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# Edaphic Attributes in Different Successional Ecological Restoration Models Consortium with Eucalyptus in the Brazilian Atlantic Forest

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## Abstract

This work aimed to evaluate the effectiveness of forest restoration consortium or not with eucalyptus in the recovery of edaphic attributes. Three of them were managed with the following forest restorations: natural regeneration after clear cutting of eucalyptus planting (RP), planting of native species after clear cutting of eucalyptus planting (RA) and planting of native species after cutting 50% of eucalyptus planting (RAE), and of a secondary forest (FR). Sixteen (16) soil samples were collected in each area for the analysis of the physical and chemical attributes. The restoration with RA promoted a less acidic pH, lower $Al^{3+}$ content, higher P content and higher V%, similar to FR. The RAE and RP restorations favor an increase in SB, CTC, N and in the organic carbon content.

**Keywords:** Recovery of degraded areas, floristic, phytosociology, forest soils.

## 1. INTRODUCTION AND OBJECTIVES

In forest restoration, passive or active models can be used (Zanini, 2021). Although methods predict the closest possible return to the conditions observed in the original ecosystem, the restoration projects running in the Atlantic Forest face various problems due to lack of diagnoses that consider the management of the areas and due to lack of monitoring (Rodrigues et al., 2009). In the active successional model, there is the introduction of native seedlings, it is desirable that silvicultural treatments are performed as well as monitoring, in order to ensure greater biodiversity (Rodrigues et al., 2009). On the other hand, the passive model invests exclusively in natural regeneration, requiring only in some cases the enclosure and forest protection (Zahawi et al., 2014).

In the case of studies with successional restoration models in the Atlantic Forest, it is a consensus among researchers that passive models, although slower, accumulate less aerial biomass carbon and use less diversity of forest species as well as being more advantageous because of low restoration costs (Brancalion et al., 2016; Zahawi et al., 2014). In succession models, species of consortium, native or exotic like Eucalyptus, can also be used (Brancalion et al., 2021). These essences can, in addition to contributing to wood provisioning services, serve to store, recover the soil chemical and physical properties. But within this context, the role of eucalyptus in the diversity of species in the forest ecosystem is discussed and how it can help or impair the ecological succession in areas subjected to forest restorations (Brancalion et al., 2021).

In Brazil, it has long been discussed about the strategies of incentives for the restoration of the Atlantic Forest, ensuring its biodiversity maintenance. Forest recomposition programs, such as the National Plan for the Recovery of Native Vegetation - Planaveg, try to foster the planting of native and exotic so that goals in the country are achieved (Bustamante et al., 2019). Modest government initiatives are considered to be taken as well as bump the problem of lack of resources once the restoration of the degraded areas is costly and, for each situation, a method is recommended.

In Mixed Eucalyptus plantings, with high diversity of native forest species in the Atlantic Forest, Amazonas et al. (2018) observed that there was a competition for resources such as water, light and nutrients with eucalyptus slowing the growth of native species, but this was not sufficient to affect their survival or overcome the native trees. Thus, forest restorations combining eucalyptus with a high diversity of native forest species are viable technically and are an important alternative for multipurpose planting in order to restore the Brazilian Atlantic Forest (Amazonas et al., 2018).

Many of the negative effects attributed to eucalyptus on the growth and natural regeneration of native trees depend on the characteristics of the production system, landscape structure, soil and climate in which they are cultivated, and not the effects promoted by the eucalyptus itself. In the Atlantic Forest region, eucalyptus can become an important ally in the restoration of tropical forests, and its use and investment opportunities should be considered within the portfolio of options supported by financing public and private policies (Brancalion et al., 2021).

Most changes in soil chemical and physical properties in response to restoration depends on the development of the plant community and ecological succession (Garesch et al., 2014; Castelli et al., 2015). According to the level of degradation and the distance from propagule sources, degraded and/or disturbed areas can respond differently depending on the type of forest restoration and management. In forest restorations, soil chemical properties are distinct in natural ecosystems (Dodonov et al., 2014). There is a gap on how chemical and physical properties are changed after the use of different forest restoration techniques over time (Dodonov et al., 2014). In this context, this work aimed to evaluate the effectiveness of each consortium forest restoration model or not with eucalyptus in the recovery of edaphic attributes.

## 2. MATERIALS AND METHODS

### *2.1. Description of the study area*

The study areas are located at Fazenda Rio Fundo, in the municipality of Itaporanga d´Ajuda and the rural campus of the Federal University of Sergipe in the municipality of São Cristovão, both in the state of Sergipe (Figure 1). The geographical coordinates of the Fazenda Rio Fundo study Area are 11º06’30 ”of southern latitude and 37º19’60” west longitude and the rural campus of the Federal University of Sergipe, 10 ° 55 ‘southern latitude and 37 ° 11’ West Longitude. The average annual temperature is 24.8ºC (minimum 21.4 ° C and maximum 28.2 ° C). The average annual precipitation is 1,300 mm (Fontes, 2010).

The relief is composed mainly of soft hills. The original vegetation is of semideciduous forest of the Atlantic Forest. The Atlantic Forest that occurs in the study region is a forest typology that encompasses semi-deciduous and deciduous species as Ingá (*Inga uruensis*), Amescla (*Protium heptaphyllum*), Embiruçu (*pseudobombax grandiflorum*), embaúba (*Cecropia pachystachya*) and Murici (*Byrsonima Crassifolia*). The region is dominated by livestock (Fernandes et al., 2017). The predominant soil class in the study areas was classified as yellow red argisol the moderate sandy loam texture.

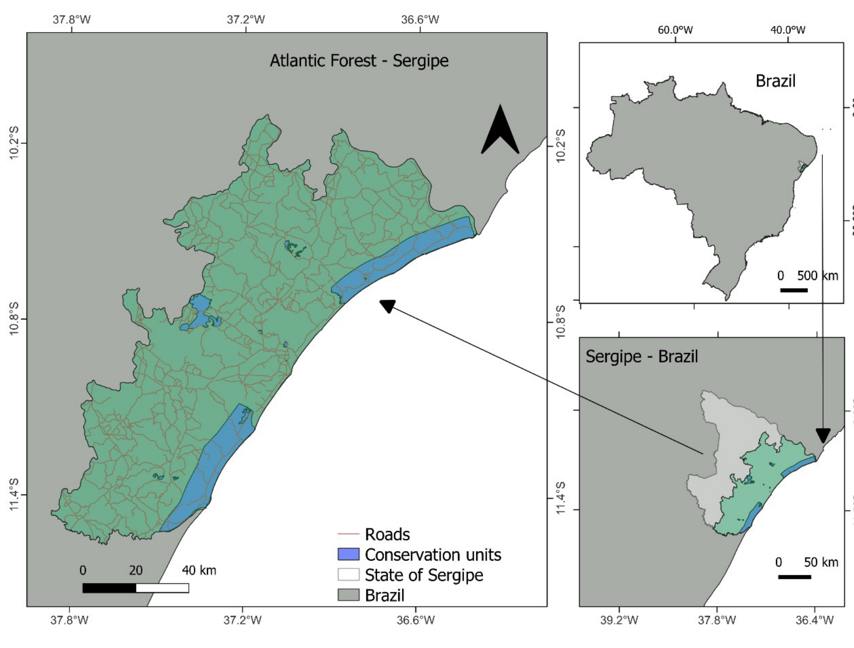


**Figure 1.** Location of the study areas.

## *2.2. Description of successional forest restoration models*

The farm Rio Fundo, has 1,563.44 ha and belongs to an industrial pulp and paper company in the municipality of Itaporanga d'Ajuda, SE state. The main activity at Fazenda Rio Fundo is the planting of eucalyptus for firewood production. In 2012, Fazenda Rio Fundo was fined by IBAMA for deforestation of native vegetation to plant eucalyptus. In 2013, Farm managers implemented 38.63 ha of forest restoration (Figure 2). In this way, a set of successional forest restoration models was carried out. Three forest restoration areas were implemented in 2013 in previous eucalyptus plantations planted in 2006.

In the first forest restoration area, all eucalyptus trees were removed, leaving the area completely deforested. Next, 30 native tree species were planted, spacing 4 x 4. This treatment was called Active Restoration (RA).

In the second forest restoration area, 30 native tree species were planted, but before planting, a selective exploration of eucalyptus was carried out (thinning around 50%) and the seedlings were planted in the places where the eucalyptus was removed. This process was called active restoration with consortium eucalyptus (RAE).

In the third forest restoration area, the eucalyptus was cleared (100% thinning), but there was no planting of native tree species, resulting in a natural regeneration process, which is called passive forest restoration (RP).

An efficient and well-performed forest restoration of the ecosystem after degradation is evaluated according to the degree of similarity between the restored site and a relatively undisturbed reference site. Therefore, we considered a fourth area as a control or reference area for the study. This area is located in the region and consists of a fragment of secondary forest in the initial stage of succession. This area was called secondary forest (RF). The data collection was carried out in four areas. The information collected in the reference area was used to compare the degree of recovery and performance of the three restoration treatments.

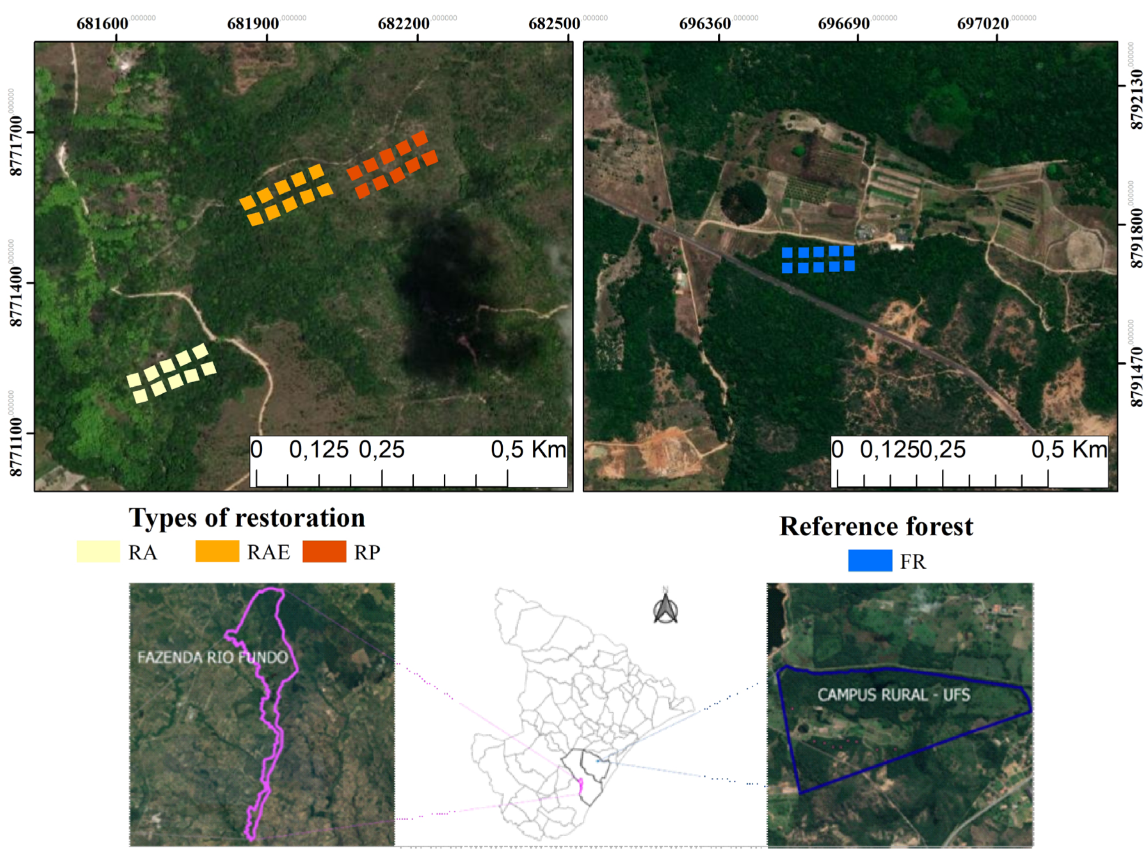


**Figure 2.** Location map of plots allocated at Fazenda Rio Fundo, Itaporanga d'Ajuda and at the Rural Campus of the Federal University of Sergipe, São Cristóvão, Sergipe state.

RA = Active Restoration; RAE = Active Restoration combined with eucalyptus; RP = Passive Restoration, FR = Secondary Forest.

### *2.3. Collection of soil samples*

Four deformed samples were collected in a completely randomized design, with the aid of a straight shovel where 500 grams of samples were collected, at depths of 0-5, 5-10 and 10-20 cm. After this step, the samples were air-dried, the aggregates are broken and passed through a 2.00 mm mesh sieve. The sieved material was used to determine the chemical properties of the soil.

The determination of total organic carbon (CO) content was determined according to the Walkley Black method. The fractionation of the organic matter was carried out according to Cambardella & Elliott (1992). To do so, 20 g of soil (air-dried fine earth) were placed in centrifuge bottles, to which 60 mL of sodium hexametaphosphate were added, before horizontal agitation, at 200 rpm, for 15 hours. The content retained on a 53 µm mesh sieve was washed, dried in an oven at 40ºC and weighed, and the CO contents were then determined. The particulate organic carbon (COP) levels were determined after correction according to the soil texture, by the following equation: COP = CO (>53 mm) x m (>53 mm)/100; where: CO (>53 mm) is the CO content in the material retained on a sieve with a mesh size greater than 53 mm; and *m* is the percentage, by mass, of the TFSA retained in that same sieve. The organic carbon associated with minerals (COAM) contents were quantified by the difference between CO and COP contents.

The chemical fractionation of soil organic matter was also carried out according to the standards of the International Society of Humic Substances, obtaining the organic carbon of each fraction: fulvic acid fraction (FA), humic acid fraction (AH) and humin (HUM) (Benites et al., 2003).

The following chemical properties of the soil were also evaluated: water pH in a ratio of 1:2.5; phosphorus and potassium were extracted with Mehlich[1] solution (0.05 mol $L^{-1}$ HCl, 0.0125 mol $L^{-1}$ $H_2SO_4$); calcium, magnesium and aluminum by $KCl^{-1}$ mol $L^{-1}$ extractor and volumetric determination of $Al^{3+}$ with diluted NaOH solution (0.025 mol $L^{-1}$). Potential acidity was obtained using a solution of 0.5 mol $L^{-1}$ calcium acetate extractor at pH 7.0. Then, the effective cation exchange capacity (CTC) was calculated from the results obtained.

### *2.4. Statistical analysis*

The areas were compared, for each variable and depth individually. Variance analyzes were carried out, applying the F test. For variables whose F test was significant, the studied means were compared, using the Tukey test at 5% probability.

## 3. RESULTS

In the restoration area with the presence of a greater number of eucalyptus individuals (RAE), a higher CO content was observed compared to the RA, RP and FR areas (Table 1). The highest COP content at a depth of 0-5 cm occurred in the RAE. At a depth of 5-10 cm the highest COP value was in RA and at a depth of 10-20 cm it occurred in RAE and RP. Regarding the COAM content at depth 0-5 cm, RA and RP present the highest values (Table 1). At a depth of 5-10 cm, RP has a higher COAM content and at a depth of 10-20 cm, RP and RAE (Table 1).

In relation to AH, RAE and RP restorations present higher values than FR and RA at all depths. RAE obtained the highest AF values at all depths compared to the others. In the 0-5 and 5-10 cm depth, RP had the highest HUM values and in the 10-20 cm layer RAE and RP presented higher values (Table 2).

The pH values demonstrate that the soils are acidic. The soil from RAE and RP has higher SB, CTC and N, indicating better fertility in relation to RA and FR. Associated with low pH values, in the studied depth there is also a low base saturation (Table 1), in the RA and FR areas, higher V% values were observed due to lower $Al^{+3}$ values at a depth of 0-5 cm. At depths of 5-10 and 10-20 cm, higher values of V% were observed in RA and RP. It should be noted that RP had the highest levels of $Al^{+3}$.

In the FR and RA areas, the highest P contents were observed at depths of 0-5 and 10-20 cm, that is, in areas without the presence of eucalyptus individuals. $K^+$ was significantly higher in the depth of 0-5 cm in the RP area. In the depth of 5-10 cm, $K^+$ was higher in RP and RAE, in the depth of 10-20 cm, FR has a higher $K^+$ content. (Table 3).

**Table 1.** Chemical attributes of the soil in forest restoration and secondary forest areas.

| Depth | Attribute | Type of Restoration | | | Natural Forest |
|---|---|---|---|---|---|
| | | RA | RAE | RP | FR |
| 0-5 cm | C-organic (g $kg^{-1}$) | 11.91b | 13.81a | 13.70a | 12.39b |
| 5-10 cm | | 9.70b | 11.14a | 13.18a | 10.13b |
| 10-20 cm | | 8.89c | 12.54a | 10.94b | 7.78c |
| 0-5 cm | COP (g $kg^{-1}$) | 3.73b | 8.03a | 4.43b | 4.16b |
| 5-10 cm | | 5.03a | 3.40b | 1.52c | 2.36b |
| 10-20 cm | | 3.02a | 3.40a | 1.11b | 2.48b |
| 0-5 cm | COAM (g $kg^{-1}$) | 8.18a | 5.78b | 9.27a | 8.23a |
| 5-10 cm | | 4.67d | wv8.34b | 11.66a | 7.78c |
| 10-20 cm | | 5.88b | 9.14a | 9.83a | 5.30b |

**Table 2.** Chemical fractionation of soil organic matter in forest restoration and secondary forest areas.

| Depth | Attribute | Type of Restoration | | | Natural Forest |
|---|---|---|---|---|---|
| | | RA | RAE | RP | FR |
| 0-5 cm | AH (g $kg^{-1}$) | 3,48b | 4,24a | 3,93ª | 2,80b |
| 5-10 cm | | 2,58b | 3,74a | 3,51ª | 1,94b |
| 10-20 cm | | 2,33b | 4,46a | 3,46ª | 0,91b |
| 0-5 cm | AF (g $kg^{-1}$) | 5,02b | 6,20a | 5,04b | 4,61b |
| 5-10 cm | | 2,99c | 7,35a | 5,00b | 4,25b |
| 10-20 cm | | 3,14b | 4,88a | 2,98b | 2,76b |
| 0-5 cm | HUM (g $kg^{-1}$) | 4,76c | 7,15b | 10,14ª | 6,51b |
| 5-10 cm | | 3,09c | 6,89b | 8,08ª | 4,01c |
| 10-20 cm | | 3,36b | 6,68a | 5,97ª | 3,42b |

**Table 3.** Soil fertility in forest restoration and secondary forest areas.

| Depth | Attribute | Type of Restoration | | | Natural Forest |
|---|---|---|---|---|---|
| | | RA | RAE | RP | FR |
| 0-5 cm | pH | 5,31a | 4,92b | 4,65b | 5,01a |
| 5-10 cm | | 5,13a | 5,32a | 4,80b | 4,77b |
| 10-20 cm | | 5,13a | 5,01a | 4,57b | 4,63b |
| 0-5 cm | N (g $kg^{-1}$) | 1,54b | 1,84a | 2,05a | 1,46b |
| 5-10 cm | | 1,49b | 1,79a | 2,00a | 1,41b |
| 10-20 cm | | 1,50b | 1,80a | 2,01a | 1,48b |
| 0-5 cm | P (mg $dm^{-3}$) | 6,92a | 2,85b | 3,3b | 5,55a |
| 5-10 cm | | 4,57a | 3,35b | 3,07b | 3,32b |
| 10-20 cm | | 4,37a | 2,65b | 2,30b | 3,32a |
| 0-5 cm | $K^+$ (mg $dm^{-3}$) | 27,25b | 30,25b | 97,00a | 33,75b |
| 5-10 cm | | 10,68b | 42,25a | 36,25a | 18,25b |
| 10-20 cm | | 7,75c | 29,00b | 22,25b | 65,25a |
| 0-5 cm | $Ca^{2+}$ ($cmol_c$ $dm^{-3}$) | 1,22b | 1,62a | 1,25b | 1,15b |
| 5-10 cm | | 1,02b | 1,75a | 1,60a | 0,92b |
| 10-20 cm | | 0,82b | 1,10a | 1,17a | 0,62b |
| 0-5 cm | $Mg^{2+}$ ($cmol_c$ $dm^{-3}$) | 0,97a | 0,82a | 1,15a | 1,10a |
| 5-10 cm | | 0,52b | 1,25a | 1,40a | 0,67b |
| 10-20 cm | | 0,70b | 1,50a | 0,85b | 0,22c |
| 0-5 cm | Na ($cmol_c$ $dm^{-3}$) | 0,03a | 0,06a | 0,07a | 0,05a |
| 5-10 cm | | 0,02b | 0,05a | 0,08a | 0,04b |
| 10-20 cm | | 0,02b | 0,06a | 0,08a | 0,04b |
| 0-5 cm | $Al^{3+}$ ($cmol_c$ $dm^{-3}$) | 0,06c | 0,39b | 0,66a | 0,14c |
| 5-10 cm | | 0,12c | 0,12c | 0,68a | 0,47b |
| 10-20 cm | | 0,12c | 0,20c | 1,42a | 0,70b |
| 0-5 cm | SB ($cmol_c$ $dm^{-3}$) | 2,30b | 2,59a | 2,72a | 2,38b |
| 5-10 cm | | 1,60b | 3,15a | 2,60a | 1,69b |
| 10-20 cm | | 1,57b | 2,74a | 2,33a | 1,05b |
| 0-5 cm | CTC ($cmol_c$ $dm^{-3}$) | 6,09b | 8,01a | 9,48a | 6,75b |
| 5-10 cm | | 5,24b | 8,07a | 9,03a | 6,34b |
| 10-20 cm | | 5,36b | 8,35a | 9,38a | 5,43b |
| 0-5 cm | V (%) | 37,75a | 32,00b | 28,25b | 34,75a |
| 5-10 cm | | 31,00b | 41,00a | 35,00a | 26,00b |
| 10-20 cm | | 29,50a | 32,75a | 24,75b | 19,25b |

In the RAE area, the highest $Ca^+$ value was quantified at a depth of 0-5 cm. However, for the values of $Mg^{+2}$ and Na, no significant differences were observed at a depth of 0-5 cm. At a depth of 5-10 cm the highest contents of $Mg^{+2}$ and Na were in RAE and RP, and at a depth of 10-20 cm the highest content of Na was in RAE and RP and $Mg^{+2}$ in RAE. In RP, the highest $Al^{+3}$ value was quantified at all depths. The CTC was higher in RAE and RP at all depths compared to the others (Table 3).

## 4. DISCUSSION

In the ecological restoration of ecosystems, an increased diversity is always associated with increased productivity (and consequent carbon stock in soil and aerial biomass), which is among the most important functions of the ecosystem (Rosa & Marques, 2022). Throughout the ecological succession, there is an increase in biomass in tropical forests due to the increase in the diversity of species from more advanced successional stages, which have greater volume and a long life cycle, consequently contributing to a greater stock of biomass and carbon (Chazdon, 2019).

A greater diversity of species in the RA and FR areas and the absence of eucalyptus in the RA area resulted in a greater amount of P and V% and a less acidic pH in the most superficial layer of the soil. Calgaro et al. (2008) in degraded areas under Cerrado soil found levels lower than P (1 mg $dm^{-3}$) and higher than Al (9 mmolc $dm^{-3}$) at a depth of 0.00 to 0.15 m, emphasizing that the absence of vegetation cover in degraded soils alters the chemical attributes of the soil, reducing P levels, favoring an increase in acidity in parallel with an increase in aluminum levels. The low pH found in the soil can interfere with P dynamics as it can be precipitated by the formation of insoluble compounds with Fe, Al and Ca (Calgaro et al., 2008).

However, the highest values of the number of eucalyptus tree individuals in RA (José, 2023) may have provided a higher content of CO, SB and CTC at all depths, through a greater supply of deciduous material. Base saturation and CTC favor the relatively rapid decomposition of soil organic matter, ensuring an adequate supply of P to vegetation even at low concentrations. A higher N content was also observed in areas with a greater amount of eucalyptus (RA and RP), which may be due to a greater supply of litter.

However, eucalyptus litter presents a slower decomposition due to the high content of ligin and extractives that make it difficult to decompose by soil fauna, bacteria and fungi, resulting in lower values of P available in the soil for plants (Aimi et al., 2017). This fact is corroborated by the higher COP content and lower COAM content in RAE in the most superficial layer of the soil (0-5 cm).

The greater number of eucalyptus individuals, adding a large amount of slowly decomposing litter, provides a larger layer of more particulate and less decomposed organic matter, and a smaller amount of organic matter associated with the mineral fractions of the soil. It also favors a higher content of HA and AF and lower HUM, which is a fraction of stable matter and is more associated with the mineral fraction of the soil at a depth of 0-5 cm. This result was observed by Machado et al. (2019), in which a greater supply of litter on the soil surface provided higher levels of HA and AF in secondary forests.

However, the same author observed that this result may also reflect the longer succession time of a secondary forest in an advanced stage of succession, which provides the soil plant residues of a greater species diversity, that is, a greater contribution of residues whose chemical composition it is more heterogeneous and can cause greater formation of HA and AF. The results observed in RAE for AF and AH at a depth of 0-5 cm contradict what was observed by Machado et al. (2019), where it was not due to greater species diversity nor a more advanced stage of succession, as the area has a composition of around 50% eucalyptus individuals. In RA and FR, the species diversity is much higher, but they have significantly lower AF and AH values compared to RAE.

At a depth of 0-5 cm in RA, once it presents a more developed and diverse root system, greater diversity of species with differentiated root architecture, it presents a higher COP content but a slower organic matter mineralization process, exhibiting lower COAM. The RP at this same depth has higher COAM due to a more established root system of eucalyptus individuals as this area did not have soil management like RAE in 2013. They also have a higher content of HUM and AH in RP at a depth of 5- 10 cm.

At a depth of 10-20 cm in RAE and RP there is a higher content of COP and COAM, these two areas were planted with eucalyptus from 2006 until 2013. Then RAE he had 50% of the individuals and RP clear cutting of the individuals of eucalyptus, however the two areas did not have soil management. In RA, in addition to the clear cutting of eucalyptus trees, the land was plowed and harrowed for the planting of native species, which may have reduced the soil organic matter in comparison to RAE and RP. This is corroborated by the higher content of more humified forms of organic matter HUM and AH present in RAE and RP at a depth of 10-20 cm.

The highest CO contents in RAE areas are in contrast to the patterns observed by Klug et al. (2020) who quantified lower CO values in eucalyptus planting areas that were 21 years old compared to an area of initial secondary forest that was 22 years old. This pattern is due to the eucalyptus litter having a low decomposition rate, due to the high lignin content and high C/N ratio, with lignin accumulating as the planting age increases (Klug et al., 2020).

According to Brancalion et al. (2021), this pattern of litter accumulation due to age occurs as a result of the rapid growth of eucalyptus. In their study, the authors quantified above-ground biomass values in areas of mixed plantations (native intercropped with eucalyptus) nine times higher than in areas of plantations composed only of native species. Another explanation for lower SB values in RAE and FR can be attributed to the immobilization of nutrients in a greater diversity of plants as well as larger plants that predominate in this system, mainly in compartments with greater plant biomass such as trunks and in smaller quantities in litter, with consequent lower nutrient cycling (Guareschi et al., 2014).

Considering the three forms of humic substances, restorations with eucalyptus (RAE and RP) presented higher levels, indicating greater humification of organic matter. In this way, planting eucalyptus in consortium with native species for ecological restoration can recover the soil more quickly in short term. On the other hand, RA must have management that increases the litter deposition and the transformation of organic matter, such as the use of species that fix atmospheric nitrogen or that form an association with mycorrhizal plants (Moraes et al., 2008).

Due to the greater production of total humic substances in restorations with the presence of eucalyptus individuals, it demonstrates the potential for using these species in ecological restorations. In case of nutrient deficit in the soil, the chemical structure of humic acids can be useful for use by soil microorganisms.

In RP, higher K levels were quantified at different depths, which are practically triple what was observed in the other areas. It should be noted that the RP area has a more open canopy, with 91% composed of eucalyptus and a greater quantity of grasses that according to Troeh; Thompson (2007), absorb large amounts of K. Furthermore, in the case of K, there is a relationship between the litter deposition of the species found, formation of organic matter in the soil and the availability of this nutrient. K is easily translocated from the litter to the soil and back to the plant (Aimi et al., 2017).

Thus, in the passive restoration area (RP) after ten years, a layer of lignified litter may be forming and slowly decomposing due to this being a drier environment with higher temperatures and less activity of decomposer organisms, which favors greater retention of K in different forms of organic matter in the soil. Indicating a slower nutrient cycling process due to greater degradation of this environment.

Higher levels of $Ca^{+2}$ were also observed in the soil in the RAE area, which can be attributed to a greater deposition of more lignified litter, such as eucalyptus, which accumulates in the most superficial layer of the soil. As it is a structural component of plant tissue cells and, therefore, a structural component of litter, it is one of the last to be released by the decomposition process (Klippel et al., 2016). Although the RA and FR areas presented the lowest CO values, the highest P values were quantified at different depths.

## 5. CONCLUSIONS

The restoration with native forest species (RA) promoted the following changes in some attributes, namely: soil with less acidic pH values, lower levels of $Al^{+3}$, higher levels of P and V% statistically equal to that determined in the Secondary Forest area. RAE and RP restorations promoted an increase in SB, CTC, CO and N values, which were higher than those observed in the Secondary Forest area.

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