. This is a problem whose solution is highly dependent on the rainy season, but it is possible that the application of an adequate irrigation volume can reduce soil resistance, especially in the first years of the revegetation process, when plants still have a shallow root system and are unable to withstand long periods of drought.

Declarations

Ethical approval and consent to participate

Not applicable.

Consent to publish

Not applicable.

Data availability

The data sets supporting the results of this article are included within the article and its additional files.

Competing interests

The authors declare that they have no conflict of interest.

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Tables

Table 1 Gravimetric moisture, density and inclination degree of slopes on open pits (N5W and N4E) and waste piles (WP_W and WP_S4) of the Fe ore mine and forest in the Carajás Mineral Province during the rainy season

	Moisture (g g ⁻¹)	Density (g dm ⁻³)	Inclination (°)
N5W	0.18	1.54	66.8
N4E	0.08	1.95	67.2
WP_W	0.14	1.27	25.4
WP_S4	0.19	1.58	31.8
Forest	0.28	1.08	-

Figures



Figure 1

Location of the study area in the state of Pará-Brazil a), complex of open pits and waste piles of an iron ore mine in Carajás b) and overview of the environment in observed open pits and waste piles c)

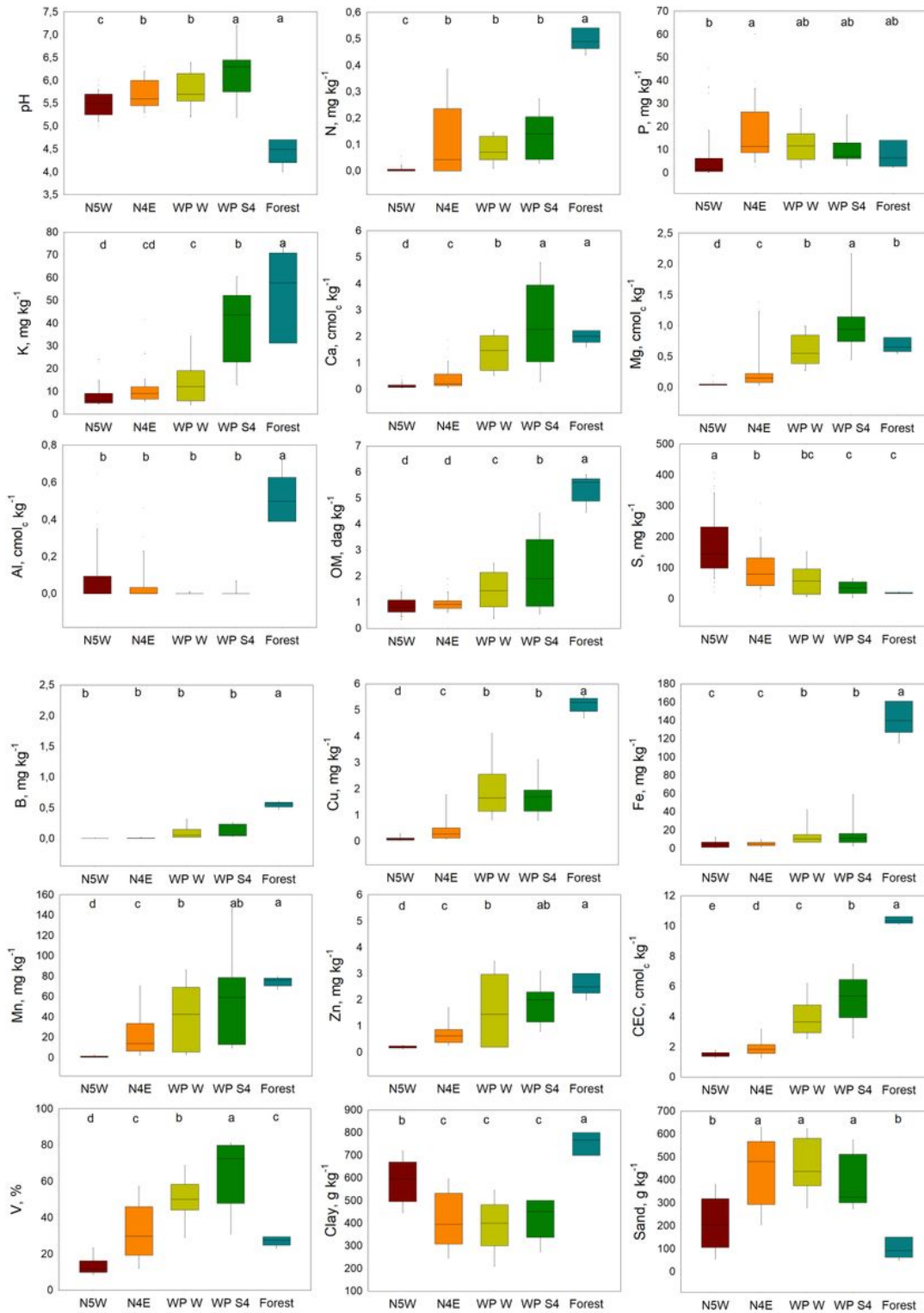


Figure 2

Soil chemical parameters in mine pits (N5W and N4E), waste piles (WP_W and WP_S4) and forest. Values followed by the same letter do not differ by the LSD test. (Cont.) Soil chemical parameters in mine pits (N5W and N4E), waste piles (WP_W and WP_S4) and forest. Values followed by the same letter do not differ by the LSD test

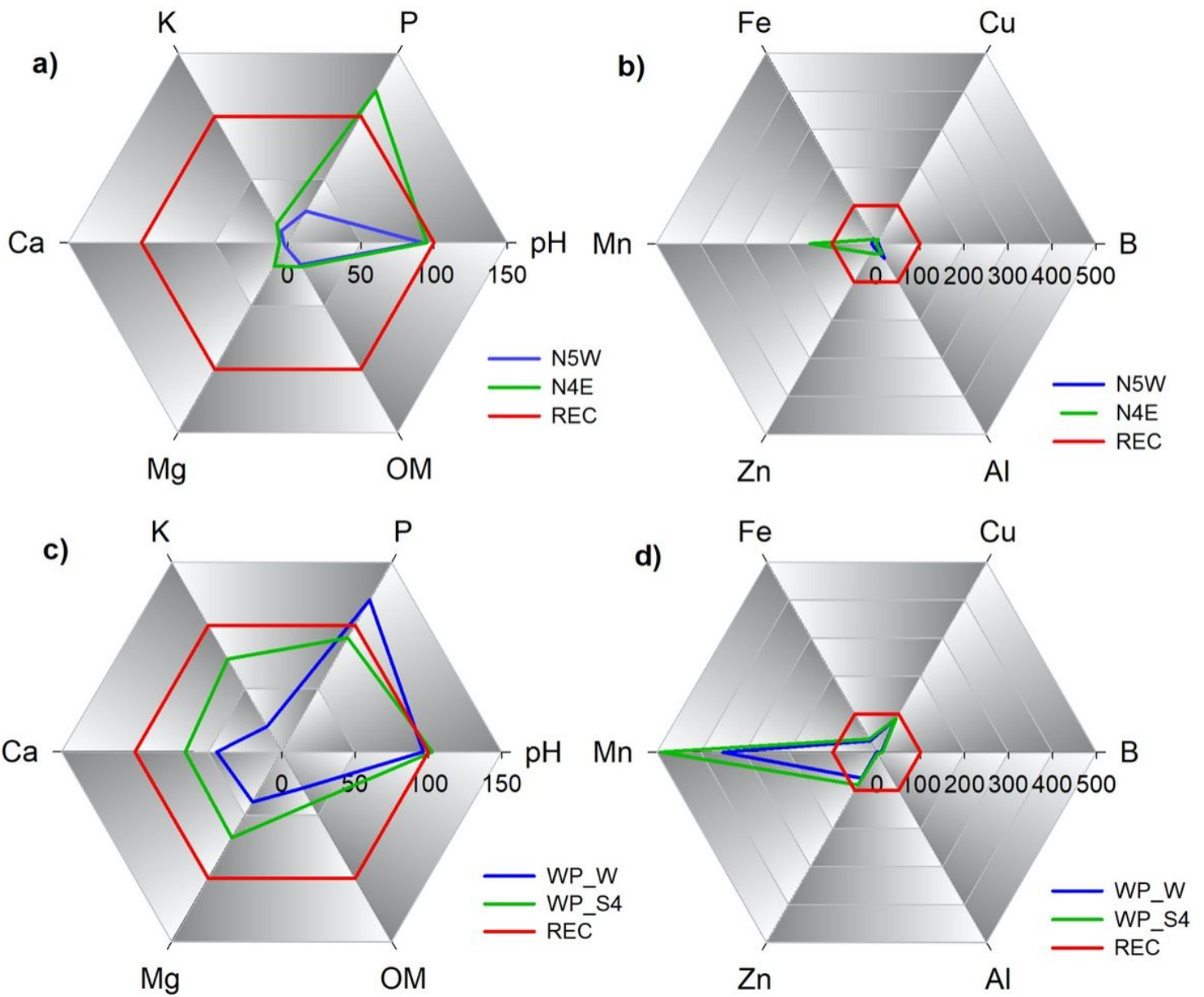


Figure 3

Relative distribution (%) of soil chemical parameters on open pit slopes (N5W and N4E) and waste piles (WP_W and WP_S4) according to the recommended values for soils in the state of Pará (REC) proposed by Cravo et al. (2010) and Tedesco et al. (2004)

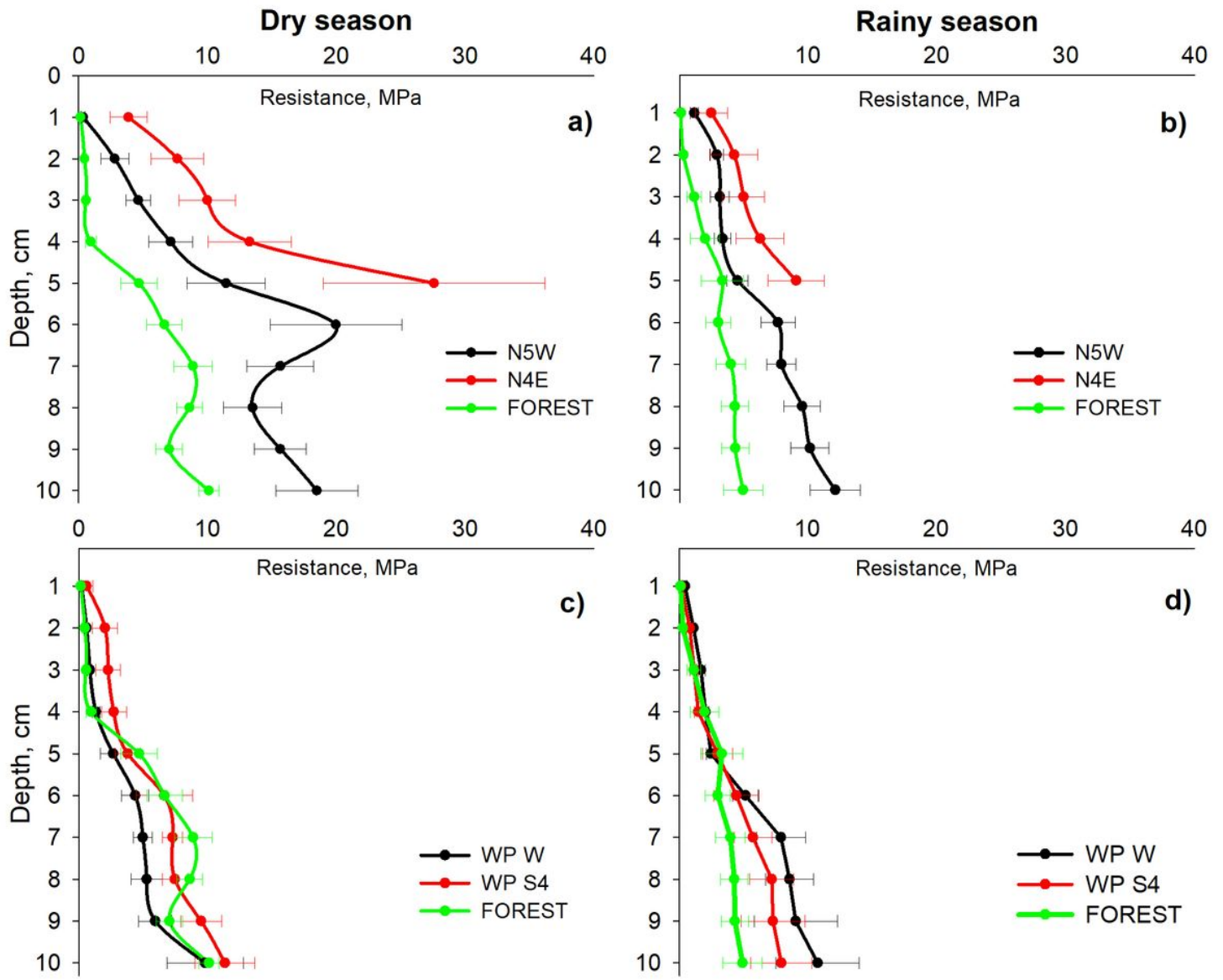


Figure 4

Soil penetration resistance for slopes on open pits and in forest areas a), b) and for waste piles and forest areas c), d) in the dry and rainy seasons. Data are presented as the mean of all points observed in each area per depth and the error bars are standard error

Supplementary Files

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