



GEOSCIENCES

Forest restoration methods, seasonality, and penetration resistance does not influence aboveground biomass stock on mining tailings in Mariana, Brazil

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Abstract: The restoration methods applied on the areas affected by the Fundão tailings dam collapse have a high priority in Mariana region. We evaluated the effect of different restoration methods and site preparation techniques, depth and seasonality on penetration resistance of tailings, and how these predictors affect tree aboveground biomass in areas affected by the Fundão dam collapse in Mariana, Brazil. No significant differences in penetration resistance and aboveground biomass between treatments were observed, but significant differences were observed between seasonal periods. The main univariate model explained the significant effects of depth and seasonality, mainly by a negatively wet effect on penetration resistance. According to the best models (univariate and multivariate) were those that had depth as a predictor. This study showed how penetration resistance can be an indicator to select the best period for restoration process in areas affected by the collapse of the Fundão dam, but no limit to the aboveground biomass recovery on tailing.

Key words: Fundão dam, penetration resistance, resilient mitigation, restoration ecology, site effects.

INTRODUCTION

The Fundão dam collapsed, in Marina, Brazil, on November 5th, 2015, unleashed approximately 40 million m³ of tailings (80% of the total contained volume) in the Gualaxo do Norte River (Carmo et al. 2017). Almost five years after the collapse, active and passive restoration methods on the Atlantic forest affected are being applied (Campanharo et al. 2020, Martins et al. 2020a, b). The Fundão tailings dam collapse directly affected 863.7 ha of Permanent Preservation Areas (as defined by the federal forest code) associated to watercourses due to the flooding of the ore tailings (Carmo et al. 2017). Therefore, identifying ecological indicators related to

natural forest recovery is essential to improve the management criteria of different active and passive restoration methods (Martins 2018, Holl et al. 2020). For example, aboveground biomass (AGB) is one of the main ecological indicators of tropical forests recovery using either active or passive restoration methods (Holl et al. 2020). Thus, passive restoration is the spontaneous forest recovery that occurs without active human intervention; nevertheless this method can also require fencing to control livestock grazing, invasive species control, and fire protection (Martins 2018, Holl et al. 2020). Meanwhile, active restoration might be more effective to speed up the recovery process (i.e. biodiversity

and ecosystem functioning), accomplished through planting of nursery-grown seedlings, direct seeding, weeding, and thinning to achieve desired recovery status (Martins 2018). The success or failure of the various methods of ecological restoration must be investigated to propose adaptations and to know the limiting factors of their success before their large-scale implementation.

In this context, the tailing management plays an important role to achieve the restoration goals, such as prioritizing efficient site preparation that allows a fast forest recovery and ecosystem functioning, for example AGB recovery (Holl et al. 2020). The correct decision of site preparation techniques depends on environmental conditions, disturbance intensity and restoration project objectives (Stuble et al. 2017). For example, site preparation techniques, such as mulching, prescribed burning, mechanical procedures, and fertilization, can remarkably influence soil recovery and forest restoration success, which designed to improve the site conditions and promotes plant growth and ecosystem functioning recovery (Löff et al. 2016, Stuble et al. 2017, Pitz et al. 2019). However a limited number of studies have directly compared the effects of restoration methods with different site preparation techniques on penetration resistance of tailing. Thus, it is still necessary to understand the relationship of environmental factors (i.e. climate) and restoration methods (i.e. planting of nursery-grown seedlings, direct seeding and natural regeneration) on the physical properties of the tailings (i.e. depth and penetration resistance), and how this relationship can affect the aboveground biomass stock on areas affected by tailing in Mariana.

Penetration resistance (or soil strength) is a physical property of the soil that reflects changes in other soil properties, such as structure,

texture, bulk density, water content, and soil organic matter (Hamza & Anderson 2003, Singh et al. 2015). Furthermore, soil strength predicts the resistance offered by soil to root penetration and can be used as a measure of soil compaction (Hamza & Anderson 2003, Singh et al. 2015). Compaction is a limiting factor for root growth, water supply and nutrient availability due to the reduction of the amount and size of soil pores leading to the decrease of soil infiltration and consequently to waterlogging and run-off (Hoefler et al. 2010, Al-Gaadi 2012). Moreover, soil is a fundamental ecosystem component directly linked to the erosional, biogeochemical and hydrological cycles (Keesstra et al. 2012, Brevik et al. 2015, Smith et al. 2015). Thus, we presume that tailing properties monitoring can be a feasible tool to the restoration success.

In this study, we evaluated the effect of different restoration methods (i.e. planting of nursery-grown seedlings, direct seeding and natural regeneration) and site preparation techniques (with and without fertilization and pH correction), depth and seasonality on penetration resistance of tailings, and how these predictors affect tree AGB stock in areas affected by the Fundão dam collapse in Mariana, Minas Gerais state, southeastern Brazil.

MATERIALS AND METHODS

Experimental site

Active and passive restoration experiments were established in areas affected by the Fundão tailings dam collapse in the district of Paracatu de Baixo (7754350 N, 686800 E), municipality of Mariana, Minas Gerais, Brazil (Figure 1). The study area is located between 505 and 515 m above sea level, and the relief varies from strongly undulating to mountainous. The climate is moderate humid and tropical, with a dry season occurring from May to September

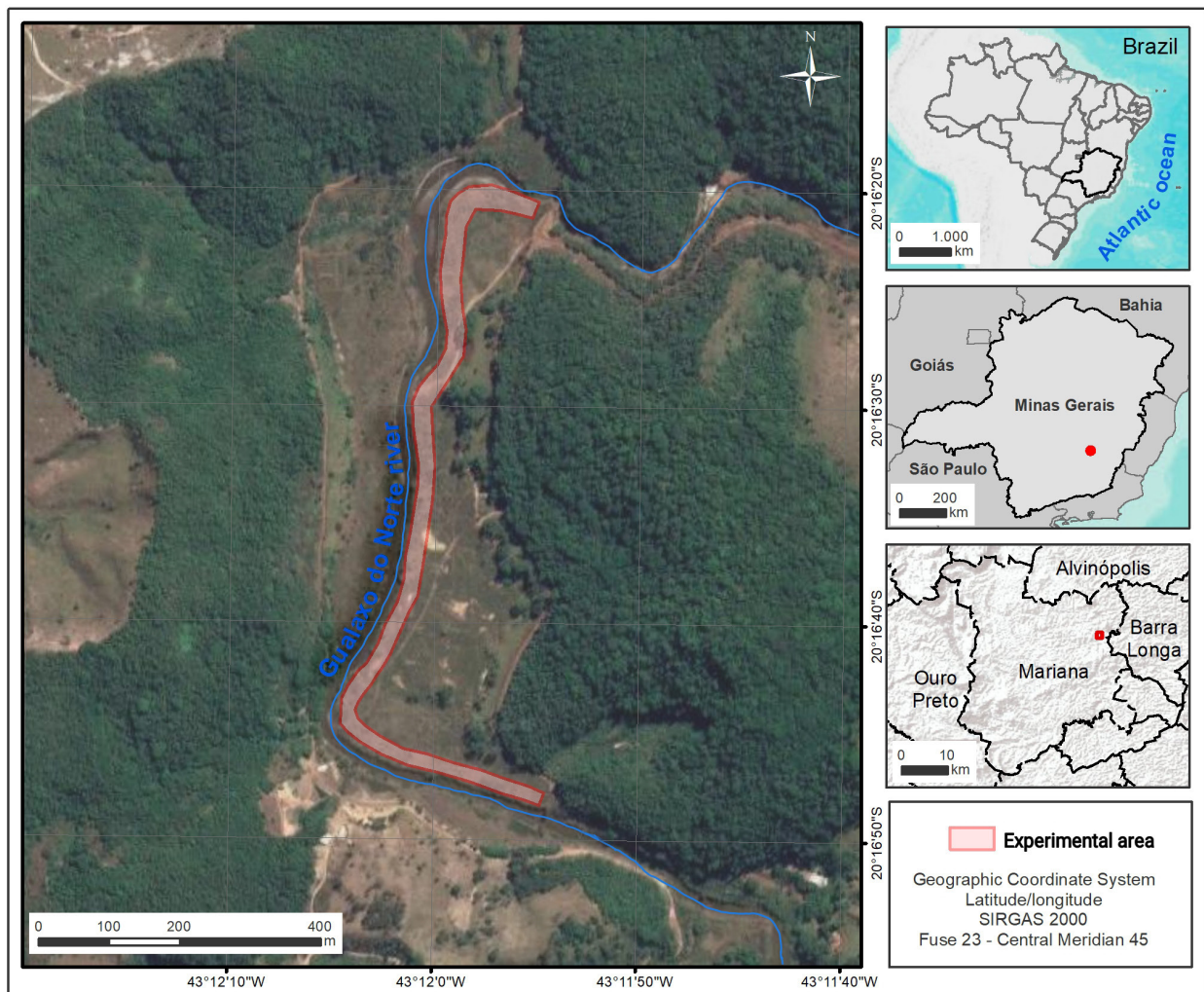


Figure 1. Location of the study area along the Gualaxo do Norte river, in relation to South America, the Minas Gerais State and the Mariana municipality.

and a wet season occurring between December and March. The mean annual precipitation is 1340 mm, mean annual air temperature is 19°C and mean annual relative humidity is ca. 80%. Two dominant soil classes are found in the site: Cambic Red-Yellow Podzolic covers the upper fluvial terraces, while Dystric Red-Yellow Latosol represents hilltops and mountainsides (Martins et al. 2020a).

The tailings accumulated in our study area present different depths (ca 50-100 cm) on a flat and homogeneous topography along river, mainly affecting the Atlantic Forest (Carmo et al. 2017) (Figure S1 - Supplementary Material).

Also, it is worth mentioning that the study area had a long history of land use based on pasture for livestock before the accumulation of mining tailings.

Experimental design

We established 36 plots with different restoration treatments, approximately 16 months after of the Fundão dam collapse, in March of 2017. A randomized block design with six restoration treatments was used, consisting of six replicates plots for each treatment: planting of native tree seedlings with fertilization and pH correction (soil acidity correction by limestone) (PSf)

and without fertilization and pH correction (PS); seeding of native trees with fertilization/correction (SDf) and without fertilization and pH correction (SD); natural regeneration with fertilization/correction (NRf) and without fertilization and pH correction (NR), as a control treatment. In the center of each plot was demarcated a regular area of 144 m² (12 × 12 m), where the data was collected, so that a possible edge effect would be eliminated (Figure 2).

Site preparation techniques and seedling material

Calcined dolomitic limestone (100 kg ha⁻¹), agricultural gypsum (350 kg ha⁻¹), ammonium sulfate (100 kg ha⁻¹), and super simple phosphate (150 kg ha⁻¹) were applied in plots with fertilization and pH correction treatments. Subsoiling was



Figure 2. General aspect of the restoration methods in the study area. Natural Regeneration (a, b), Seeding (c, d), Seedlings (e, f).

carried out with a depth of 60 centimeters in all the treatments to mix the remaining soil (when available) and breakup the interface between the covered soil and the tailings cover. Native seedlings were planted using a spacing of 3 × 2 m while the plots where seeding were foreseen the spacing was 3 m between lines of seeding (see species list in Tables SI, SII - Supplementary Material).

Substrate compaction measurement

The substrate compaction was measured in all plots of each treatment using an electronic soil compaction meter (penetroLOG Falker), which indicates the soil penetration resistance value corresponding to each centimeter at different depths (0-20 cm). The measurements were done in two periods, during the wet season (March 2019) and the dry season (September 2019), two years and half post restoration interventions. Systematically, in the center of each plot, five measurements were taken in the wet season and three during the dry season, totaling 30 and 18 replicates per treatment, respectively. It is worth mentioning that less replicates were taken in the dry season due to the elevated compaction of the substrate, moreover, for the same reason, in many measurement points were not possible to exceed the first eleven centimeters in depth, while in the wet season, for all the measured points, was possible to reach 20 centimeters in depth.

Vegetation data collection and aboveground biomass

In each plot were measured the diameter at breast height (DBH ≥ 2 cm at 1,30 m) and also the total height of them. The aboveground biomass of all individual for each treatment was estimated using tree DBH (cm), height (H, m) and wood density (ρ , g cm⁻³) based on a general allometric equation (Chave et al. 2014). The total

aboveground biomass per plot was the sum of the aboveground biomass of all trees, which was then converted into megagrams per hectare (Mg ha^{-1}) (Rodrigues et al. 2020).

Data analyses

All analyses were run in R 3.6.0 (R-Core Team 2019). We tested the normal distribution of all variables using the Shapiro-Wilk test and the Q-Q plot, and homogeneity of variances by Bartlett's test (Crawley 2013). To compare penetration resistance and aboveground biomass (non-normally distributed data) between treatments of site conditions, we used Kruskal-Wallis's test followed by a posterior Dunn's test performed with the 'dunn.test' package. For test compare penetration resistance (non-normally distributed data) between periods (dry and wet periods) we used Wilcoxon test (Crawley 2013, R-Core Team 2019).

We tested generalized linear mixed-effect models (GLMM) to investigate the effect of treatments, seasonality and depth on penetration resistance (continuous response variable), and after checking the effects of these predictors on tree aboveground biomass. Thus, predictor variables were grouped into three categories, i.e. tailing depth (continuous explanatory variable), seasonality (wet and dry period) as a categorical explanatory variable, and the restoration treatments of site conditions (categorical explanatory variable). Then we evaluated the effect of these predictors on AGB. The treatments included six levels (i.e. each treatment of site condition). We tested alternative models with individual effects of predictors and different combinations of predictors with low correlation, and the plots were considered as a random effect (1| plot). All models were calculated using the package 'lme4' in the platform R (Crawley 2013, R-Core Team 2019).

RESULTS

Penetration resistance of tailings between treatments and periods

No significant differences in penetration resistance between treatments were observed (Figure 3); however significant differences were observed between periods (Figure 4). The mean per treatment followed this order in the wet period: NRf (1484.23 kPa) < PSf (1607.86 kPa) < Sdf (1710.60 kPa) < NR (1758.91 kPa) < PS (1894.32 kPa) < SD (1933.22 kPa). However in the dry period the order was: NR (3075.95 kPa) < SD (3084.63 kPa) < PS (3114.85 kPa) < NRf (3120.29 kPa) < PSf (3159.11 kPa) < Sdf (3161.01 kPa). The average resistance over all observations for the treatments in the dry season was 3130.98 kPa while for the wet season was 1731.07 kPa; the mean of maximum pressures per sampling point during the dry season was 5445.31 kPa and during the wet season 3572.33 kPa (Figure 4).

Vertical penetration resistance

The vertical substrate penetration resistance distribution maintained a similar pattern between treatments (Figure 5, Figure S2). For both periods, the deeper the substrate layer the greater was the penetration resistance. However, in only 3 out of 108 sampling points were possible to reach 20 cm deep during the dry period and the pressure commonly exceeded 5000 kPa. On the other hand, during the wet season was possible to reach 20 centimeters in depth for all the 180 sampling points. The penetration resistance at this depth, for all the treatments, was around 3000 kPa, but did not exceed 4000 kPa (Figure 5, Figure S2).

Effects of treatments, depth and seasonality on substrate penetration resistance

The main univariate model explained the significant effects of depth (GLMM: estimate =

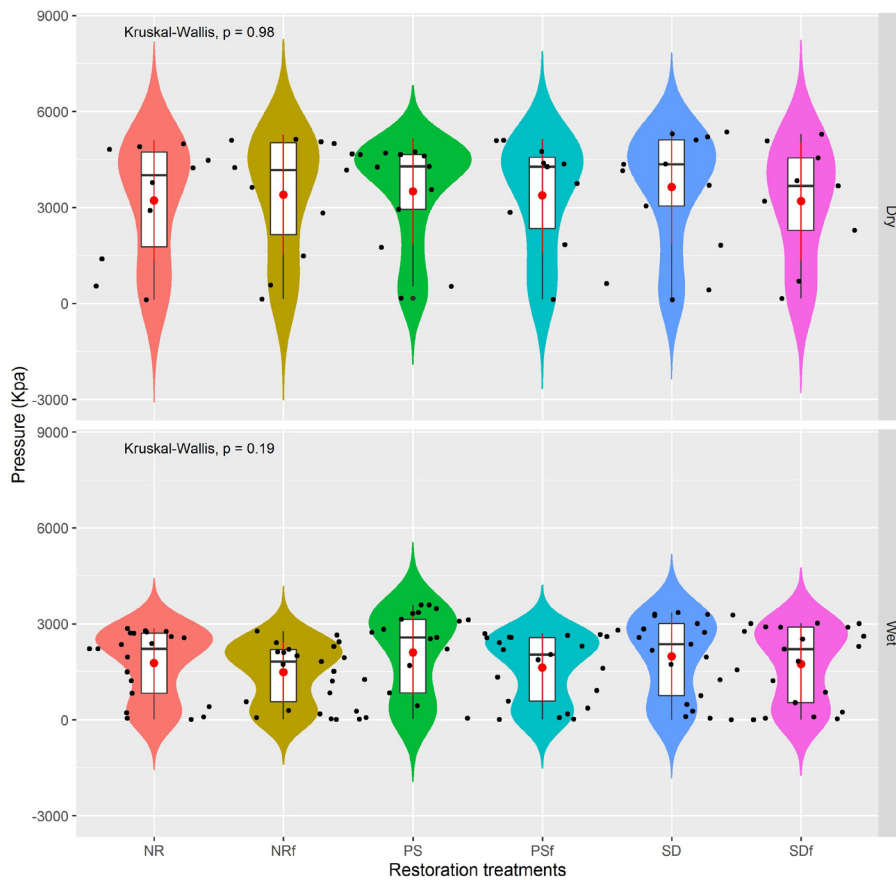


Figure 3. Penetration resistance differences between treatments. A randomized block design with six restoration treatments was used, consisting of six replicates for each treatment: Seedlings with fertilization/pH correction (PSf); Seedlings without fertilization/pH correction (PS); Natural Regeneration with fertilization/pH correction (NRf); Natural Regeneration without fertilization/pH correction (NR); Seeding with fertilization/pH correction (SDf); Seeding without fertilization/ pH correction (SD).

0.11, $t = 71.96$, $p < 0.001$, Figure 6) and seasonality, mainly by negatively wet effect (GLMM: estimate = -0.85 , $t = -19.33$, $p < 0.001$) on penetration resistance of the substrate (Table I, Figure 6). According to multivariate model selecting depth and seasonality as predictors, had negatively influences on penetration resistance (GLMM: estimate = -0.17 , $t = -32.43$, $p < 0.001$, Figure 6). According to the best models (univariate and multivariate) were those that had depth as a predictor (Table I, Figure 7, Figure S3).

Aboveground biomass

Although there are no differences in the substrate penetration resistance, the results show that the aboveground biomass stock is maintained without differences between treatments (Figure

S4). Thus, our tested models show that there are no significant effects of restoration treatments, tailing depth, penetration resistance, and seasonality on aboveground biomass.

DISCUSSION

The penetration resistance was significantly higher on the dry substrate, almost the double when compared all the observations for the dry (3130.98 kPa) with the wet period (1731.07 kPa). Moreover, we have to consider that the means for the dry period are underestimated when compared to the wet period because the penetrometer did not reach 20 cm, according with GLMM approach, the pressure needed to reach this depth would be much higher.

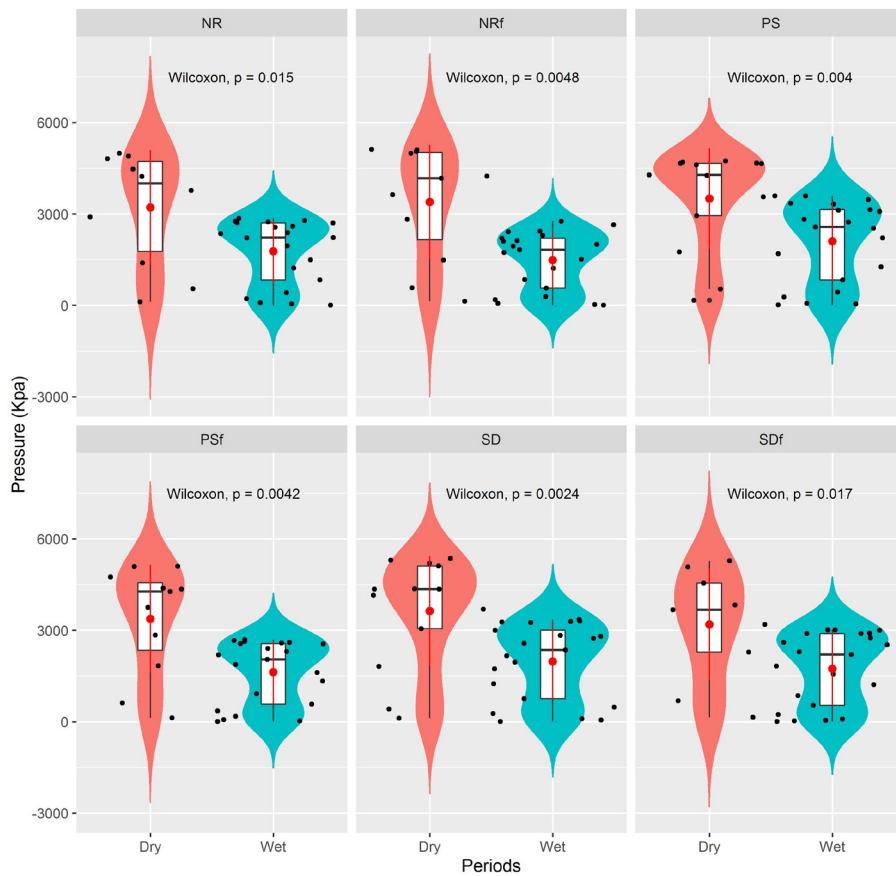


Figure 4. Penetration resistance differences between periods. A randomized block design with six restoration treatments was used, consisting of six replicates for each treatment: Seedlings with fertilization/pH correction (PSf); Seedlings without fertilization/pH correction (PS); Natural Regeneration with fertilization/pH correction (NRf); Natural Regeneration without fertilization/pH correction (NR); Seeding with fertilization/pH correction (SDf); Seeding without fertilization/pH correction (SD).

Probably, this can be explained because the mud dynamic presents similarly to a common soil, which normally shows higher compaction when dry. Previous studies that have been conducted using penetrometer readings found similar differences comparing the same sites but with variations in soil moisture (Bécel et al. 2012, Silva et al. 2016, Singh et al. 2015). For example, a study carried out by Assis et al. (2009) compared the penetration resistance of four soil types under four moisture conditions and the means ranged from 1130 kPa to 5830 kPa. Additionally, the region, as well as, the study area before the Fundão tailings dam collapse, is traditionally used for livestock (cattle), which has caused soil compaction due to overgrazing (Curtinhas 2010).

As expected, substrate water correlated negatively with penetration resistance, explaining 85 % of its variation while depth was

positively correlated with penetration resistance, explaining 11 % of the pressure variation. Penetration resistance increases naturally with depth due to shaft friction and overburden pressure of the weight of the soil above, as well as, changes in soil texture, structure and anthropogenic causes such as agricultural traffic (Manuwa 2013). The determination of the penetration resistance in dry soil conditions results in high levels of compaction (Moraes et al. 2014). Thus, soil water content affects negatively the penetration resistance (Hamza & Anderson 2003, Assis et al. 2009, Singh et al. 2015). Tree root development is significantly impeded at penetration resistance values of between 2000 and 3000 kPa (Sinnott et al. 2018) and its growth is diminished in compacted soils because both root growth rate and elongation are reduced (Vocanson et al. 2006, Bécel et al. 2012, Singh

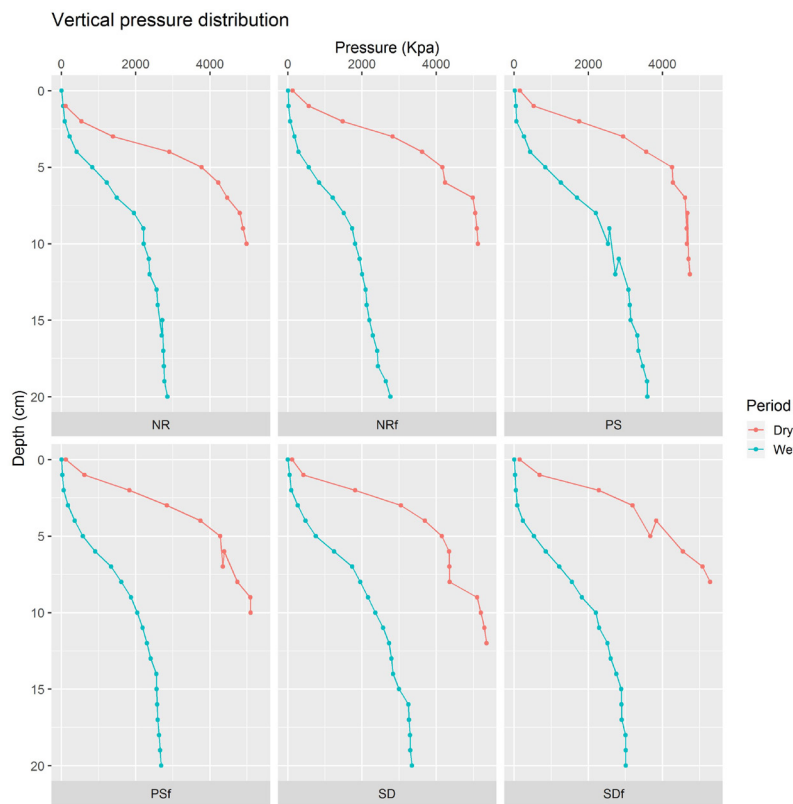


Figure 5. Vertical substrate penetration resistance distribution. Treatments: Seedlings with fertilization/pH correction (PSf); Seedlings without fertilization/pH correction (PS); Natural Regeneration with fertilization/pH correction (NRf); Natural Regeneration without fertilization/pH correction (NR); Seeding with fertilization/pH correction (SDf); Seeding without fertilization/pH correction (SD).

et al. 2015). Furthermore, the branching and the root system shape can be affected (Bécel et al. 2012). However, the soil structure commonly provides alternative ways for the roots explore the profile through fissures or cracks, which might overestimate the real resistance that a root is submitted once the penetrometer is inserted vertically into the soil (Moraes et al. 2014, Sinnett et al. 2018).

During the wet period the permittivity ranged from 14.54 (SD) to 16.67 (SDf) which is expected for wet soils where values commonly stay between 10 and 20 (Mohamed & Paleologos 2018). On the other hand, for dry soils the permittivity commonly ranges from 2 to 6 (Mohamed & Paleologos 2018). Another possibility is a possible influence due to the high temperature in the day that the measurements were taken. The dielectric permittivity is sensitive to changes in temperature (Seyfried & Grant 2007). In some soils, as it does in the

water, the molecular vibrations increases with the temperature and, these vibrations, with the presence of an electric field applied; hinder the rotational dipole moment (Dyck et al. 2019, Mohamed & Paleologos 2018). In practical terms, the dielectric permittivity decreases as the temperature increases. However, other variables such as mineralogy, salinity and bulk density could have also influenced the permittivity readings (Mohamed & Paleologos 2018, Wu et al. 2015).

The AGB stored in restored forest treatments ranged from 0.06 Mg ha⁻¹ (NR) to 10.49 Mg ha⁻¹ (PSf), indicating that despite of the early stage of restoration interventions the substrate properties are not impeding the AGB recovery. In addition, in the plots where active restoration was used the trees presented a considerable development, as noticed during the fieldwork. During the first years of restoration is expected a lower AGB stock for passive methods (e.g.

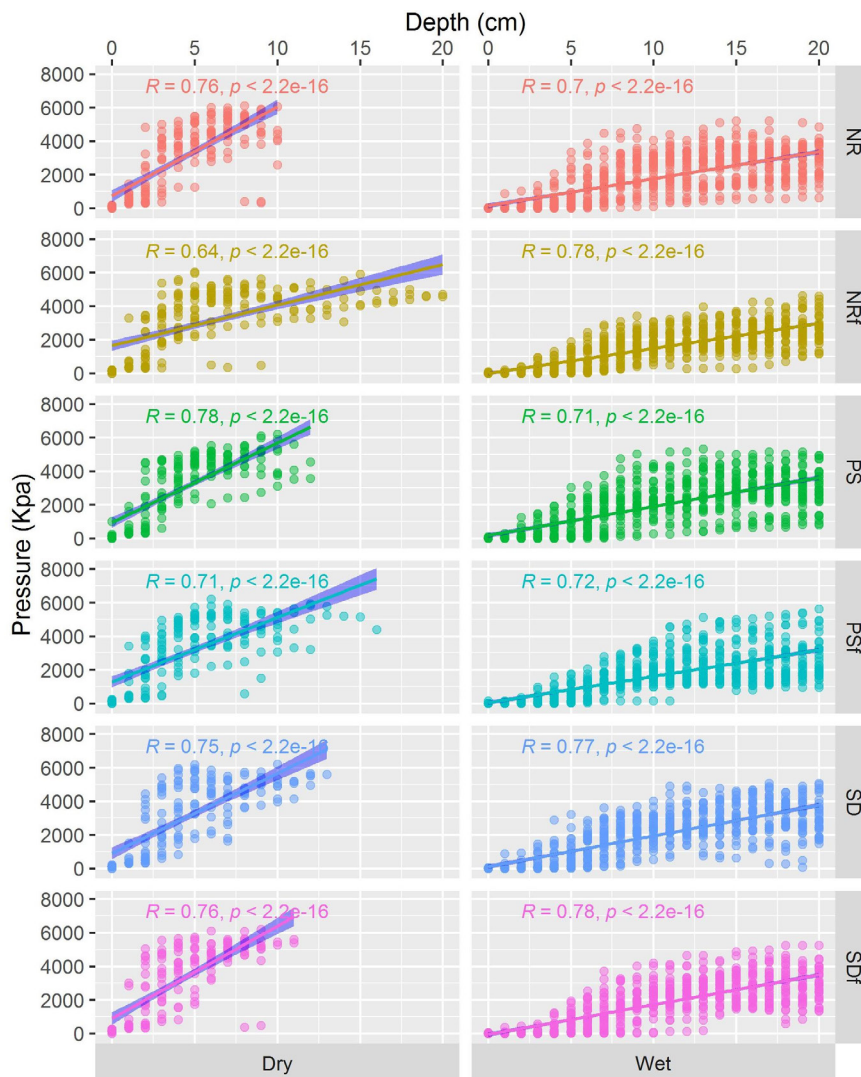


Figure 6. Penetration resistance and the main predictors' relationship according with GLMM approach. The effect of depth on pressure between periods. Color fill circles indicate data per treatments. Solid lines represent the fitted values (prediction) of the models, and the shaded area the 95 % confidence interval of the predicted values of each model. Treatments: Seedlings with fertilization/pH correction (PSf); Seedlings without fertilization/pH correction (PS); Natural Regeneration with fertilization/pH correction (NRf); Natural Regeneration without fertilization/pH correction (NR); Seeding with fertilization/pH correction (SDF); Seeding without fertilization/pH correction (SD).

Wheeler et al. 2016). We also believe that the natural regeneration was limited by the competition with invasive grasses (e.g. Gioria & Pyšek 2015), because Pilocelli (2020), also studying an area which faced the same impact, found high abundance and richness of naturally regenerated trees where invasive grasses were not a problem.

Overall, we presumed that the active restoration treatments induced a decrease of herbaceous cover due to the shade created by the coverage of the trees. In addition, this shade condition provides a more suitable microenvironment for the establishment of

late secondary tree species (Elgar et al. 2014). Furthermore, probably the root growth in these treatments can contribute to the soil restoration through technosol structuring and nutrient cycling, as well as, the improvement of the soil properties through the incorporation of organic matter, nutrients and preventing erosion processes (Brevik et al. 2015). Thus, contributing to the technosol formation in the areas affected by the collapse of the Fundão dam can provide valuable ecosystem services during forest recovery, for example soil carbon stock (Ruiz et al. 2020).

Table I. The subset of models predicting the main effect of treatment, depth, and seasonality on pressure (Generalized linear mixed-effect model). The result of information-theoretic-based model selection is indicated. We present only the models with values of $\Delta AICc < 2$. The Akaike information criterion corrected for small samples (AICc).

	Model 1	Model 2	Model 3	Model 4
(Intercept)	0.24 *** (0.05)	0.16 * (0.07)	0.66 *** (0.04)	1.87 *** (0.05)
Depth	0.68 ***(0.01)			1.66 (0.03) ***
GroupNR		-0.04 (0.11)		
Group SD		0.01 (0.11)		
Group PSf		-0.11 (0.11)		
Group NRF		-0.17 (0.11)		
Group Sdf		-0.07 (0.11)		
Period			-0.85 (0.04) ***	-2.18 (0.05) ***
Depth:Period				-1.05 (0.03) ***
N	4835	4835	4835	4835
N (Replicate)	281	281	281	281
AIC	917.04	1028.28	963.88	926.79
BIC	942.97	1280.15	989.82	965.69
R² (fixed)	0.32	0.00	0.12	0.61
R² (total)	0.74	0.21	0.19	0.73

All continuous predictors are mean-centered and scaled by 1 standard deviation.

*** p < 0.001; ** p < 0.01; * p < 0.05. Model1 <- glmer(Pressure ~ Depth + (1|Plot), data=dados); Model2 <- glmer(Pressure ~ Treatment + (1|Plot), data=dados); Model3 <- glmer(Pressure ~ Period + (1|Plot), data=dados); Model4<- glmer(Pressure ~ Depth * Period + (1|Plot), data=dados).

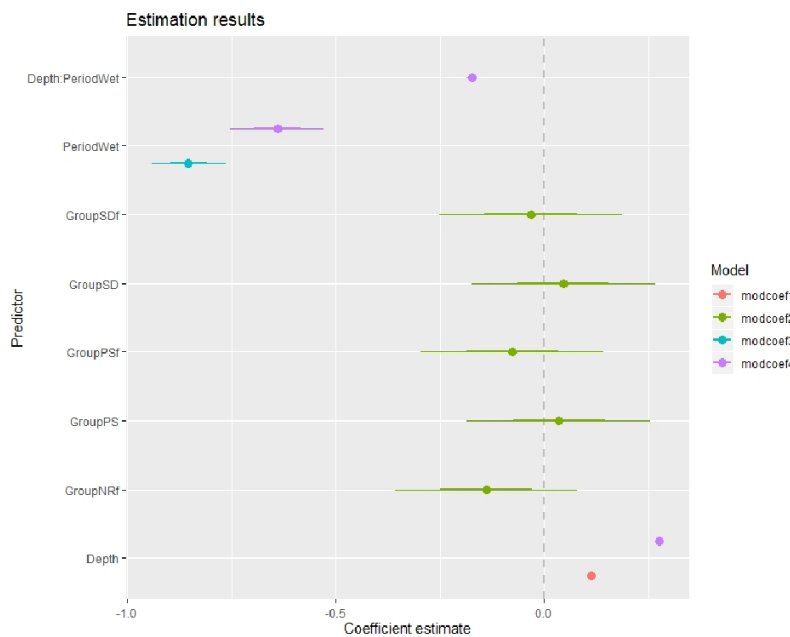


Figure 7. Effects of multiple predictors on penetration resistance in Mariana, Brazil. Results are presented for the mean distributions. We show the averaged parameter estimates (standardized regression coefficients) of model predictors, the associated 95% confidence intervals and the relative importance of each factor, expressed as the percentage of explained variance. Our tested models show that there are no significant effects of tailing depth and penetration resistance, and seasonality on aboveground biomass, thus the coefficients were not presented. mod1 <- lmer(Pressure ~ Depth + (1|Plot), data=dados); mod2 <- lmer(Pressure ~ Treatment + (1|Plot), data=dados); mod3 <- lmer(Pressure ~ Period + (1|Plot), data=dados); mod4 <- lmer(Pressure ~ Depth * Period + (1|Plot), data=dados).

CONCLUSION

We concluded that penetration resistance showed differences between seasons, but there were no significant differences between treatments. However, despite of the early stage of restoration interventions the substrate properties are not limiting the AGB recovery. Therefore, the study results show how resistance can be an indicator to select the best period to manage the soil and the restoration process in areas affected by the collapse of the Fundão tailings dam. The relationship between penetration resistance and water content might play a great importance in the forest restoration success.

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SUPPLEMENTARY MATERIAL

Figures S1, S2, S3 and S4.

Tables SI and SII.

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