

SURFACE RUNOFF IN TWO REHABILITATION PERIODS OF A BAUXITE MINE

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ABSTRACT – The objective of this study was to monitor and compare runoff at 2.5 and 3.5 years of rehabilitation of a mined bauxite area with clonal planting of *Eucalyptus*. Seven plots were allocated for collecting runoff and precipitation was recorded with a pluviograph. The physical and environmental factors which interfere with runoff were characterized in both periods and subjected to principal component analysis (PCA) to show the most explanatory factors. The average monthly runoff percentage at 2.5 years was 0.25% ($\pm 0.26\%$) of precipitation and equal (p -value <0.05) to the 3.5 years ($0.15 \pm 0.22\%$) of rehabilitation. Both values were lower than the *Eucalyptus* plantation area without mining (0.56%) in the same region and declivity. The high vegetation cover percentage by *Eucalyptus* crowns and *Brachiaria sp.* and the high infiltration rates were the determining factors in PCA, and may explain the statistically equal runoff values between the rehabilitation periods. The combination of good edaphic conditions and the fast coverage of the plants resulted in runoff below 1% in a rehabilitated area after bauxite mining.

Keywords: Mining; Infiltration; Vegetal cover.

ESCOAMENTO SUPERFICIAL EM DOIS PERÍODOS DE REABILITAÇÃO DE UMA MINA DE BAUXITA

RESUMO – O objetivo deste estudo foi monitorar e comparar o escoamento superficial aos 2,5 e 3,5 anos de reabilitação de uma área minerada de bauxita com plantio clonal de *eucalipto*. Sete parcelas foram alocadas para coleta de escoamento superficial e a precipitação foi registrada com pluviógrafo. Os fatores físico-ambientais que interferem no escoamento superficial foram caracterizados nos dois períodos e submetidos à análise de componentes principais (ACP) para evidenciar os mais explicativos. O escoamento superficial percentual médio mensal aos 2,5 anos foi 0,25% ($\pm 0,26\%$) da precipitação e igual (p -valor $<0,05$) ao de 3,5 anos ($0,15 \pm 0,22\%$) de reabilitação. Ambos os valores foram inferiores ao de área de plantio de *Eucalyptus* sem mineração (0,56%) na mesma região e declividade. A elevada porcentagem de cobertura de vegetação, pelas copas de *Eucalyptus* e pela *Brachiaria sp.*, e as elevadas taxas de infiltração foram os fatores determinantes na ACP, e podem explicar os valores estatisticamente iguais de escoamento superficial entre os períodos de reabilitação. A combinação de boas condições edáficas e a rápida cobertura das plantas resultou em escoamento abaixo de 1% em uma área reabilitada, após a mineração de bauxita.

Palavras-Chave: Mineração; Infiltração; Cobertura vegetal.



1. INTRODUCTION

Bauxite is among the minerals extracted in Brazil, coming from surface mines, which are also called open-pit mines (ABAL, 2018). Surface mining starts by removing vegetation and the upper soil horizons to expose the ore. After ore removal, the original waste and organic soil are replaced to reconstruct the topography of the area, and revegetation is carried out at the end (Vilas Boas et al., 2018).

The superficial mining process causes changes in the landscape such as topographical drawdown (Kuter, 2013), an increase in soil density (Barros et al., 2013), and the formation of cracks and fissures in the soil surface (Haigh and Sansom, 1999), thereby modifying hydrological processes with a reduction in runoff due to soil turning and the presence of species with high vegetation coverage (Merino-Martin et al., 2012).

The return to a similar or better functional ecosystem than that before the mining is the rehabilitation goal after surface mining (Reynolds and Reddy, 2012). A challenge in this process is controlling the water runoff (Rubio et al., 2013). Several techniques have been used to control it such as revegetation, which helps in recovering organic matter, restructuring the mined soil (Banning et al., 2008), and unpacking the soil with subsoiling, which can induce positive hydrological results in rehabilitated ecosystems when associated with revegetation (Sheoran et al., 2010). Thus, monitoring changes in soil and vegetation properties associated with hydrological processes (such as runoff) in sequential rehabilitation periods is essential to assess and improve the implemented techniques (Shrestha and Lal, 2011).

Eucalyptus has shown high survival and rapid growth in mined areas (Schiavo et al., 2010), in addition to assisting in recovering organic matter from the mined soil (Banning et al., 2008). Planting *Eucalyptus* in rehabilitation is conditioned to the interest of the landowner in producing wood for economic purposes (Schiavo et al., 2010). It is known that runoff in areas without mining in Minas Gerais State is between 0.5 and 3.8% of rainfall in *Eucalyptus* plantations (Silva et al., 2011).

Runoff has been monitored in surface mines, mainly in China, the United States and Spain through

field experiments by installing plots in situ under simulated (Gomez-Gonzalez et al., 2016) and natural rain conditions (Merino-Martin et al., 2012), or by estimates using precipitation data (Liang et al., 2019; Taylor et al., 2009). However, only one study on the efficiency of micro-damming in retaining runoff has been recorded in Brazil (Rubio et al., 2013). The lack of runoff monitoring in mining areas in Brazil may be related to the lack of requirements in legislation and procedures related to the environmental licensing process (Jeber and Profeta, 2018).

Therefore, the objective of this study was to monitor runoff in a rehabilitated area with clonal planting of *Eucalyptus* 2 years after interrupting a bauxite mining operation; to compare the runoff of 2.5 years with 3.5 years of rehabilitation; and to characterize the physical-environmental factors which interfere in runoff, seeking to discriminate those which can be improved.

2. MATERIALS AND METHODS

2.1 Study area

The study was carried out in a rehabilitated bauxite mine (21° 3' 57.84" S, 42° 35' 42.38" W) in the municipality of Mirai, southeastern Minas Gerais, Brazil (Figure 1A). The climate of the region is subtropical in altitude (Cwb) according to the Köppen classification with two well-defined seasons, namely a rainy summer and a dry winter. Annual rainfall is 1,336 mm and average annual temperature is 19.3 °C (Alvares et al., 2013). The original vegetation type is Semi-deciduous Seasonal forest and a stratified physiognomy of the Atlantic Forest which loses 25-50% of the canopy leaves in the dry period (Arruda et al., 2018). The predominant original soils are typical dystrophic Red-Yellow Latosol (Borges, 2013). The relief is rugged with hills and bauxite tops, forming part of the range of granulitic rocks called "*Complexo Juiz de Fora*" (Lopes and Adilson, 1990).

The mine of the rural property was leased by the mining company and the bauxite was extracted from July 2013 to July 2014. The ore removal was preceded by soil stripping with subsequent return to the topographic reformation stage in August 2014. Revegetation was subsequently performed in December of the same year, following the operating standard of the mining company which is specific to the mined soils in the region (Lopes and Barros,

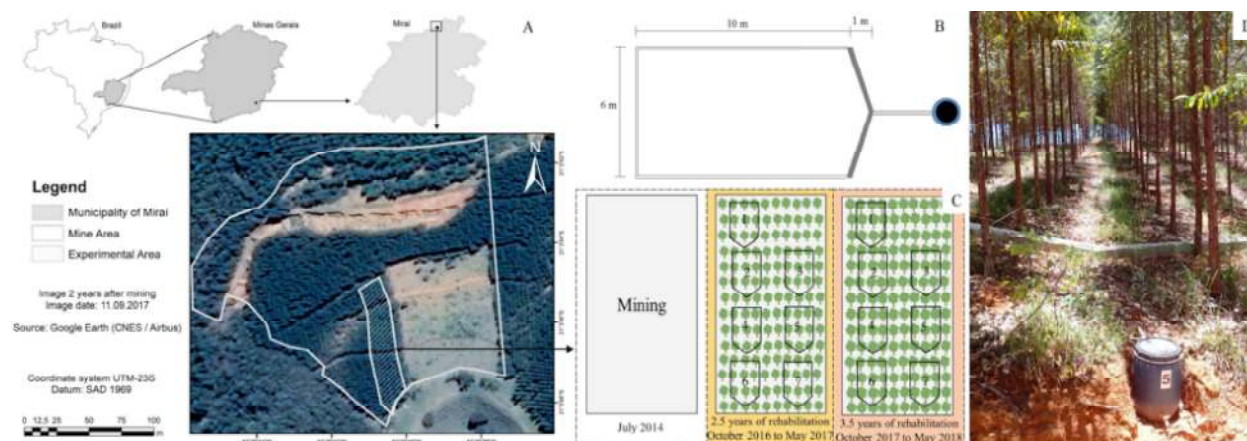


Figure 1 – Location of the experimental area in the rehabilitated mine area in the municipality of Mirai, Minas Gerais, Brazil (A); Design of the collection plots for surface runoff (B), sketch of the experimental design (C) and field installed plot (D).

Figura 1 – Localização da área experimental na área da mina reabilitada no município de Mirai, Minas Gerais, Brasil (A); Estrutura das parcelas de coleta do escoamento superficial (B), croqui do design experimental (C) e parcela instalada in situ (D).

2017). The procedure starts with liming (4,000 kg ha⁻¹ of dolomitic limestone) and phosphorus fertilization (2,000 kg ha⁻¹ of reactive natural phosphate) to be carried out before planting. The clonal planting of *Eucalyptus* (hybrid AEC I144) at 2 x 3 m spacing was performed at a level with application of 300 grams of NPK (04-14-08) per seedling (Lopes and Barros, 2017). *Brachiaria* sp. was manually sown between the planting rows. The maintenance silvicultural treatments were replanting, covering fertilization and controlling ants (Lopes and Barros, 2017).

2.2. Surface runoff

A total of seven runoff collecting plots were installed in October 2016 in the experimental area inside the rehabilitated bauxite mine. Runoff was monitored from October 2016 to May 2018. The seven plots had dimensions of 10 x 6 m plus a triangular taper of 1 m in height from its base. The area and slope of the plots were: plot 1: 61.90 m² and 12.2°; plot 2: 61.96 m² and 12.7°; plot 3: 62.22 m² and 14.5°; plot 4: 62.04 m² and 12.9°; plot 5: 61.64 m² and 13.8°; plot 6: 61.73 m² and 15.1°; and plot 7: 61.46 m² and 15.4°. The plots were delimited by polyvinyl chloride (PVC) sheets and a triangular bottleneck was constructed with bricks at the lowest altitude (flow direction) for directing the water. A pipe was installed at the end of the triangular bottleneck to conduct the flow to a container with a capacity of 100 liters (Figure 1B and 1D). The water volume drained in the plots was measured after rain events, with each

collection consisting of one or more rains and then the collections for each month were added to obtain the monthly total. The runoff was calculated considering the runoff volume in relation to the contribution area of each plot (Equation 1):

$$R = V/A \quad (\text{Eq.1})$$

Where: R = runoff (mm); V = flow water volume (L); A = plot area (m²).

The runoff was divided by the precipitation to obtain the runoff coefficient and multiplied by 100 to obtain the runoff in percentage (RP). Runoff was monitored in a calendar year (January to December 2017) and compared between 2.5 years (October 2016 to May 2017) and 3.5 years (October 2017 to May 2018) of rehabilitation, both monitored periods under natural rain (Figure 1C).

2.3 Measurement of factors which interfere with surface runoff

Precipitation: The amount (P) and intensity (I) of precipitation were measured by a pluviograph (RainLog 2.0 RainLog 2.0 model from RainWise® Inc) installed 50 m from the experimental area. The daily precipitation data (mm) were exported in an Excel spreadsheet and added to obtain the monthly total. The intensity data (mm.h⁻¹) were used to obtain the maximum monthly intensities.

Vegetation cover: The plant stem circumference at the height of 1.30 m and the projection radius of the crowns were measured with a tape measure to

calculate the diameter at breast height (DBH) and the crown area (Wink et al., 2012), and to characterize the *Eucalyptus* coverage in three plots previously selected at 2.5 (February 2017) and 3.5 years (February 2018) of rehabilitation.

Litter: Three litter samples at 2.5 (May 2017) and 3.5 years (May 2018) of rehabilitation were collected to check the litter water retention capacity (LWRC). A 0.25 m² square template was launched at three randomly selected points within a range 1.5 m away from the runoff collecting plots to collect the litter deposited on the soil surface. The saturated mass (after being submerged in water for 72 hours) and the dry mass (in an oven at 75 °C with forced air circulation) of the samples were measured to calculate the LWRC by Equation 2:

$$\text{LWRC} = (\text{LSM} - \text{LDM}) / \text{LDM} \quad (\text{Eq.2})$$

Where: LWRC = litter water retention capacity (kg/kg); LSM = litter saturated mass (kg); LDM = litter dried mass (kg).

Physical properties of the soil: The texture, the overall density (Ds), the macro (ma) and microporosity (mi), the total porosity (TP) and the particle density (Pd) of the soil at 2.5 and 3.5 years of rehabilitation were analyzed to characterize their physical attributes (Teixeira et al., 2017).

Water infiltration into the soil: The initial infiltration rate (IIR), infiltration capacity (IC) and the stable infiltration rate (SIR) were measured in situ by the double ring infiltrometer method using an IN2-W infiltrometer from Turf-TecInternational[®]. The top layer of litter was removed to measure the water infiltration rates into the soil. The tests were conducted until the infiltration rate was constant in at least three consecutive measurements, reaching the stable infiltration rate (SIR). Three trials were performed at 2.5 (May 2017) and 3.5 years (May 2018) of rehabilitation. Soil moisture at a depth of 0 to 20 cm was measured by the gravimetric method (Teixeira et al., 2017) on the respective test days and compared by the t-test ($p \leq 0.05$) before comparing the infiltration rates. The infiltration rate was calculated by the relation between the infiltrated water column by time interval (Equation 3):

$$\text{IR} = \Delta h / \Delta t \quad (\text{Eq.3})$$

Where: IR = Infiltration rate (mm h⁻¹); h = height of the infiltrated column of water (mm); t = time interval to infiltrate the water column (hours).

The initial infiltration rate (IIR) was the rate measured in the first instant of the test. The infiltration capacity (IC) was considered the maximum rate that the soil can absorb water after the infiltration stabilized in a given time interval. The water slide height value was transformed into IC by Equation 4:

$$\text{IC} = 60hAc / tAc \quad (\text{Eq.4})$$

Where: IC = infiltration capacity (mm h⁻¹); hAc = height of the accumulated infiltrated column of water (mm); tAc = accumulated time interval (min).

Mechanical resistance of soil to penetration: The mechanical resistance of the soil to penetration was measured using an automated SoloTrack PLG5300 penetrometer from Falker[®]. Six observations were made to characterize the mechanical resistance of the soil to penetration at 2.5 (March 2017) and 3.5 years (March 2018) of rehabilitation. Soil moisture (0 to 20 cm) was measured by the gravimetric method (Teixeira et al., 2017) on the respective test days.

2.4 Statistical analysis

The data normality of the monthly runoff in percentage (RP), litter water retention capacity (LWRC), litter dry mass (LDM), physical characteristics of the soil, initial (IIR) and stable (SIR) infiltration rate and infiltration capacity (IC) was analyzed by the Shapiro-Wilk test and analyzes of variance were performed to verify the differences in these parameters between the 2.5 years with the 3.5 years of rehabilitation. The Scott-Knott test ($p \leq 0.05$) was applied to group similar soil mechanical resistance to penetration values in each rehabilitation period. Pearson linear correlation (r^2) between runoff and precipitation was calculated to verify its influence on runoff ($p \leq 0.05$).

A principal component analysis (PCA) was applied to the dataset of the factors which interfere with surface runoff to check the interrelated variables and highlight the factors with the greatest influence. The factors used in the PCA were: precipitation (P), initial infiltration rate (IIR), stable infiltration rate (SIR), infiltration capacity (IC), mechanical resistance of the soil to penetration (RSP), overall soil density (Ds), soil particle density (Dp), total porosity (TP), macroporosity (ma), microporosity (mi), vegetation cover area (VCA) and litter water retention capacity (LWRC).

The data were entered and processed in Microsoft Excel and the statistical analyses were performed using the R program (R Core Team, 2020).

3. RESULTS

3.1 Runoff and precipitation

The total precipitation in 2017 was 1,152 mm, generating a cumulative total of 3.3 mm of runoff in the area rehabilitated with *Eucalyptus* after bauxite mining, meaning that 0.29% of the rainfall was converted into runoff. The average monthly runoff percentage was 0.14%. The largest runoff occurred in November (2.1 mm), corresponding to 0.65% of the 317.4 mm of precipitation. The lowest precipitation (1.8 mm) and absence of the runoff were in September. The lowest runoff was between June and October, with

an average of 0.01% of rainfall. These months were characterized by the lowest precipitation intensities of 0.63 mm h^{-1} (Figure 2A).

The average monthly runoff percentage at 2.5 years was 0.25% ($\pm 0.26\%$) of precipitation and equal (p -value < 0.05) to 3.5 years ($0.15 \pm 0.22\%$) of rehabilitation. This runoff percentage varied between months and was higher in February (0.68%) and November (0.65%) at 2.5 and 3.5 years of rehabilitation, respectively (Figure 2B). The runoff in the rainy season at 2.5 years of rehabilitation (October to May) was 5.0 mm (0.42%) for 1,193 mm of precipitation. Moreover, the surface runoff in the same months at 3.5 years was 2.5 mm (0.20%) for 1,292 mm precipitation. The maximum and minimum values of runoff occurred in different months at 2.5 and 3.5 years of rehabilitation. The maximum

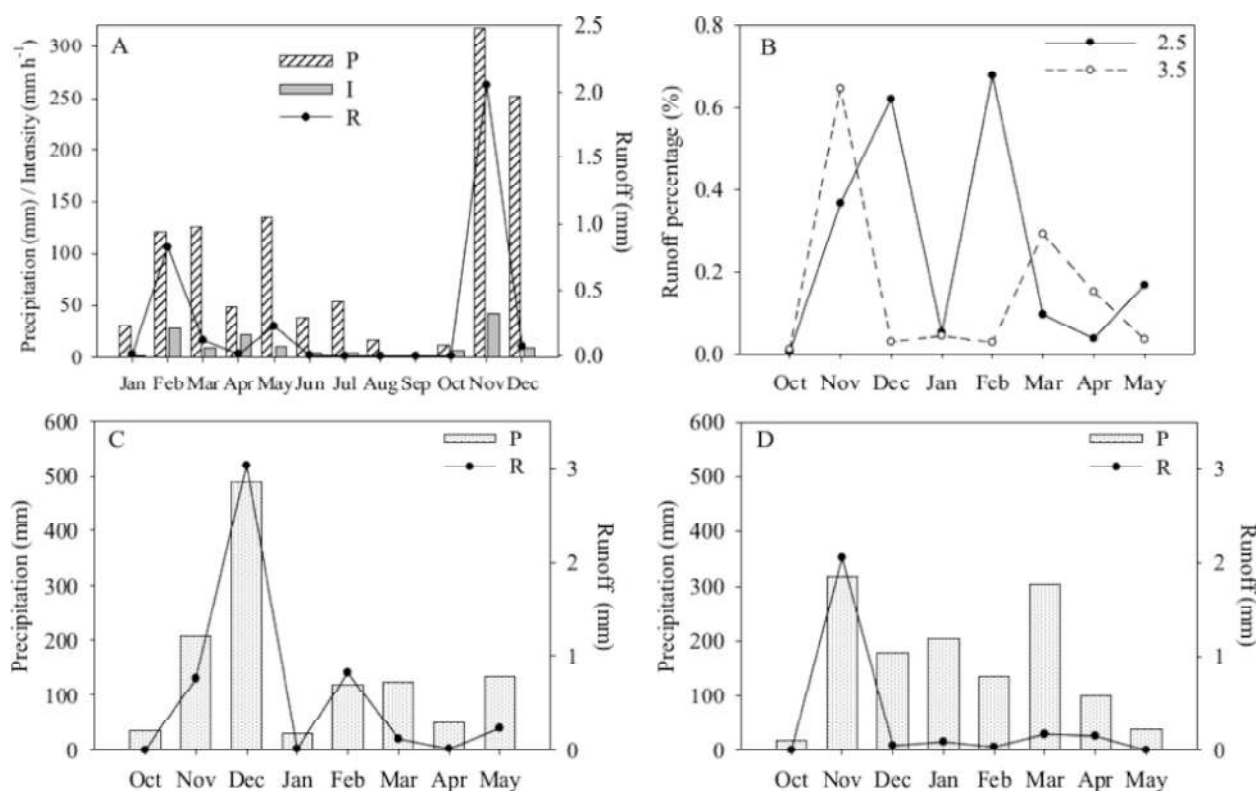


Figure 2 – Precipitation (P), maximum precipitation intensity (I) and runoff (R) in 2017 (A); Runoff percentage (%) at 2.5 years (October 2016 to May 2017) and at 3.5 years of rehabilitation (October 2017 to May 2018) (B); Precipitation (mm) and monthly runoff (mm) at 2.5 years (October 2016 to May 2017) (C); and at 3.5 years of rehabilitation (October 2017 to May 2018) (D) in the municipality of Mirai, Minas Gerais, Brazil.

Figura 2 – Precipitação (P), intensidade de precipitação máxima (I) e escoamento superficial (ES) no ano de 2017 (A); Escoamento superficial percentual (%) aos 2,5 anos (outubro de 2016 a maio de 2017) e aos 3,5 anos de reabilitação (outubro de 2017 a maio de 2018) (B); Precipitação (mm) e escoamento superficial mensal (mm) aos 2,5 anos (outubro de 2016 a maio de 2017) (C); e aos 3,5 anos de reabilitação (outubro de 2017 a maio de 2018) (D) no município de Mirai, Minas Gerais, Brasil.

runoff (3.1 mm) at 2.5 years of rehabilitation was in December for a precipitation of 489 mm, while the minimum was in January with 30 mm of precipitation and 0.01 mm of runoff. The maximum runoff (2.1 mm) for 3.5 years of rehabilitation was in February, which constituted 0.64% of the rains in that month (317 mm). In contrast, the minimum runoff (0.001 mm) was in October, equivalent to 0.01% of the rains of 18 mm (Figure 2C and 2D).

3.2 Factors which interfere with surface runoff

The vegetation cover area estimated by the projection area of the *Eucalyptus* crowns increased 27% from 2.5 years to 3.5 years of rehabilitation. The mean stem diameter increased from 10.94 cm (± 1.60 cm) to 12.09 cm (± 1.99 cm), and was equivalent to a basal area of 15.95 m² ha⁻¹ and 19.55 m² ha⁻¹ for 2.5 and 3.5 years of rehabilitation, respectively (Table 1).

Rehabilitation at 3.5 years of age showed a higher mean (p-value<0.05) accumulated litter mass (14.53 \pm 1.79 Mg ha⁻¹) than at 2.5 years (8.07 \pm 0.85 Mg ha⁻¹). A greater water retention of accumulated litter was found at 3.5 years (2.39 \pm 0.13 kg kg⁻¹) than at 2.5 years (1.91 \pm 0.11 kg kg⁻¹) after bauxite mining (Table 1).

The substrate humidity at 2.5 years (16.20% \pm 1.33%) was equal to 3.5 years (17.08% \pm 1.70%) of rehabilitation on the days of the infiltration tests. The initial infiltration (184 and 198 cm h⁻¹), infiltration capacity (124.4 and 88.7 cm h⁻¹) and stable infiltration rate (105.1 and 109.4 cm h⁻¹) did not differ (p-value \leq 0.05) between sampling of 2.5 and 3.5 years of rehabilitation (Table 1).

The physical analysis of the soil showed that the clay content, soil density, particle density, microporosity and total porosity were equal between the rehabilitation periods. In contrast, the sand content increased and the macroporosity decreased at 3.5 years (Table 1).

The soil moisture at the time of the soil resistance to penetration test of 2.5 years (19.60 \pm 0.063%) was equal to that of 3.5 years (21.59 \pm 0.47%) of rehabilitation. The reconstructed soil reached the maximum penetrometer resistance (6,800 kPa) in the six samples in both periods, but this resistance was reached at greater depths at 3.5 years (Figure 3A and 3B). The average soil resistance of 2.5 years (4900.02 kPa) was equal (p-value \leq 0.05) to 3.5 years (4756.87 kPa) of rehabilitation. The lowest resistances were at

Table 1 – Vegetable cover area (VCA), diameter at breast height (DBH) and basal area (BA) of trees stem, average saturated mass (Mg ha⁻¹) and average dry mass (Mg ha⁻¹) of accumulated litter and litter water retention capacity (LWRC) (kg kg⁻¹), initial infiltration rate (IIR), stable infiltration rate (SIR), infiltration capacity (IC) and physical soil properties.

Tabela 1 – Área de projeção das copas (APC), diâmetro do fuste (dap) e área basal (AB) do tronco das árvores, massa saturada média (Mg ha⁻¹) e massa seca média (Mg ha⁻¹) da serapilheira acumulada e capacidade de retenção hídrica (CRH) da serapilheira (kg kg⁻¹), taxa de infiltração inicial (IIR), taxa de infiltração estável (TIE), capacidade de infiltração (CI) e propriedades físicas do solo.

Variable	Unit	2.5 years	3.5 years	
Vegetable cover	DBH	10.94 \pm 1.6	12.08 \pm 1.99	
	BA	15.95 \pm 1.19	19.54 \pm 1.98	
	VCA	7.367.2 \pm 178.05	10.060.69 \pm 392.68	
Litter	Saturated mass	23.46 \pm 2.90 a	49.43 \pm 7.16 b	
	Dried mass	8.07 \pm 0.85 a	14.53 \pm 1.79 b	
	LWRC	1.91 \pm 0.11 a	2.39 \pm 0.13 b	
Infiltration	IIR	184 \pm 59.75 a	198 \pm 52.38 a	
	SIR	105.06 \pm 11.97 a	109.40 \pm 40.20 a	
	IC	124.42 \pm 22.68 a	88.75 \pm 47.04 a	
Physical soil	Coarse sand	13.67 \pm 0.47 a	17.45 \pm 1.70 b	
	Thin sand	10.67 \pm 0.47 a	14.15 \pm 0.79 b	
	Silt	14.33 \pm 0.94 a	8.53 \pm 3.34 a	
	Clay	61.33 \pm 0.47 a	61.27 \pm 2.31 a	
	Overall density	kg dm ⁻³	1.24 \pm 0.06 a	1.19 \pm 0.10 a
	Particle density		2.55 \pm 0.12 a	2.57 \pm 0.05 a
	Macroporosity	dm ³ dm ⁻³	0.36 \pm 0.05 a	0.23 \pm 0.01 b
	Microporosity		0.28 \pm 0.04 a	0.34 \pm 0.02 a
Total porosity		0.52 \pm 0.02 a	0.54 \pm 0.04 a	

Source: The authors. The same letter on the line does not differ by analysis of variance (p<0.05).

Fonte: Os autores. Mesma letra na linha não difere pela análise de variância (p < 0,05).

depths of 10 and 20 cm, with 30, 40, 50 and 60 cm being the most resistant in both periods (Figure 3C and 3D).

3.3 Correlation coefficients and principal component analysis

Positive correlations between runoff and precipitation and a reduction in this coefficient were observed from 2.5 (0.96; p-value 0.001) to 3.5 years (0.61; p-value 0.105).

The principal components analysis of the factors which interfered in the runoff at 2.5 years of age after bauxite mining explained 69.10% of the total variability in the first two components, where 44.70%

was explained by Component 1. Precipitation, rate and infiltration capacity, macro and microporosity were the most explanatory factors in Component 1. Furthermore, soil density and vegetation cover had the highest eigenvectors in Component 2 (24.4%) (Figure 4A). After 3.5 years of rehabilitation, the first two components explained 75.90% of the total variability, while 39.40% of the variance was explained by Component 1 and 36.50% by Component 2. Precipitation, vegetation cover, soil density and total porosity, macro and micro porosity were the most explanatory variables in the 39.40% explanation of Component 1. Infiltration rates and capacity were the most explanatory in Component 2 (Figure 4B).

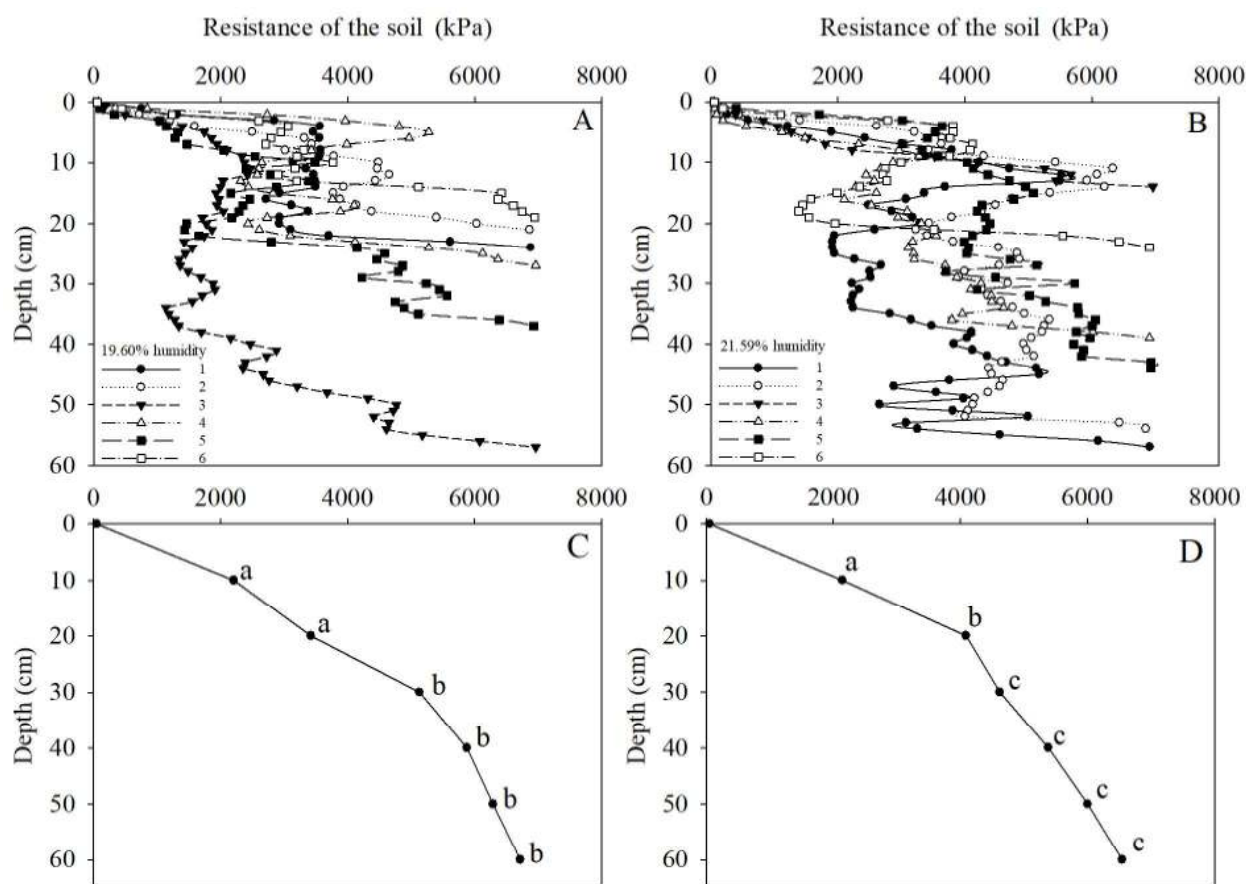


Figure 3 – Mechanical resistance of the soil to the penetration of the six samples at 2.5 years (A) and 3.5 years (B) of rehabilitation; grouping of resistances at 2.5 years (C) and 3.5 years (D) of rehabilitation. Similar letters indicate groupings of soil resistance between depths in the same treatment by the Scott-Knott test (p-value < 0.05).

Figura 3 – Resistência mecânica do solo à penetração das seis amostragens aos 2,5 anos (A) e aos 3,5 anos (B) de reabilitação; agrupamento das resistências aos 2,5 anos (C) e aos 3,5 anos (D) de reabilitação. Letras similares indicam agrupamentos da resistência do solo entre as profundidades no mesmo tratamento pelo teste de Scott Knott (p-valor < 0,05).

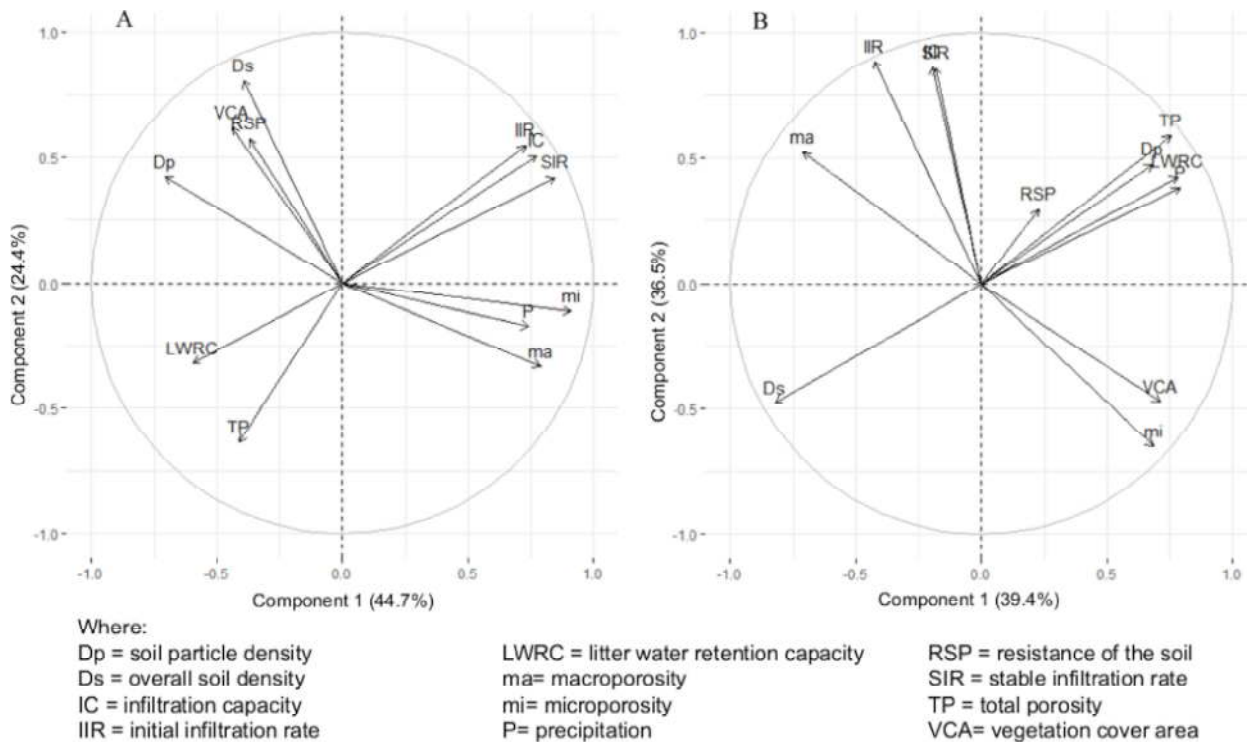


Figure 4 – Principal components analysis for the physical-environmental factors which interfere with runoff at 2.5 (A) and 3.5 (B) years of rehabilitation after bauxite mining in the municipality of Mirai, Minas Gerais, Brazil.

Figura 4 – Análise de componentes principais para os fatores físicos-ambientais que interferem no escoamento superficial na idade de 2,5 (A) e 3,5 (B) anos de reabilitação, após mineração de bauxita no município de Mirai, Minas Gerais, Brasil.

4. DISCUSSION

The total annual rainfall was 408 mm less than expected in the climatological normal estimated from 1981 to 2010 for the region (1,560 mm) (INMET, 2018). The higher runoff in November can be explained by the greater amount and intensity of precipitation that occurred in that month, which reached 41.40 mm h⁻¹ (Dourte et al., 2015). The accumulated runoff in 2017 and in the rainy season at 2.5 and 3.5 years of rehabilitation were lower than that found in *Eucalyptus* plantations with a slope of 17.6% in the Vale do Rio Doce region, Minas Gerais (1.2%) (Silva et al., 2011), and also for that reported in the rainy season in a *Eucalyptus* plantation with the same slope in a bauxite pre-mining area in southeastern Minas Gerais (0.56%) (Silveira, 2017). Surface runoff lower than that of non-mined areas may indicate that a greater amount of water is infiltrating the mined soil, mainly due to the soil turning and high vegetation cover which traps the runoff, allowing greater water infiltration into the soil (Merino-Martin et al., 2012).

The similarity of the runoff between 2.5 and 3.5 years of rehabilitation after bauxite mining can be explained by the rapid establishment of vegetation in the first period (2.5 years) with more than 90% of the plots covered, which reduces runoff even in the early stages of rehabilitation (Carroll et al., 2004; Loch, 2000). Insignificant differences in runoff were also observed after vegetation was established in freshly mined plots in Central Queensland (Carroll et al., 2004).

The increase in the canopy projection area, diameter and basal area of *Eucalyptus* stem from 2.5 to 3.5 years of rehabilitation are associated with the growth dynamics of the plants which increases the occupied space over time (Wink et al., 2012). The diameter and basal area values are higher than those of *Eucalyptus* plantations via seeds in the region of this study (Silveira, 2017), and similar to the values of commercial plantations of the same age (Wink et al., 2012). The 27% increase in vegetation cover in one year is within expectations for the mining area, which

could reach 60.26% in five years, as recorded in China (Li et al., 2017). This high vegetation cover reduces runoff due to greater rainfall interception (Freitas et al., 2016; Zou et al., 2015) and decreased impact of raindrops on the soil (Armenise et al., 2018).

The greater accumulated litter stock after 3.5 years of rehabilitation can be explained by the larger size and growth of trees, which enhances the production and deposition of leaves in the soil (Mateus et al., 2013). The litter cover reduces the runoff speed, thereby facilitating rainwater infiltration into the soil (Loch, 2000).

The statistically equal values of the initial infiltration rate, infiltration capacity and stable infiltration rate between the rehabilitation periods (2.5 and 3.5 years, Table 1) can be explained by the similar humidity conditions and the physical properties of the soil, as reported in surface mines in Texas, United States, with infiltration rates between 3 to 22 cm h⁻¹ (Jarocki, 1994). Greater infiltration occurs when the soil is dry and when texture and structure conditions have more empty spaces, constituting a characteristic which requires long periods for changes (Jarocki, 1994). The stable infiltration rates at 2.5 and 3.5 years of rehabilitation are considered high when compared to natural soils in *Eucalyptus* plantations (78 and 165 mm h⁻¹) and pasture (47 and 50 mm h⁻¹) in Oxisols (Almeida et al., 2014; Silveira, 2017) and mined areas in Texas, United States (3 to 22 cm h⁻¹) (Jarocki, 1994). The higher infiltration rates in this study can be explained by the thick and porous topsoil layer which facilitates water infiltration after mining (Huang et al., 2015) and by the presence of cracks and crevices resulting from the cross-subsoiling carried out during the soil preparation in rehabilitation (Haigh and Sansom, 1999).

The reduction in macroporosity and an increase in the sand content from 2.5 to 3.5 years of rehabilitation may be due to the reconstructed soil having a heterogeneous structure in the area generated by the disruption of soil horizons to remove ore (Li et al., 2014). The short period (one year) between sampling at 2.5 and 3.5 years of rehabilitation was not enough to modify the other physical soil characteristics (Table 1), as already reported in other surface mines (Chen et al., 2011; Ngugi et al., 2017).

The reconstructed soil reached the maximum penetrometer strength due to the presence of remaining

saprolite concretions after mining (Silveira, 2017). These concretions result in a higher stony index from 20 cm deep due to the soil horizon restructuring after mining (Barros et al., 2013). The structural similarity of the soil explains the equal mechanical resistance values of the soil to penetration between 2.5 and 3.5 years of rehabilitation (Ngugi et al., 2017). The lower strengths up to 20 cm in depth are explained by the replacement of the topsoil layer removed before mining (Martín-Moreno et al., 2016).

The reduction in the correlation coefficient between runoff and precipitation at 3.5 years can be explained by the increase in vegetation cover. Vegetation intercepts rain drops, reducing its direct influence of precipitation (Freitas et al., 2016; Zou et al., 2015) and contributing to reduce runoff (Zhang et al., 2014).

The largest eigenvectors for infiltration rate and capacity, macro and microporosity and soil density allow to infer that soil characteristics can be used to explain the equal runoff values (Santos et al., 2018). Except for macroporosity, these soil characteristics did not differ in the interval of one year between the rehabilitation periods (2.5 and 3.5 years), demonstrating that they demand more time for modification (Liu et al., 2017). Vegetation cover is another factor with a greater eigenvector in PCA and can explain the equal runoff values between the two rehabilitation periods due to its efficiency in reducing runoff by interception after 2.5 years of rehabilitation (Vásquez-Méndez et al., 2010). Although the collections of factors which interfere with runoff were not carried out in the same month, it is believed that the difference of a few days between collections in the same period is not significant (Liu et al., 2017), since there is a 12-month interval between collections for each period.

5. CONCLUSION

The runoff in the rehabilitated area after two years of bauxite mining showed the same pattern as unmined areas, with higher values in the rainiest months (November, December and February). The runoff was similar between 2.5 and 3.5 years of rehabilitation after bauxite mining, and less than the pre-mining runoff.

The physical soil characteristics showed insignificant changes between the two samplings,

but the litter mass and its water retention capacity increased. Vegetation cover and soil characteristics, mainly infiltration rates, were the determining factors for the runoff similarity in the two periods, indicating that the combination of adequate soil management and rapid plant cover provided runoff below 1% in a rehabilitated area after bauxite mining.

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7. AUTHOR CONTRIBUTIONS

Aline Gonçalves Spletzer: Conceived and designed the analysis, collected and analysis the data and wrote the paper. Lucas Jesus da Silveira: collected and analysis the data. Alexandre Simões Lorenzon and Aurora Yoshiko Sato: technical review. Herly Carlos Teixeira Dias: Conceived and designed the analysis and technical review.

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