Universidade Federal Rural do Semi-Árido
Pró-Reitoria de Pesquisa e Pós-Graduação
https://periodicos.ufersa.edu.br/index.php/caatinga
ISSN 1983-2125 (online)

http://dx.doi.org/10.1590/1983-21252024v3712193rc

Scientific Article

Stocks of elements in roots in areas of post-pebble mining recovery in the Pará state

Estoques de elementos em raízes sob áreas em recuperação por mineração de seixos no Pará

Samila B. Lima[1], Jamilie B. de Castro[1], Victor C. Piscoya[2], Helaine C. G. Pires[3], Milton M. Fernandes[4], Renisson N. de Araújo Filho[1]*

[1]Postgraduate Program in Forestry and Environmental Sciences, Universidade Federal do Tocantins, Gurupi, TO, Brazil. [2]Department of Rural Technology, Universidade Federal Rural de Pernambuco, Recife, PE, Brazil. [3]Department of Forest Sciences, Universidade Federal Rural da Amazônia, Capitão Poço, PA, Brazil. [4]Department of Forest Sciences, Universidade Federal de Sergipe, São Cristovão, SE, Brazil.

ABSTRACT - Mining in the municipality of Capitão Poço, Pará, has resulted in soil degradation as the main consequence. Therefore, this study aimed to evaluate the stocks of the elements (N, P, K^+, Na^+, Ca^{2+}, Mg^{2+}, Fe, Zn, Cu, and Mn) in roots in areas of post-pebble mining recovery in Pará, Brazil. The study was carried out in four areas, namely the area under recovery with soil bioengineering techniques (complementary construction technique and soil stabilization technique), the area under recovery with a natural regeneration process, the degraded area, and the native forest located in the municipality of Capitão Poço-PA. Roots were collected at 0-10, 10-20, 20-30, 30-40, 40-50, 50-60, 60-80, and 80-100 cm soil layers, quantified the dry biomass and contents of macro and micronutrients, and then, estimated the stocks of elements in roots. The data of the element stocks in roots were subjected to the Shapiro -Wilk normality tests and analysis of variance. Means were compared using the Tukey test at 5% significance using the SISVAR statistical software. The highest average Na+, Ca2+, and Mg2+ values in fine roots were in areas with bioengineering and native forest. The native forest presented the highest average values of macro and micronutrients in fine and thick roots. Furthermore, the lowest stocks of elements in roots were in the degraded area. However, bioengineering techniques are effective in recovering degraded soils, as vegetation cover reestablishes the balance of the soil-plant system.

Keywords: Oxisol. Degradation. Bioengineering. Nutrients.

RESUMO - A mineração no município de Capitão Poço, Pará tem acarretado, como principal consequência, a degradação do solo. Desta forma, o objetivo desse estudo foi avaliar os estoques dos elementos N, P, K^+, Na^+, Ca^{2+}, Mg^{2+}, Fe, Zn, Cu e Mn em raízes sob áreas em recuperação por mineração de seixos no Pará, Brasil. O estudo foi desenvolvido em quatro áreas, sendo elas a área em recuperação com técnicas de bioengenharia de solos (técnica de construção complementares e técnica de estabilização de solo), a área em recuperação com processo de regeneração natural, a área degradada e a floresta nativa, localizadas no município de Capitão Poço. Para análise dos estoques de elementos em raízes, foram coletados raízes nas profundidades 0-10, 10-20, 20-30, 30-40, 40-50, 50-60, 60-80 e 80-100 cm, depois quantificada a biomassa seca e macros e micronutrientes. Para obtenção dos resultados, os estoques de elementos em raízes foram submetidos aos testes de normalidade Shapiro e Wilk e às análises de variância. A comparação das médias foi realizada pelo teste de Tukey a 5% de significância e utilizado o software estatístico SISVAR. Os maiores valores médios de Na^+, Ca^{2+}, Mg^{2+} em raízes finas foram nas áreas com bioengenharia e floresta nativa. Ademais, a floresta nativa apresentou os maiores valores médios de macro e micronutrientes em raízes finas e grossas. Outrossim, os menores estoques de elementos em raízes foram na area degradada. Contudo, as técnicas de bioengenharia são eficazes para recuperar solos degradados, dado que, a cobertura vegetal reestabelece o equilíbrio do sistema solo-planta.

Palavras-chaves: Latossolos. Degradação. Bioengenharia. Nutrientes.

Conflict of interest: The authors declare no conflict of interest related to the publication of this manuscript.

Received for publication in: September 14, 2023.
Accepted in: February 23, 2024.

***Corresponding author:**
<renisson@uft.edu.br>

INTRODUCTION

Mining in Brazil began in the mid-17th century with the discovery of gold and intensified in the 13th century, which led to the growth of the Brazilian economy, urbanization, and population (CASTRO et al., 2021). Furthermore, the first mineral discoveries occurred in Minas Gerais, Mato Grosso, Bahia, and Goiás, so they became known as the mining states.

Initially, the mineral production was mainly destined for the domestic market. However, over the centuries and with the advent of the Industrial Revolution, several countries began to acquire Brazilian ore, thus generating a great demand for exported commodities (NASSIF et al., 2020). Therefore, the demand for natural resources and labor increased, contributing to the country's economic development (NASSIF et al., 2020).

Nowadays, the state of Pará has received great prominence in the production and exploitation of minerals, mainly iron, gold, bauxite, copper, kaolin, nickel, manganese, gems, limestone, pebbles, and sand (SOUSA et al., 2021). In 2021, the state was responsible for 43% of Brazilian mining (CASTRO et al., 2021). Within the state of Pará, the northeastern mesoregion excels in extracting pebbles and sand, which are generally used in civil construction.

In the northeastern region of Pará, this work focused on the municipality of Capitão Poço, where the mining activity has brought benefits such as income generation, jobs, and socio-economic development, but there has been damage to the environment, including the destruction of species' habitats, ecological imbalance, the reduction of local flora and soil impoverishment and pollution (SOUSA et al., 2021). In this municipality, the soil is characterized as Oxisol (SOIL SURVEY STAFF, 2014), and pebble mining occurs as an economic and social result. According to Castro et al. (2021), mining in Capitão Poço resulted in the loss of macro and micronutrients in the soil and the removal of local fauna and flora.

In order to solve the problems caused by mining, such as soil degradation, some environmental recovery techniques have been developed over the years, including phytoremediation, which consists of using plant species to remediate contaminated soils, and soil bioengineering, which uses living matter, such as plants, combined with inert materials to restructure the soil (SAIFUDDIN; OSMAN; KHANDAKER, 2022). The techniques described above efficiently recover degraded areas and have a low implementation cost (O'CONNOR et al., 2019).

Studies show that in soils disturbed, for example, by mining, there is a reduction in the root biomass and, consequently, the elements stored (ROQUETTE, 2018). Roots also comprise a large part of the underground biomass and play a key role in the soil-plant system by allocating and transporting elements. These are divided into thick roots, which provide support, and thin roots, which capture and transport nutrients to other parts of the plant (CASTRO et al., 2021).

The roots have a key role in nutrient cycling, so it is important to check the stock of elements in the roots that indicate their storage capacity to determine the quality of the soils affected by mining activities (ROQUETTE, 2018). Thus, this study aimed to evaluate the stocks of the elements (N, P, K^+, Na^+, Ca^{2+}, Mg^{2+}, Fe, Zn, Cu, and Mn) in roots in areas of post-pebble mining recovery in Pará, Brazil.

MATERIALS AND METHODS

Study area

The research was conducted in a mining area in the municipality of Capitão Poço, in the northeast Pará, at 1º34'21.85"S and 47º06'39.91"W (Figure 1).

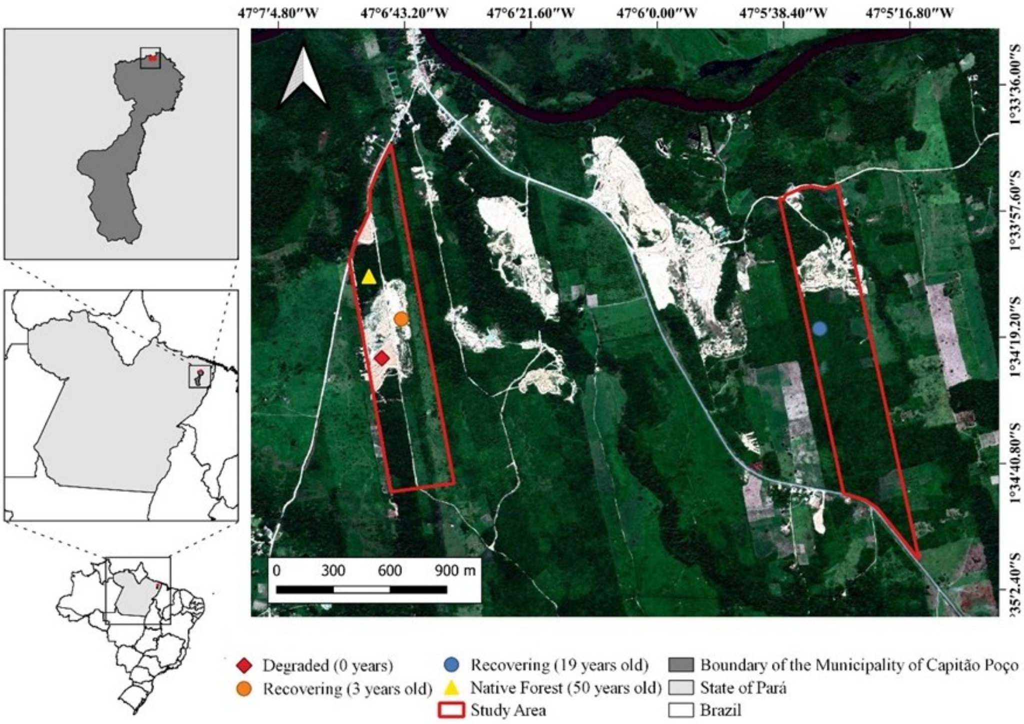

Figure 1. Study areas located in the municipality of Capitão Poço, PA, Brazil.

According to Köppen, the region has an Am-type climate with an average annual rainfall of 2,500 mm to 2,800 mm, with the dry season from September to November, an average temperature of 26 °C and average monthly rainfall of 60 mm in the dry season (SOUSA et al., 2021).

The soil has different characteristics, but with a predominance of oxisol (SOIL SURVEY STAFF, 2014). The vegetation is of the dense and mixed ombrophilous forest type, equatorial evergreen forest and secondary vegetation in different stages (SAUMA FILHO et al., 2020).

The study areas are represented by four sites: a degraded area (DE) due to mining activities, an area undergoing post-mining recovery using soil bioengineering techniques (BE), an area undergoing post-mining recovery using natural regeneration (RE), and a native forest area (FN) as a control area.

The degraded area is approximately 5.16 ha and has been degraded for seven months after the pebble ore was mined. No recovery techniques were applied to this degraded area.

The area being reclaimed using the soil bioengineering technique is 4.92 hectares. The technique was introduced between February and June 2018, and this treatment has been in place for three years. The species used for planting were jack bean (*Canavalia ensiformis* (L.) DC), velvet bean (*Stiolozobium aterrimum* Piper & Tracy), brown hemp (*Crotalaria juncea* L.), and Pigeon pea (*Cajanus cajan* (L.) Millspaugh). Seven grams of seeds were sown every four meters (CASTRO et al., 2021). In fertilization, urea, potassium chloride, and triple superphosphate were added, providing 4 kg ha^{-1} of N, 40 kg ha^{-1} of K_2O, and 50 kg ha^{-1} of P_2O_5 (CASTRO et al., 2021). Afterward, bamboos were used as an inert material to contain the slope of the area to prevent it from collapsing and reduce the force of the water coming from surface runoff (CASTRO et al., 2021).

The area under recovery with natural regeneration has 51.7 ha of vegetation suppressed due to pebble mining at the end of the 90s. After exploitation, the soil was covered with waste from washing the ore. The recovery technique adopted was natural regeneration, and this treatment has lasted 19 years. The plant species present in the area are *Vismia guianensis* (Clusiaceae), *Guatteria amazônica* (Annonaceae), *Lacistema aggregatum* (Lacistemaceae), *Banara guianensis* (Salicaceae), *Annona paludosa* (Annonaceae), *Ingá macrophylla* (Fabaceae-Mimosoideae), *Miconia densis* (Melastomataceae), *Stryphnodendron guianensis* (Mimosaceae), *Lecythis lúrida* (Lecythidaceae), *Inga alba* (Fabaceae-Mimosoideae), *Licaria canella* (Lauraceae), *Ormosiopsis flava* (Leguminosae), *Cecropia guianensis* (Urticaceae), and *Casearia decandra* (Salicaceae) (CASTRO et al., 2021).

The native forest area covers 6.4 hectares and has been in use for 100 years, with no anthropogenic influence and no records of information on the use of this area before this period. According to Castro et al. (2019), this area is home to 282 individuals, distributed in 48 species and 27 families: *Tapirira guianensis* Aubl. (Anacardiaceae), *Inga alba* (Fabaceae), *Vismia guianensis* (Aubl) (Clusiaceae), *Lacistema aggregatum* (Lacistemataceae), *Casearia arborea* (Rich.) Urb. (Salicaceae), *Lecythis lúrida* (Lecythidaceae), *Cupania* L. (Sapindaceae), *Licania canescens* (Chysobalanaceae), *Gustavia augusta* (Lecythidaceae), *Eugenia bracteata* (Myrtaceae), *Virola sebifera* Aubl. (Myrtaceae), *Neea floribunda* (Nyctaginaceae), *Himatanthus sucuuba* (Apocynaceae), *Myrcia tomentosa* (Myrtaceae), *Stryphnodendron pulcherrimum* (Fabaceae), *Dipteryx odorata* (Fabaceae), *Tapura guianensis* (Dichapetalaceae), *Talisia esculenta* (Sapindaceae), *Inga sp* (Fabaceae), and *Trisodium spruciano* (Anacardiaceae).

Physical characterization of the soil areas

The determination of the distribution of soil particle sizes showed the following averages in the 0-100 cm layer: degraded area - sand 787.38 g kg^{-1}, silt 40.13 g kg^{-1}, and clay 172 g kg $^{-1}$; the area with soil bioengineering - sand 707.75 g kg^{-1}, silt 42.25 g kg $^{-1}$, and clay 280 g kg^{-1}; natural regeneration area - sand 725.38 g kg^{-1}, silt g kg^{-1}, and clay 241.88 g kg^{-1}; native forest area - sand 773.25 g kg^{-1}, silt 34.25 g kg^{-1}, clay 192.5 g kg^{-1} (CASTRO et al., 2021). Soil density presented the following averages in the 0-100 cm layer: degraded area: 1.43 g cm^{-3}, the area with soil bioengineering: 1.42 g cm^{-3}, natural regeneration area: 1.30 g cm^{-3}, and native forest area 0.97 g cm^{-3} (CASTRO et al., 2021).

Soil and root sampling

Soil sampling followed the methodology used by Marinho Júnior et al. (2021) and roots by Lima et al. (2022), in which, in each area studied, eight representative trenches were manually opened for the areas with dimensions 70 × 70 × 100 cm at different points, totaling thirty-two trenches in total. Before opening the trenches, it was necessary to clean the area where the soil samples were collected. Soil and root collections were conducted using Uhland augers and volumetric rings in the soil layers of 0-10, 10-20, 20-30, 30-40, 40-50, 50-60, 60-80, and 80-100 cm. The disturbed soil samples were used for the particle size analysis (TEIXEIRA et al., 2017) and undisturbed for soil density analysis (ALMEIDA et al., 2017).

For roots, sampling was conducted at each soil layer mentioned above, weighing 1 kg of soil on a portable scale and then sieved through a 4 mm mesh, retaining the root biomass (LIMA et al., 2022). Therefore, the roots on the sieve underwent manual picking, followed by treatment with 70% alcohol to inhibit microbial action, and then storage in plastic bags (LIMA et al., 2022).

Determination and quantification of root biomass

The roots stored in plastic bags were separated into two classes according to the diameter: thin roots ≤ 5 mm and thick roots > 5 mm (ALBUQUERQUE et al., 2015). In addition, there was no differentiation between dead and live roots and plant species (ALBUQUERQUE et al., 2015). Thus, the roots were stored in kraft paper bags, dried in ovens at 65° C, and finally weighed on an analytical balance, obtaining the dry biomass in grams (LIMA et al., 2022).

The root biomass stocks were calculated for each soil layer in Mg ha^{-1} as shown below (LIMA et al., 2022):

$$E_{ST}B_R = (B_R \times D_s \times P)/ 10$$

$E_{ST}B_R$ is the root biomass stock in the soil layer (Mg ha^{-1}), BR is the root biomass concentration in the soil (g kg^{-1}), Ds is the soil density in the layer (kg dm^{-3}), and P is the thickness of the soil layer sampled (cm).

The root biomass value of each soil layer was added, obtaining the total value considering the soil layer from 0-100 cm (LIMA et al., 2022).

Quantification of macro and micronutrient stock concentrations in roots

In the laboratory, after drying, the roots were processed by grinding in a mill and passing through a 30 mesh sieve, then stored in plastic containers to conduct chemical analyses of N, P, K^+, Na^+, Ca^{2+}, Mg^{2+}, Fe, Zn, Cu, and Mn (TEIXEIRA et al., 2017). Sulfuric and nitric-perchloric digestion were conducted then an aliquot of the extract from the solution was separated to conduct the chemical analyses. The concentrations of macro and micronutrients were determined by atomic absorption spectrometry (TEIXEIRA et al., 2017).

Nutrient stocks were obtained by calculation according to the methodology of Lima et al. (2023), as shown below:

$$E_{ST}N_R = (N_R \times D_s \times P)/ 10$$

$E_{ST}N_R$ is the nutrient stock in root biomass (Mg ha^{-1}), NR is the nutrient concentration in root biomass (g kg^{-1}), Ds is the soil density in the layer (kg dm^{-3}), and P is the thickness of the soil layer sampled.

After calculating the nutrient stock in dry root biomass for each layer, the correction was made, considering the differences in soil mass from the reference area to the native forest (LIMA et al., 2023). The stock value of each element in each soil layer was added, obtaining the total stock considering the soil layer from 0-100 cm.

Statistical analysis

The data from the stocks of elements in roots were subjected to the Shapiro-Wilk normality test and analysis of variance to ascertain the differences between the study areas at the different soil layers 0-10, 10-20, 20-30, 30-40, 40-50, 50-60, 60-80 and 80-100 cm. The means were compared using the Tukey test at 5% significance and the SISVAR statistical software (FERREIRA, 2011).

RESULTS AND DISCUSSION

The nutrients present in root biomass are commonly relevant for assessing disturbed soils (ROQUETTE, 2018) since the vegetation cover provides macro- and micronutrients necessary for the composition of underground biomass (SAHU; KATHIRESAN, 2019).

The average values of the macronutrients stored in the fine roots are shown in Table 1. According to Wambsganss et al. (2021), fine roots are involved in absorbing and transporting water and nutrients to the vascular and fundamental systems of plants. Environmental variations, such as temperature, precipitation, and forest characteristics, influence the biomass of fine roots and, consequently, the concentration of nutrients (WAMBSGANSS et al., 2021).

Table 1. Macronutrient stocks in fine roots in areas of post-pebble mining recovery.

Study area	N	P	K^+	Na^+	Ca^{2+}	Mg^{2+}
	---------- Mg ha^{-1} ----------					
	0-100cm soil layer					
DE	215.38 C	265.67 D	47.10 D	37.88 D	306.06 B	52.74 D
BE	529.46 B	899.02 C	86.50 C	105.23 A	475.98 A	129.07 A
RE	523.63 B	1572.52 B	94.58 B	61.99 B	316.28 B	55.57 C
FN	741.36 A	2067.20 A	104.07A	103.28 A	476.92 A	79.12 B

*Average values in soils under post-mining recovering areas at different times; DE - degraded area; BE - recovering area with soil bioengineering techniques; RE - recovering area with natural regeneration technique; FN - native forest area.
*Uppercase letters in the columns indicate differences between study areas by the Tukey test at a 5% probability ($P \leq 0.05$).

Thus, it can be seen that the highest significant average values of N in the fine roots were in the FN area, followed by the RE area (Table 1). The largest nitrogen stocks in the forest area are based on the fact that N is one of the most abundant elements in plant tissues (ALVES et al., 2017). The highest values are possibly linked to the C/N ratio of organic matter deposited by the forest. This can provide a favorable environment for the bacterial community to reestablish itself since, according to Araújo and Monteiro (2007), changes in the microbial community can be configured in a series of changes in the chemical and physical characteristics of the soil, indicating degradation or rehabilitation from the soil.

In a study by Alves et al. (2017), this chemical element stood out among the others in the plant biomass of regenerating and native forests. According to these authors, the cycling of this nutrient, the characteristics of the soil, and the physiological characteristics of the vegetation are factors that contributed to this result.

The highest significant average values of P and K^+ in the fine roots were in the FN area (Table 1). The presence of vegetation leads to high litter production which, according to Garlet and Schumacher (2020), is a crucial factor for the development of fine root biomass and, as a result, greater nutrient accumulation. Carvalho et al. (2019), when evaluating the nutrient content in the litter of four vegetation areas under latosol, found the highest levels of P and K^+ in the native forest area.

In Table 1, the highest significant average values of Na^+ in the fine roots were in the BE and FN areas. According to Taques et al. (2020), soils with a high content of organic matter from vegetation cover provide nutrient input to the soil -plant system and, therefore, higher concentrations of nutrients in the fine roots.

The highest significant average values of Ca^{2+} in the fine roots were found in the areas with BE and FN (Table 1). According to Martins et al. (2018), in areas with vegetation cover, initial fertilization and litter favor greater availability of Ca^{2+} in the soil, which is absorbed by the root biomass present in these areas. Therefore, the increase in fertilization and mobility of this nutrient in the soil are factors that can infer this result for the area with BE (LIMA et al., 2023), although, for the area with FN, the forest composition and decomposition of organic matter at the over the years may have contributed to higher values of this nutrient in fine roots

(MORAES et al., 2016). In the studies by Carvalho et al. (2019), the highest average values of this element were found in the litter of the Preserved Permanent Area.

The fine roots showed the highest significant average values of Mg^{2+} in the BE area (Table 1). According to Azevedo et al. (2018), this result shows the capacity of the vegetation applied in this area to store biomass, mainly because it is growing. Thus, nutrients take longer to make available to the soil, meaning they are stored longer in the root biomass.

In Table 2, the highest significant average values of Fe, Zn, Cu, and Mn stored in fine roots were in the area with FN. These results indicate that research on the stock of micronutrients in root biomass is of great relevance to understanding how much vegetation cover influences the dynamics of nutrients in the soil, given that micronutrients, despite being required in low quantities, are essential for the performance of any vegetation and, consequently, of the soil (CASTRO et al., 2021). Therefore, according to Garlet and Schumacher (2020), the biomass of fine roots is related to factors such as soil texture, the presence or absence of Al^{3+}, and species with high growth potential, directly affecting the concentration of nutrients present in these roots.

Table 2. Micronutrient stocks in fine roots in areas of post-pebble mining recovery.

Study area	Fe	Zn	Cu	Mn
	----------Mg ha^{-1}----------			
	0-100cm soil layer			
DE	103536.60 D	5272.78 C	3569.42 D	4202.20 C
BE	474271.37 C	14759.44 B	7521.32 C	8080.23 B
RE	710169.40 B	14157.27 B	9177.00 B	8664.86 B
FN	1291774.77 A	20761.34 A	11216.51 A	10230.98 A

*Average values in soils under post-mining recovering areas at different times; DE - degraded area; BE - recovering area with soil bioengineering techniques; RE - recovering area with natural regeneration technique; FN - native forest area.
*Uppercase letters in the columns indicate differences between study areas by the Tukey test at a 5% probability ($P \leq 0.05$).

According to Taques et al. (2020), the decomposition of plant litter and roots provides an input of nutrients to the soil-plant system. This organic matter is the main source of nutrients for the roots, especially the fine ones, responsible for absorbing and transporting nutrients in plants (TAQUES et al., 2020). In this way, soils with greater plant cover tend to make higher concentrations of nutrients available to the roots. Furthermore, root biomass produces and releases exudates through the rhizosphere, which are important for determining the chemical, physical, and biological attributes of the soil, being influenced by the nutritional conditions of the vegetation (MONTEIRO et al., 2012; FERREIRA; ANTUNES, 2017).

Macronutrients stored in the thick roots in the recovery areas are shown in Table 3. The highest significant average values of N, P, K^{+}, Na^{+}, Ca^{2+}, and Mg^{2+} were found in the FN area, followed by the RE area. Alves et al. (2017), when comparing the macronutrients present in the plant litter on soils under a regenerating forest area and a preserved area, found higher values of these nutrients in the preserved area. Lima et al. (2023) also found results corroborating this study's findings. Riggs et al. (2015) state that the vegetation composition, the physiological characteristics, the dynamics of the soil-plant system, and the cycling of these nutrients contribute to this result.

Table 3. Macronutrient stocks in fine roots in areas of post-pebble mining recovery.

Study area	N	P	K^{+}	Na^{+}	Ca^{2+}	Mg^{2+}
	----------Mg ha^{-1}----------					
	0-100cm soil layer					
DE	15.25 D	6.75 D	2.41 D	1.68 D	14.89 D	2.65 D
BE	240.54 C	373.00 C	32.26 C	36.05 C	200.98 C	52.14 C
RE	561.89 B	1686.76 B	97.85 B	67.50 B	366.62 B	63.11 B
FN	883.98 A	2305.83A	116.48 A	120.70 A	548.69 A	93.17 A

*Average values in soils under post-mining recovering areas at different times; DE - degraded area; BE - recovering area with soil bioengineering techniques; RE - recovering area with natural regeneration technique; FN - native forest area.
*Uppercase letters in the columns indicate differences between study areas by the Tukey test at a 5% probability ($P \leq 0.05$).

Since macronutrients are chemical elements that plants need in large quantities (RATUCHNE et al., 2016), Azevedo et al. (2018) state that the diversity and age of the vegetation justify the higher concentrations of these in roots since they act on the capacity to store nutrients in the root biomass in forest ecosystems.

Table 4 shows the micronutrients stored in the thick roots, where the highest significant average values of Fe, Zn, Cu, and Mn were obtained in the FN area, followed by the RE area. The higher concentrations of these elements are influenced by the type of vegetation and soils present in the Amazon biome since the soils in this region are characterized by high weathering and low nutrient concentration, being dependent on the litter for the input of chemical elements to ensure efficient nutrient cycling in the soil-plant system (RODRIGUES et al., 2021).

Table 4. Micronutrient stocks in fine roots in areas of post-pebble mining recovery.

Study area	Fe	Zn	Cu	Mn
	$Mg\ ha^{-1}$			
	0-100cm soil layer			
DE	3069.69 D	267.43 D	158.15 D	254.98 D
BE	165503.20 C	5752.17 C	2931.43 C	3167.06 C
RE	752834.15 B	15772.84 B	9616.94 B	10200.25 B
FN	1369957.69 A	23416.50 A	12945.56 A	11132.23 A

*Average values in soils under post-mining recovering areas at different times; DE - degraded area; BE - recovering area with soil bioengineering techniques; RE - recovering area with natural regeneration technique; FN - native forest area.
*Uppercase letters in the columns indicate differences between study areas by the Tukey test at a 5% probability ($P \leq 0.05$).

Lima et al. (2023) found higher concentrations of micronutrients in the root biomass of native forests. In addition, these authors state that areas under forest have greater protection of the root system and soil against degrading agents than areas without vegetation cover. In this way, there is greater conservation of organic material and, consequently, greater availability of nutrients in the roots of this soil.

However, analyzing the results of all the tables in this research, in the depth 0-100 cm, where the native forest obtained lower nutrient values, the scholars Martins et al. (2018) state that in this area there is less soil interference and greater variability of plant species. These factors contribute to the longer nutrient cycling time and, consequently, interfere with the amount of nutrients in the root biomass since these areas are protected from degrading agents, and the nutrient concentration time may be longer in the shoot than in the roots.

CONCLUSIONS

The nutrient stocks in fine and thick roots were higher in the area with the native forest. The degraded area had the lowest stocks of macro and micronutrients in roots. It was, therefore, found that the elements stored in the root biomass in the areas under recovery are close to those obtained in the area with native forest, contributing to the protection and recovery of these areas against degrading agents. In this way, it can be said that areas under forest, whether planted or native, reestablish and maintain the soil balance.

REFERENCES

ALBUQUERQUE, E. R. et al. Root biomass under stem bases and at different distances from trees. **Journal of Arid Environments**, 116: 82-88, 2015.

ALMEIDA, K. S. S. A. et al. Variabilidade espacial da condutividade hidráulica do solo saturado em Latossolo Amarelo Distrocoeso, no município de Cruz das Almas. **Irriga**, 22: 259-274, 2017.

ALVES, A. R. et al. Nutrientes na biomassa aérea e na serapilheira em áreas de caatinga em Floresta, PE. **Pesquisa Florestal Brasileira**, 37: 413-420, 2017.

ARAÚJO, A. S. F.; MONTEIRO, R. T. R. Indicadores biológicos de qualidade do solo. **Bioscience Journal**, 23: 66-75, 2007.

AZEVEDO, A. D. et al. Estoque de carbono em áreas de restauração florestal da Mata Atlântica. **Revista Floresta**, 48: 183-194, 2018.

CARVALHO, H. C. S. et al. Estoque de nutrientes na serapilheira acumulada em quatro tipos de vegetação no Cerrado em Goiás, Brasil. **Revista Ecologia e Nutrição Florestal-ENFLO**, 7: 1-11, 2019.

CASTRO, J. B. et al. Quantification of root biomass in post-mining áreas in the municipality of Capitão Poço-PA, Brazil. **Annual Research & Review in Biology**, 36: 84-92, 2021.

FERREIRA, D. F. Sisvar: a computer statistical analysis system. **Ciência e Agrotecnologia**, 35: 1039-1042, 2011.

FERREIRA, L. V.; ANTUNES, L. E. C. Exsudatos radiculares de portaenxertos prunus. **Revista Científica Rural-Urcamp**, 19: 37-59, 2017.

GARLET, C.; SCHUMACHER, M. V. Biomassa e comprimento de raízes finas em uma área de restauração florestal. **Revista Brasileira de Gestão Ambiental e Sustentabilidade**, 7: 351-361, 2020.

LIMA, D. S. et al. Root biomass under different soil uses and native Cerrado in Tocantins, Brazil. **Research, Society And Development**, 11: 1-9, 2022.

LIMA, D. S. et al. Stocks of elements in radicular biomasses in different coverages in the cerrado of tocantins, Brazil. **Revista Caatinga**, 36: 124-134, 2023.

MARINHO JUNIOR, J. L. et al. Carbon Dynamics in Humic Fractions of Soil Organic Matter Under Different Vegetation Cover in Southern Tocantins. **Floresta e Ambiente**, 28: e20200024, 2021.

MARTINS, J. R. et al. Soil microbial attributes under agroforestry systems in the cerrado of Minas Gerais. **Floresta e Ambiente**, 25: 2-9, 2018.

MONTEIRO, F. P. et al. Exsudatos radiculares de plantas de cobertura no desenvolvimento de Sclerotinia sclerotiorum. **Bioscience Journal**, 28: 87-93, 2012.

MORAES, M. T. et al. Soil physical quality on tillage and cropping systems after two decades in the subtropical region of Brazil. **Soil & Tillage Research**, 155: 351-362, 2016.

NASSIF, A. et al. Economic development and stagnation in Brazil (1950–2011). **Structural Change and Economic Dynamics**, 53: 1-15, 2020.

O'CONNOR, D. et al. Fitorremediação: Resiliência às mudanças climáticas e avaliação de sustentabilidade em um redesenvolvimento de brownfield costeiro. **Ambiente internacional**, 130: 104945, 2019.

RATUCHNE, L. C. et al. Estado da arte na quantificação de biomassa em raízes de formações florestais. **Floresta e Ambiente**, 23: 450-462, 2016.

ROQUETTE, J. G. Distribuição da biomassa no cerrado e a sua importância na armazenagem do carbono. **Ciência Florestal**, 28: 1350-1363, 2018.

RIGGS, C. E. et al. Contrasting effects of plant species traits and moisture on the decomposition of multiple litter fractions. **Oecologia**, 179: 573-584, 2015.

RODRIGUES, J. I. M. et al. Aporte e estoque de serapilheira no Brasil: uma análise bibliométrica da produção científica de 2008 a 2019. **Scientia Plena**, 17: 1-19, 2021.

SAHU, S. K.; KATHIRESAN, K. A idade e a composição de espécies da floresta de mangue influenciam diretamente a produtividade primária líquida e o potencial de sequestro de carbono. **Biocatálise e Biotecnologia Agrícola**, 20: 101235, 2019.

SAIFUDDIN, M.; OSMAN, N.; KHANDAKER, M. M. Evaluation of root profiles and engineering properties of plants for soil reinforcement. **Journal of Tropical Forest Science**, 34: 176-186, 2022.

SAUMA FILHO, M. et al. Chemical attributes of soil built after pebble extraction in captain well, Pará, Brazil. **Brazilian Journal of Development**, 6: 64608-64623, 2020.

SOUSA, E. J. B. et al. Uso de espécies nativas na restauração de ecossistemas florestais alterados pela retirada de seixo no nordeste paraense. **Research, Society and Development**, 10: e32310916937, 2021.

SOIL SURVEY STAFF. **Keys to Soil Taxonomy**. 12 ed. Washington, DC: USDA, 2014. 300 p.

TAQUES, A. C. F. S. et al. Classification of radicular biomass and monitoring of litter in Pantanal and Cerrado Mato-Grossense. **Revista Ibero-Americana de Ciências Ambientais**, 11: 501-512, 2020.

TEIXEIRA, P. C. et al. **Manual e métodos de análise de solo**. 3. ed. Brasília, DF: Embrapa, 2017. 574 p.

WAMBSGANSS, J. et al. Tree species mixing reduces biomass but increases length of absorptive fine roots in European forests. **Journal of Ecology**, 109: 2678-2691, 2021.