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ORIGINAL ARTICLE – Conservation of Nature

Green Manure as an Alternative for Soil Recovery in a Bauxite Mining Environment in Southeast Brazil

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Abstract

The objective of this study was to evaluate plant cover and dry mass produced by green manures and their influence on the chemical attributes of soil for the ecological restoration of an area around bauxite mine environment in Southeast Brazil. Soil preparation, chemical fertilization and sowing of three species of green manures were carried out: *Cajanus cajan*, *Crotalaria juncea* and *Stylosanthes guianensis*. In general, *C. cajan* and *C. juncea* showed the best performance in plant cover. *C. cajan* and *S. guianensis* produced more phytomass. Green manures were efficient to promote rapid plant cover and increase in soil organic matter and total-N contents in all treatments. Therefore, green manure is a viable alternative that contributes to the success of ecological restoration projects in areas in the bauxite mining environment.

Keywords: alternative techniques, ecological restoration, mined areas, recovery of degraded areas, sustainable mining.

1. INTRODUCTION AND OBJECTIVES

Bauxite is an important ore, from which aluminum, the third most abundant element on the Earth's crust (USGS, 2022). This mineral is found in high quantity and quality (>40% Al_2O_3) in Brazilian reserves (ANM, 2021; USGS, 2022). For this reason, Brazil has a prominent position in the production and exploration of mineral reserves existing in its territory (MME, 2021). In this sense, mining has great relevance to the Brazilian economy, the mineral production in 2020 contributed to the Brazilian GDP with an estimated gross value of USD 43.7 billion (ANM 2021). Mineral extraction activities accounted for about 2.4% of the country's GDP and promotes regional socio-economic development by generating direct and indirect jobs (ANM, 2021; USGS, 2022).

The mineral exploration of bauxite occurs in the topsoil and superficial outcrops, ranging from one a to three months and occurs in small areas (Martins et al., 2020). Thus the recovery of mined areas and areas under the influence of bauxite mining is relatively rapid (Fonseca, 2021). Generally, after bauxite exploration, mining companies carry out topographic reconfiguration, transposition of the topsoil that was removed and stored before the activities, soil preparation, fertilization, and fencing of the area (Balestrin et al., 2019; Melo & Sánchez, 2020; Balestrin et al., 2020; Martins et al., 2020). In addition, to ensure sustainability, mining companies carry out restoration actions both in mined areas and in compensation areas, aiming at environmental recovery, either through active restoration techniques such as seedling planting, direct seeding, green manure and nucleation or by natural regeneration (Martins, 2018; Martins et al.,2020; Cosimo et al., 2021; Fonseca, 2021; Martins et al., 2022).

In this context, plant cover is essential to mitigate the impacts of water erosivity and soil erodibility, especially in areas under the influence of mining (Ferreira et al., 2021). The main negative impacts of bauxite mining are the removal of topsoil and exposure of soil layers devoid of organic matter and nutrients (Anache et al., 2017; Hou et al., 2021). Soil degradation causes disruption of ecosystem functioning and decline of biodiversity worldwide, especially in tropical regions (Butchart et al., 2010; Kaiser-Bunbury et al., 2017). In this sense, as each area presents different levels of impacts, it is essential to adapt ecological restoration projects to the specific needs of each environment (Stuble et al., 2017; Martins, 2018; Villa et al., 2022). Thus, it is important that the restoration techniques also accelerate plant cover in an economically viable way and in the shortest possible time (Gann et al., 2019; Ribeiro et al 2019; Martins et al., 2022).

Green manure is a potential alternative for ecological restoration of ecosystems, given the numerous physical, chemical, and biological benefits in soil properties (Martins et al., 2015; Vásquez-Castro et al., 2020) and its contribution to climate change mitigation through carbon sequestration (Delgado et al., 2021). The ecological restoration techniques after mining disturbance are essential to ecosystem functioning recovery and stability (i.e., soil fertility, erosion mitigation, plant invasion reduction). Thus, green manures stand out for promoting rapid plant cover and protecting the soil from invasive plants (Reis et al., 2019; Melander et al., 2020; Santana et al., 2020), as well as attenuating erosion processes and increasing aggregate stability, ensuring improvements in soil water infiltration (Bonini & Alves, 2011; Ma et al., 2021). In addition, green manures can carry out symbiotic relationships with nitrogen-fixing bacteria and, therefore, can increase this nutrient in the soil, thus allowing a reduction in expenses with nitrogen fertilization. Furthermore, due to significant amounts of phytomass, green manures increase the soil organic matter content (Gao et al., 2018; Silva et al., 2022). Consequently, there is a reduction in acidity, increased cation exchange capacity, and improvements in soil microclimate and nutrient cycling (Isernhagen et al., 2014). In addition, green manures can establish interactions with fauna, facilitating the succession process and contributing to increased diversity (Marshall & Lynch, 2020).

Therefore, this study aimed to evaluate the plant cover and dry mass produced by three species of green manures and their influence on the chemical attributes changes in an area around bauxite mine environment. Thus, the hypothesis of this study is that green manure can contribute to the success of restoration projects and contribute to the sustainability of bauxite mining.

2. MATERIALS AND METHODS

2.1. Study area

This study was carried out in the municipality of Miraí (21°04’05”S and 42°33’28”W), in the region called Zona da Mata, in the Southeast of the state of Minas Gerais–Brazil. According to Koppen’s classification, the climate in the region is Cwa type, characterized as humid temperate with dry winter and hot summer. Annual precipitation is 1,564 mm and annual mean temperature is 23.5ºC (AGEVAP, 2013).

The relief is characterized as wavy solid and mountainous, with an altitude of 715 m and according to the Brazilian Soil Classification System (Santos et al., 2018), the predominant soil in the region is the typical dystrophic Yellow-Red Latosol. The characteristic vegetation of the region is classified as Montana Seasonal Semideciduous Forest, inserted in the Atlantic Forest Domain (IBGE, 2012).

This study was conducted in an area of 2.0 ha, which until the end of 2016 was used for the administrative office sector of Companhia Brasileira de Alumínio–CBA (Figure 1). With the change in the location of the company’s administrative office sector, all buildings were removed and, consequently, the layer of soil exposed to the surface (subsoil) was highly compacted and had low levels of organic matter and nutrients. Thus, this area was included in the company’s environmental compensation program for bauxite mining (Fonseca, 2021).

Soil preparation was carried out with a ripper subsoiler at a depth of 60 cm to break the compacted layer and homogenize the soil surface. In sequence, acidity correction was carried out in the total area with 4 tons ha^{-1} of limestone and fertilization with 2 tons ha^{-1} of reactive phosphate rock and 1 ton ha^{-1} of NPK 10-30-10. Subsequently, three green manures species were sowed in furrows at 150 kg ha^{-1}. In addition, seedlings of 18 native tree species with different successional characteristics were planted, in a spacing of 4 x 4 meters (Table 1) (Fonseca & Martins, 2021).

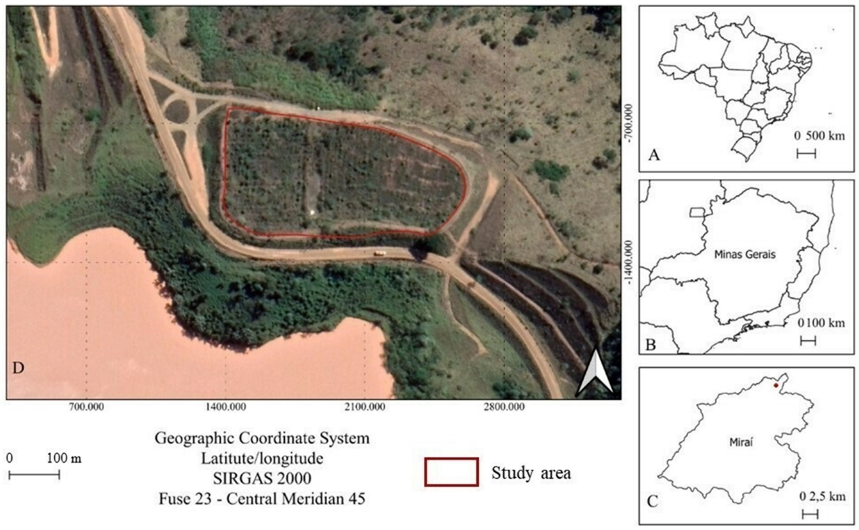

Figure 1. Study area location, in Miraí-MG, Brazil.

Table 1. Plant species list planted in the study area.

Botanical family	Species	SC	DS
Bignoniaceae	*Handroanthus heptaphyllus* (Vell.) Mattos	LS	Ane
	Handroanthus impetiginosus (Mart. Ex DC.) Mattos	LS	Ane
	Tabebuia roseoalba (Ridl.) Sandwith	ES	Ane
	Jacaranda micrantha Cham	ES	Ane
Cannabaceae	*Trema micrantha* (L.) Blume	P	Zoo
Euphorbiaceae	*Alchornea glandulosa* Poepp.	P	Zoo
	Sapium glandulosum (L.) Morong	P	Zoo
Fabaceae	*Bauhinia forficata* Link	P	Aut
	Caesalpinia pluviosa DC.	ES	Aut
	Clitoria fairchildiana R.A.Howard	ES	Aut
	Senegalia polyphylla (DC.) Britton & Killip	P	Aut
Malvaceae	*Pseudobombax grandiflorum (Cav.) A.Robyns*	P	Ane
Melastomataceae	*Tibouchina granulosa* (Desr.) Cogn.	P	Ane
Myrtaceae	*Psidium guajava L.*	P	Zoo
Solanaceae	*Solanum pseudoquina* A. St.-Hil.	ES	Zoo
Urticaceae	*Cecropia glaziovii* Snethl.	P	Zoo
	Cecropia hololeuca Miq.	P	Zoo
Verbenaceae	*Citharexylum myrianthum* Cham.	ES	Zoo

SC: Successional category (P: Pioneer, ES: Early secondary, LS: Late secondary); DS: Dispersal syndrome (Ane: anemochory, Aut: autochory, Zoo: zoochory).

2.2. Field procedures

The three green manure species sown in January 2017 were *Cajanus cajan* L. Millsp. (Pigeon pea), *Crotalaria juncea* L. (Sunn hemp), and *Stylosanthes guianensis* Aubl. Sw. (Stylo). The view of the soil surface after the removal of the built structures and the earthworks, the advancement of the cover and the management of the sown green manures can be seen in Figure 2.

Ten 1 m x 1 m plots were allocated to evaluate the cover potential of each green manure species after 18 months of sowing. Thus, three treatments, with ten repetitions each, distributed in a completely randomized design, were tested. Treatment T1 – *C. cajan* (CAJ); o T2 – *C. juncea* (CRO) and T3 – *S. guianensis* (STY).

The plant cover rate was obtained through the visual evaluation of the plots through the percentage scale in which the grade 0 corresponded to the absence of vegetation cover and the grade 100 corresponds to the complete plant cover. In addition, phytomass production was evaluated by collecting all aboveground plant material using a 0.25 m² template in each plot. The harvested material was stored in plastic bags identified which were transported to the Forest Restoration Laboratory (LARF/UFV), where it was dried in an oven at 72ºC for 48 hours and the dry weight was measured.

For the soil chemical analysis, soil samples (0-20 cm depth) were collected with a Dutch auger from 30 random sampling points within each treatment. These samples were combined into one composite sample per treatment. To evaluate and compare the chemical properties under the three green manures, soil samples were collected at 0, 18, and 24 months after sowing.

The composite samples were sent to the Soil Laboratory of the Federal University of Viçosa for proper analyses. Subsequently, the results were interpreted according to the Recommendation Guide for Correctives and Fertilizers of Minas Gerais (Alvarez et al., 1999) and compared with soil analyses before implementing restoration techniques.

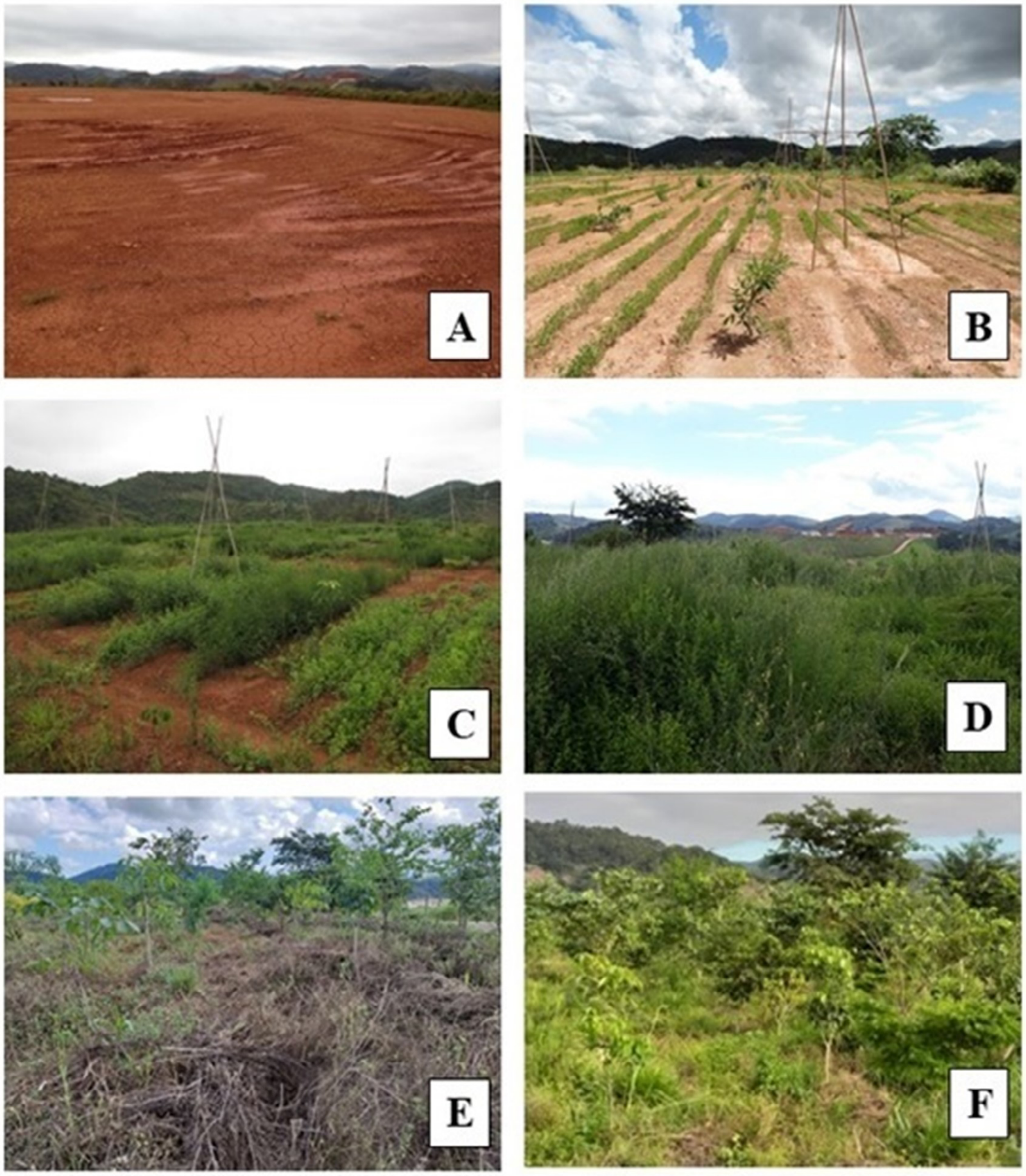

Figure 2. Initial soil surface condition, growth and management of green manures. (A: exposed soil surface - initial situation; B: Green manures after 6 months of sowing; C: Green manures after 12 months of sowing; D: Green manures, after 18 months of sowing; E: Management of green manures to favor the development of planted seedlings; F: Area after 4 years of implementation of restoration techniques).

2.3. Data processing and analyses

To compare mean values of plant cover and dry weight obtained in the three treatments one-way ANOVA was used followed by Tukey test for independent samples ($p<0.05$) (Crawley, 2013). The R software version 3.5.3 (R Core Team, 2019) was used for the statistical analyses.

3. RESULTS

3.1. Soil Analyses

According to the Recommendation Guide for Correctives and Fertilizers of Minas Gerais (Alvarez et al., 1999), the soil samples collected before the soil preparation and fertilization techniques (month 0) indicated an average acidification level (pH=5.39), very low organic matter content (OM=0.25 dag/kg), low base sum (SB=0.82 cmolc/dm^3), low cation exchange capacity (CEC=2.32 cmolc/dm^3) and low base saturation (V=35.3%). Thus, to evaluate, relating, and comparing the soil's chemical properties under the three green manures at different times (0, 18 and 24 months after sowing), Table 2 was prepared.

Liming effectively raised soil pH and increased the concentration of calcium (Ca^{2+}) and magnesium (Mg^{2+}) nutrients. Phosphating increased phosphorus (P) concentration in the soil. The sum of bases (SB) and base saturation (V%) increased after the actions taken, while the exchangeable acidity decreased. There was an increase in total-N of the soil in all treatments after 18 months of sowing the green manures, in the soil grown with *Crotalaria juncea* and *Cajanus cajan* there was an increase of 245% and in the soil grown with *Stylosanthes guianensis* a rise of 177%, about the values obtained before the implementation of the restoration project, reflecting the contribution of the three green manures through biological nitrogen fixation.

Accordingly, there was an improvement in the other chemical properties of the soil, according to criteria proposed by Alvarez et al., (1999), presented in Table 3. In the soil grown with *C. juncea* there was a medium level of acidification (pH=6.97), low organic matter content (OM=1.88 dag/kg), very high sum of bases (SB=6.21 cmolc/dm^3), medium capacity for cation exchange (CEC=6.81 cmolc/dm^3) and a very high base saturation (V=91.2%). Although organic matter receives a low rating, there was an increase of 652% compared to the previous analysis.

The soil under *S. guianensis*, was observed: neutral pH (pH=7.06), low organic matter content (OM=1.75 dag/kg), high sum of bases (SB=4.51 cmolc/dm^3), medium exchange capacity cationic (CEC=4.51 cmolc/dm^3) and a very high base saturation (V=100%). In the soil grown with *C. cajan*, has observed: a weak acidification level (pH=6.84), average content of organic matter (OM=2.28 dag/kg), low cation exchange capacity (CEC=4.30 cmolc/dm^3) and very high base saturation (V=93.0%).

After 24 months of green manure sowing, there was an increase in the contents of nutrients N, P, K, Ca^{2+} and Mg^{2+} and P-rem in all treatments. The decomposition of the phytomass of green manures promoted an increase in pH, by promoting complexation of H^+ and Al^{3+} with compounds from the vegetable residue, leaving Ca^{2+}, Mg^{2+} and K^+ freer in solution. This process resulted in an increase in CEC saturation by these basic reaction cations.

There was a weak alkalinity level in all treatments and a very high classification in the properties: phosphorus, calcium, magnesium, SB, V%, and P-rem. As for CEC, all green manures showed medium classification. The soil-grown with *C. juncea*, had high organic matter content, while soils under stylo and pigeon pea had medium OM content (Table 4).

To favor the growth of planted tree species, green manure management was carried out by mowing without incorporation 18 months after sowing. Consequently, 24 months after sowing, an increase in total-N and organic matter contents is observed. As for the organic matter contents, there was a significant increase in the soil grown with *C. juncea* (1936%) concerning the initial value obtained in the exposed soil, followed by the soil grown with ground under *C. cajan* (1204%) and in the soil grown with *S. guianensis* (1072%). The same pattern was observed in the total-N contents of the soil; there was an increase in all treatments, especially for the soil grown with *C. juncea*, with an increase of 914% with the initial situation of exposed soil, followed by *S. guianensis* with an increase in 536% and *C. cajan* with a 532% increase.

Table 2. Chemical analyses of soil from different treatments in the 0-20cm layer at different times (0, 18 and 24 months after sowing).

Parameters	months	CRO	STY	CAJ
pH (H_20)	0	5.39	5.39	5.39
	18	6.97	7.06	6.84
	24	7.54	7.49	7.40
OM (dag/kg)	0	0.25	0.25	0.25
	18	1.88	1.75	2.28
	24	5.09	2.93	3.26
Total-N (dag/kg)	0	0.022	0.022	0.022
	18	0.076	0.061	0.076
	24	0.223	0.140	0.139
P (mg/dm^3)	0	4.40	4.40	4.40
	18	463.1	463.1	283.8
	24	614.7	509.7	547.6
K (mg/dm^3)	0	21	21	21
	18	89	52	58
	24	283	98	161

Table 2. Continued...

Parameters	months	CRO	STY	CAJ
Ca^{2+} (cmolc/dm^3)	0	0.59	0.59	0.59
	18	4.22	3.52	3.13
	24	4.87	4.2	4.46
Mg^{2+} (cmolc/dm^3)	0	0.18	0.18	0.18
	18	1.76	0.86	0.72
	24	2.16	1.83	2.00
H+Al (cmolc/dm^3)	0	1.5	1.5	1.5
	18	0.6	0.0	0.3
	24	0.0	0.2	0.6
SB (cmolc/dm^3)	0	0.82	0.82	0.82
	18	6.21	4.51	4.00
	24	7.76	6.28	6.87
ECEC (cmolc/dm^3)	0	0.82	0.82	0.82
	18	6.21	4.51	4.00
	24	7.76	6.28	6.87
CEC (cmolc/dm^3)	0	2.32	2.32	2.32
	18	6.81	4.51	4.30
	24	7.76	6.48	7.47
V (%)	0	35.3	35.3	35.3
	18	91.2	100	93.0
	24	100	96.9	92.0
P-rem (mg/L)	0	12.9	12.9	12.9
	18	17.6	18.2	18.6
	24	26.4	24.4	20.8

CAJ (*Cajanus cajan*); CRO (*Crotalaria juncea*); STY (*Stylosanthes guianensis*); OM (Organic Matter); Total-N (Total Nitrogen); P (Phosphorus); K (Potassium); Ca^{2+} (Calcium); Mg^{2+} (Magnesium); H + Al (Potential acidity); SB = (Sum of bases); ECEC (Effective Cation Exchange Capability); CEC (Cation Exchange Capacity at pH 7.0); V (Base Saturation Index); P-rem (Remaining Phosphorus).

Table 3. Classification of chemical properties of the soil, 18 months after sowing green manures, according to the recommendations for the use of correctives and fertilizers in Minas Gerais. VL= Very low; L=Low; M=Medium; H= High; VH= Very high.

Green manures	pH	OM	P	K	Ca^{2+}	Mg^{2+}	H+Al	SB	ECEC	CEC	V	P-rem
CRO	Weak acid	L	VH	H	VH	VH	VL	VH	H	M	VH	VH
STY	Neutral	L	VH	M	H	M	VL	H	M	M	VH	VH
CAJ	Weak acid	M	VH	M	H	M	VL	H	M	L	VH	VH

CRO (*Crotalaria juncea*); STY (*Stylosanthes guianensis*); CAJ (*Cajanus cajan*).

Table 4. Classification of chemical properties of the soil, 24 months after sowing green manures, according to the recommendations for the use of correctives and fertilizers in Minas Gerais. VL= Very low; L=Low; M=Medium; H= High; VH= Very high.

Green manures	pH	OM	P	K	Ca^{2+}	Mg^{2+}	H+Al	SB	ECEC	CEC	V	P-rem
Cro	Weak alkali	H	VH	VH	VH	VH	VL	VH	H	M	VH	VH
Sty	Weak alkali	M	VH	H	VH	VH	VL	VH	H	M	VH	VH
Caj	Weak alkali	M	VH	VH	VH	VH	VL	VH	H	M	VH	VH

CRO (*Crotalaria juncea*); STY (*Stylosanthes guianensis;* CAJ (*Cajanus cajan*).

3.2. Plant cover

The analysis of variance showed differences between treatments, both for plant cover and the dry weight ($p<0.05$). The highest percentage of plant cover was observed in *Cajanus cajan*, with an average of 89%, followed by *Crotalaria juncea* with 75%. *Stylosanthes guianensis* had the lowest percentage of cover, with an average of 59.5%, being statistically lower than *C. cajan* and similar to *C. juncea* by Tukey's test (Figure 3).

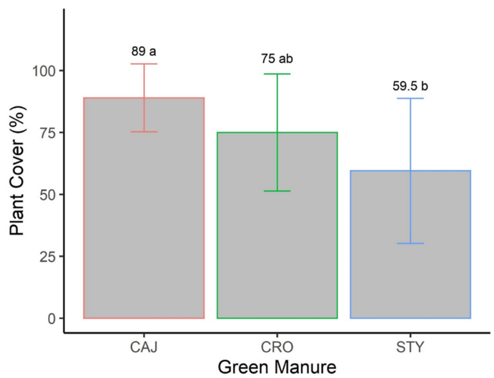

Figure 3. Plant cover averages (%) of green manure species. Means followed by different letters are statistically different $p \leq 0.05$ (Tukey). Error bars represent standard deviation. CAJ = *Cajanus cajan*; CRO = *Crotalaria juncea* and STY = *Stylosanthes guianensis*.

3.3. *Dry weight of phytomass*

The species that produced the highest values of dry phytomass were *C. cajan* with an average of 853.90 $g.m^{-2}$ and *S. guianensis* with 716.18 $g.m^{-2}$. *C. juncea* had a lower dry weight, equivalent to 402.26 $g.m^{-2}$, being considered statistically lower than *C. cajan*, but similar to *S. guianensis* by Tukey test $p \leq 0.05$ (Figure 4).

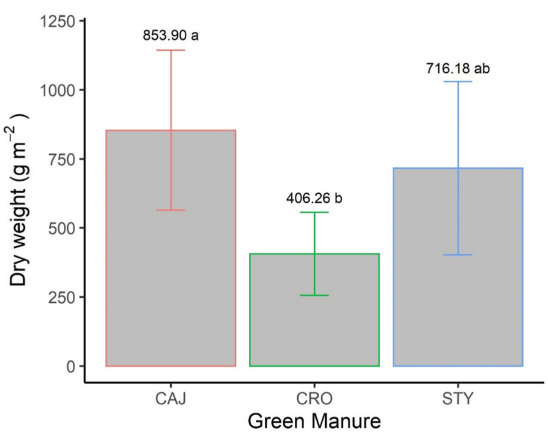

Figure 4. Means dry weight of green manure species. Means followed by different letters are statistically different $p \leq 0.05$ (Tukey). Error bars represent standard deviation. CAJ = *Cajanus cajan*; CRO = *Crotalaria juncea* and STY = *Stylosanthes guianensis*.

4. DISCUSSION

4.1. *Soil Analyses*

Soils in tropical regions are generally weathered, acidic and have low natural fertility (Neto et al., 2021). In this context, liming is a practice commonly used to neutralize soil acidity, provide calcium and magnesium, reduce the toxicity of some elements, increase the cation exchange capacity and, consequently, increase the availability of nutrients for plants (Carmeis-Filho et al., 2017; Bossolani et al., 2020). In this sense, soil preparation techniques, liming, and phosphate fertilization are important for soil recovery and green manure can contribute to this process. The contributions of green manure in increasing soil pH were described by Neto et al. (2021) in a study carried out in Yellow-Red Latosol. In addition, Nascimento et al. (2019) stated that mechanical soil scarification increased the dry mass yield of four cover crops, including *Cajanus cajan* and *Crotalaria juncea*. Thus, the phytomass decomposition green manures this study may explain the increase in pH (Table 2), mainly due to the contribution of organic matter.

In this perspective, improving the quality and quantity of soil organic matter (SOM) in tropical soils is essential to increase ecosystem sustainability (Carmeis-Filho et al., 2017). In the present study, the three species of green manures contributed to the increase in SOM contents. This result corroborates experiments conducted in different regions and with different species of green manures, in which they observed an increase in SOM levels and CEC (Sharma et al., 2017; Oliveira et al., 2017; Gao et al., 2018; Liu et al., 2020). The decomposition of organic matter is a complex and very important ecological process as it directly influences the soil microbiota and nutritional dynamics, mainly carbon and nitrogen (Soares et al., 2020). Given this relevance, the relationship between SOM and nitrogen is the subject of studies in post-bauxite mining areas (Banning et al., 2008) and in other tropical regions (Hicks et al., 2019; Sellan et al., 2020).

Nitrogen is the most dynamic nutrient in tropical soils, found in mineral, organic, ionic and gaseous forms (Amazonas et al., 2011; Kumari & Maiti, 2022). These constant transformations occur quickly in the soil influenced by numerous factors such as soil moisture, temperature, pH, microorganisms, fertility, C/N ratio of residues, N-fixing plants, soil preparation and management, among others (Figueiredo et al., 2019; Rastetter et al., 2020; Rocha et al., 2021). Given this complexity, no methodology addresses all these factors and provides a standard nitrogen availability index (Prezotti & Guarçoni, 2013; Figueiredo et al., 2019). In green manure, leguminous species are the main nitrogen fixators through the symbiotic relationship with soil bacteria (*Rhizobium* and *Bradyrhizobium*) (Muller et al., 2021).

Biological N fixation performed by green manures can also provide N for non-legume species. Thus, it is possible that the tree species planted in the area have absorbed part of the N and incorporated it into its biomass, considering that N is one of the nutrients that most limits the growth of tree species in tropical regions (Amazonas et al., 2011;

Bossolani et al., 2020). The use of N by planted tree species was also verified by Silva et al. (2016) in studies conducted in the region and in a post-mining bauxite area. The authors have reported that planting seedlings intercropped with *C. cajan* resulted in a greater increase in basal area, lower mortality, rapid soil recovery, improvements in fertility and greater nitrogen availability due to biological fixation. Saldanha et al. (2017) have highlighted that green manure with *C. cajan* provides physical benefits in soil conservation. However, it cannot supply the nitrogen demand of the main crop. Thus, considering that biological nitrogen fixation is a complex process (Borges et al., 2016) and that the regions with a predominance of Latosol naturally present soils with low fertility, it is recommended that ecological restoration projects carry out complementary nitrogen fertilization, management of green manures and monitoring of soil fertility periodically (Soares et al., 2020).

The total-N contents after 2 years of sowing of green manures (Cro=0.223 dag/kg; Sty=0.140 dag/kg; Caj=0.139 dag/kg) corroborate what was verified by Balestrin (2018), in an area after 6 years of restoration through conduction of natural regeneration (0.130 dag/kg) and with Balestrin et al. (2019), in an area after 14 years of restoration by planting seedlings (0.139 dag/kg), both studies conducted in areas after bauxite mining by Companhia Brasileira de Alumínio in the same region. However, green manures were efficient in recovering total-N contents in soil in a shorter restoration time than other mined areas. As a result, the total-N contents of the soil increased considerably after 24 months of sowing the green manures (Cro:914%; Sty:536%; Caj:532%) compared to the initial values of the same soil. The superior results observed indicate that *C. juncea* is a key species for soil recovery in ecological restoration projects in the region and confirms recent studies that highlighted the potential of *C. juncea* to incorporate nitrogen and improve soil fertility (Barbosa et al., 2020; Yao et al., 2021; Ma et al., 2021), increasing biomass (Subaedah et al., 2016) and restoring topsoil in bauxite mines (Narayanan et al., 2021).

In this sense, the management of green manures after 24 months of sowing has proved to be efficient in the incorporation of organic matter in the soil, considering that this technique favored the decomposition of the phytomass of the green manures and consequently promoted an increase in the fertility of the soil (Silva et al., 2022). In the soil-plant system, Nitrogen sho higher turnover by plant residues or phytomass (Hungria et al., 2015). For example, the phytomass incorporation using green manures can promotes biological nitrogen fixation and increase the total-N levels in the soil by decomposition (Hungria et al., 2015).

Thus, green manure is a promising alternative for soil recovery and conservation in impacted areas because of physical, chemical, and biological improvements in soil attributes and ecosystem services. In addition, recent studies indicate that cover crops can contribute to climate change mitigation due to plant cover, erosion reduction and organic carbon fixation through the incorporation of organic matter (Yao et al., 2019; Delgado et al., 2021). It should be noted that the effects provided by green manure vary according to the species used, soil microorganisms, soil and climatic conditions, management and the ecological adaptation of green manure to local conditions (Alcântara et al., 2000). Therefore, the peculiarities of each environment and the intrinsic characteristics of each species are crucial for planning green manure as an alternative for soil recovery in ecological restoration projects.

4.2. Plant cover

The fast covering of the soil promoted by green manures ensured greater protection of the soil against solar radiation and the impact of raindrops, thus minimizing erosion processes. Furthermore, this fast covering of the soil can contribute to reducing the infestation of undesirable plants, as indicated by studies in different tropical regions with the species *C. cajan* (Silva et al., 2015; Nascimento et al., 2019; Souza et al., 2021). *Cajanus cajan* showed the best results in land cover and dry weight. Thus, it is a key crucial species to maximize the benefits of green manures and be a viable option in ecological restoration projects in areas with exposed soil (Martins, 2018). The plant cover rate promoted by *C. cajan* in this study (89.0%) was higher than that indicated by Pacheco et al. (2017) for the same species (74.9%) after 156 days after sowing. Furthermore, the authors observed similar cover values similar followed in species of the genus *Stylosanthes* (55.3%) and lower values in the genus *Crotalaria* (41.6%-55.6%). This contrast reinforces the need for this study since the results are closely related to edaphic conditions, rainfall, management, experimental conditions and evaluation period.

The effects of green manures *C. cajan*, *C. juncea* and *S. guianensis* on plant cover, soil protection and improvement of physical properties are described in several studies (Long et al., 2017; Martins, 2018; Melander et al.,2020; Soares et al., 2021; Silva et al., 2021; Neto et al., 2021). These authors highlighted that *C. cajan*, *C. juncea* and *S. guianensis* promoted increased fertility and improvements in the aggregate stability index and resistance to root penetration. In addition, these authors reinforce the benefits of intercropping between legumes and grasses, aiming at enhancing the effects on soil recovery.

4.3. *Dry weight of phytomass*

As for dry weight phytomass, the highest production by *C. cajan* (853.90 g.m^{-2}) verified in this study, corroborates Cavalcante et al. (2012), when compared to six other cover crops, including two species of the genus Crotalaria (*C. juncea* and *C. spectabilis* Roth). The production of *C. cajan* described by the authors (870 g.m^{-2}) was similar to this study, although the production of crotalaria was lower (250-300 g.m^{-2}) and the material was collected at 129 days. Furthermore, superior results were also found in other Brazilian regions as observed by Carneiro et al. (2008); Xavier et al. (2017) and Nascimento et al. (2019). On the other hand, in the same forest typology of the study area and in Yellow-Red Latosol, lower dry mass values of *C. cajan* (301 g.m^{-2}) were found (Mendonça et al., 2017). As for *S. guianensis*, lower values (339.18 g.m^{-2}) were found in research conducted in a degraded area (Godoi et al., 2008). Given these variations, it is necessary to evaluate green manures in different conditions and environments (Alcântara et al., 2000).

5. CONCLUSIONS

The green manures used in this study were efficient in recovering soil fertility. The increase in nutrient contents, the improvement in soil chemical parameters and the deposition of significant amounts of phytomass indicate that green manuring is a technique capable to promote rapid plant cover and assist in ecological restoration projects in mined areas.

C. cajan and *C. juncea* stood out for covering the soil, while *C. cajan* and *S. guianensis* were more efficient in producing dry mass. All species positively influenced the organic matter content and contributed to the increase in the total-N content of the soil, due to biological nitrogen fixation. *C. juncea* was the most promising species in recovering soil total-N levels.

Thus, this study adds novelties for revegetation of areas in mining environment, especially for soil reconstruction and is important to demonstrate the sustainability of bauxite mining in the region. Future research may evaluate the effects of green manures in the control of invasive grasses and mitigation of climate change.

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REFERENCES

Agevap. Plano municipal de saneamento básico, São Sebastião da Vargem Alegre, MG. PrintPaper Editora Gráfica; 2013.

Alcântara FA, Furtini Neto AE, Paula MB, Mesquita HA, Muniz JA. Adubação verde na recuperação da fertilidade. Pesquisa Agropecuária Brasileira 2000; 35(2): 277-88. https://doi.org/10.1590/S0100-204X2000000200006

Amazonas NT, Martinelli LA, Piccolo MC, Rodrigues RR. Nitrogen dynamics during ecosystem development in tropical forest restoration. Forest Ecology and Management 2011; 262(8): 1551-1557. https://doi.org/10.1016/j.foreco.2011.07.003

Anache JA, Wendland EC, Oliveira PT, Flanagan DC, Nearing MA. Runoff and soil erosion plot-scale studies under natural rainfall: A meta-analysis of the Brazilian experience. Catena 2017; 152(1): 29-39. https://doi.org/10.1016/j.catena.2017.01.003

ANM. Anuário Mineral Brasileiro - Principais Substâncias Metálicas 2021. Brasília: Agência Nacional de Mineração; 2021.

Balestrin D, Martins SV, Schoorl JM, Lopes AT, Andrade CF. Phytosociological study to define restoration measures in a mined area in Minas Gerais, Brazil. Ecological Engineering 2019; 135(1): 8-16. https://doi.org/10.1016/j.ecoleng.2019.04.023

Balestrin D, Martins SV, Fonseca CA. Ecological restoration and forest coverage advancement in a region influenced by bauxite mining, Minas Gerais, Brazil. In: de Vlieger K, editor. Recent advances in ecological restoration. New York: Nova Science Publishers; 2020.

Banning NC, Grant CD, Jones DL, Murphy DV. Recovery of soil organic matter, organic matter turnover and nitrogen cycling in a post-mining forest rehabilitation chronosequence. Soil Biology and Biochemistry 2008; 40(8): 2021-2031. https://doi.org/10.1016/j.soilbio.2008.04.010

Barbosa IR, Santana RS, Mauad M, Garcia RA. Dry matter production and nitrogen, phosphorus and potassium uptake in *Crotalaria juncea* and *Crotalaria spectabilis*. Pesquisa Agropecuária Tropical 2020; 50(1): e61011. https://doi.org/10.1590/1983-40632020v5061011

Bonini CDSB, Alves MC. Recovery of soil physical properties by green manure, liming, gypsum and pasture and spontaneous native species. Revista Brasileira de Ciência do Solo 2011; 35(4): 1397-1406. https://doi.org/10.1590/S0100-06832011000400034

Borges WL, Prin Y, Ducousso M, Le Roux C, Faria SM. Rhizobial characterization in revegetated areas after bauxite mining. Brazilian Journal of Microbiology 2016; 47(2): 314-321. https://doi.org/10.1016/j.bjm.2016.01.009

Bossolani JW, Crusciol CAC, Merloti LF, Moretti LG, Costa NR, Tsai SM et al. Long-term lime and gypsum amendment increase nitrogen fixation and decrease nitrification and denitrification gene abundances in the rhizosphere and soil in a tropical no-till intercropping system. Geoderma 2020; *375*(19): e114476. https://doi.org/10.1016/j.geoderma.2020.114476

Butchart SH, Walpole M, Collen B, Van Strien A, Scharlemann JP, Almond R et al. Global biodiversity: indicators of recent declines. Science 2010; 328(5982): 1164-1168. https://doi.org/10.1126/science.1187512

Carmeis-Filho AC, Penn CJ, Crusciol CA, Calonego JC. (2017). Lime and phosphogypsum impacts on soil organic matter pools in a tropical Oxisol under long-term no-till conditions. Agriculture, Ecosystems & Environment 2017; 241(6): 11-23 http://dx.doi.org/10.1016/j.agee.2017.02.027

Carneiro MAC, Cordeiro MAS, Assis PCR, Moraes ES, Pereira HS, Paulino H et al. Produção de fitomassa de diferentes espécies de cobertura e suas alterações na atividade microbiana de solo de cerrado. Bragantia 2008; 67(2): 455-462. https://doi.org/10.1590/S0006-87052008000200021

Cavalcante VS, Santos VR, dos Santos ALN, dos Santos MA, dos Santos CG, Costa LC. Biomassa e extração de nutrientes por plantas de cobertura. Revista Brasileira de Engenharia Agrícola e Ambiental 2012; 16(5): 521-529. https://doi.org/10.1590/S1415-43662012000500008

Cosimo LHE, Martins SV, Gleriani JM. Suggesting priority areas in the buffer zone of Serra do Brigadeiro State Park for forest restoration compensatory to bauxite mining in Southeast Brazil. Ecological Engineering 2021; 170: e106322. https://doi.org/10.1016/j.ecoleng.2021.106322

Crawley MJ. The R book .2nd ed. West Sussex: John Wiley & Sons; 2013.

Delgado JA, Mosquera VHB, Alwang JR, Villacis-Aveiga A, Ayala YEC, Neer D et al. (2021). Potential use of cover crops for soil and water conservation, nutrient management, and climate change adaptation across the tropics. In Sparks DL, editor. Advances in Agronomy. London: Academic Press; 2021.

Ferreira AM, da Silva AM, dos Passos CA, Valentino CH, Gonçalves FA, Menezes PHBJ. Estimated water soil erosion by the Water Erosion Prediction Project model in the Gigante Stream Basin, Minas Gerais, Brazil. Engenharia Sanitaria e Ambiental 2021; 26(3): 471-483. https://doi.org/10.1590/S1413-415220190216

Figueiredo V, Enrich-Prast A, Rütting T. Evolution of nitrogen cycling in regrowing Amazonian rainforest. Scientific reports 2019; 9(1): 1-8. https://doi.org/10.1038/s41598-019-43963-4

Fonseca WS. Bioindicadores para avaliação e monitoramento da restauração ecológica de área em ambiente de mineração de bauxita, Miraí, MG [dissertação]. Viçosa: Universidade Federal de Viçosa; 2021. https://locus.ufv.br//handle/123456789/28543

Fonseca WS, Martins SV. Monitoramento de fauna como indicador de restauração florestal de uma área em ambiente de mineração de bauxita na Zona da Mata Mineira. In Oliveira RJ, editor. Águas e Florestas: Desafios Para Conservação e Utilização. Guarujá: Editora Científica Digital; 2021. https://dx.doi.org/10.37885/210404406

Gann GD, McDonald T, Walder B, Aronson J, Nelson CR, Jonson J et al. International principles and standards for the practice of ecological restoration. Restoration Ecology 2019; 27(S1): 1-46. https://doi.org/10.1111/rec.13035

Gao SJ, Gao JS, Cao WD, Zou CQ, Huang J, Bai JS et al. Effects of long-term green manure application on the content and structure of dissolved organic matter in red paddy soil. Journal of integrative agriculture 2018; 17(8): 1852-1860. https://doi.org/10.1016/S2095-3119(17)61901-4

Godoi EL, Borges JD, Leandro WM. Índices de cobertura vegetal e fitomassa de *Stylosanthes guianensis* Cv. Mineirão em área degradada, fertilizada com adubo mineral e biossólido. Pesquisa Agropecuária Tropical 2008; 38(1): 21-26. https://www.revistas.ufg.br/pat/article/view/3622/3414

Hicks LC, Meir P, Nottingham AT, Reay DS, Stott AW, Salinas N et al. (2019). Carbon and nitrogen inputs differentially affect priming of soil organic matter in tropical lowland and montane soils. Soil Biology and Biochemistry 2019; 129(2): 212-222. https://doi.org/10.1016/j.soilbio.2018.10.015

Hou T, Filley TR, Tong Y, Abban B, Singh S, Papanicolaou AL et al. Tillage-induced surface soil roughness controls the chemistry and physics of eroded particles at early erosion stage. Soil and Tillage Research 2021; 207(3): e104807. https://doi.org/10.1016/j.still.2020.104807

Hungria M, Nogueira MA, & Araujo RS. (2015). Soybean seed co-inoculation with Bradyrhizobium spp. and Azospirillum brasilense: a new biotechnological tool to improve yield and sustainability. American Journal of Plant Sciences 2015; 6(6): 811–817. http://dx.doi.org/10.4236/ajps.2015.66087

IBGE. Manual Técnico da Vegetação Brasileira. 2ª ed. Rio de Janeiro: Instituto Brasileiro de Geografia e Estatística; 2012.

Iserhagen I, Brancalion PHS, Rodrigues RR. Adubação verde na restauração florestal. In: Lima Filho OF, Ambrosano EJ, Rossi F, Carlos JAD, editores. Adubação verde e plantas de cobertura no Brasil: fundamentos e prática. Brasília: Embrapa; 2014.

Kaiser-Bunbury CN, Mougal J, Whittington AE, Valentin T, Gabriel R, Olesen J M et al. Ecosystem restoration strengthens pollination network resilience and function. Nature 2017; 542(7640): 223-227. https://doi.org/10.1038/nature21071

Köppen W. Climatologia: con un estudio de los climas de la tierra. México: Fondo de Cultura Econômica; 1948

Kumari S, Maiti SK. Nitrogen recovery in reclaimed mine soil under different amendment practices in tandem with legume and non-legume revegetation: A review. Soil Use and Management 2022; 38(1): e12787 https://doi.org/10.1111/sum.12787

Liu S, Wang J, Pu S, Blagodatskaya E, Kuzyakov Y, Razavi BS. Impact of manure on soil biochemical properties: A global synthesis. Science of The Total Environment 2020; 745(48): 141003. https://doi.org/10.1016/j.scitotenv.2020.141003

Long H, Zhang D, He G. The effects of planted and plowed Stylosanthes guianensis on degrading soil fertility in hilly countries of dry-hot valley. Acta Ecologica Sinica 2017; 37(5): 279-283. https://doi.org/10.1016/j.chnaes.2017.02.004

Ma D, Yin L, Ju W, Li X, Liu X, Deng X et al. Meta-analysis of green manure effects on soil properties and crop yield in northern China. Field Crops Research 2021; 266(7): 108146. https://doi.org/10.1016/j.fcr.2021.108146

Marshall CB, Lynch DH. Soil microbial and macrofauna dynamics under different green manure termination methods. Applied Soil Ecology 2020; 148(4): 103505. https://doi.org/10.1016/j.apsoil.2020.103505

Martins SV, Miranda Neto A, Ribeiro TM. Uma abordagem sobre diversidade e técnicas de restauração ecológica. In Martins SV, editor. Restauração ecológica de ecossistemas degradados. Viçosa: Editora UFV; 2015

Martins SV. Alternative Forest Restoration Techniques. In: Viana H, editor. New Perspectives in Forest Science. London: IntechOpen; 2018.

Martins SV, Cosimo LHE, Balestrin D, Fonseca WS, Andrade CF, Barros RS. Restoration of Tree and Shrub Diversity Post Bauxite Mining, in the Southeastern Region of Minas Gerais, Brazil. In: Vlieger K, editor. Recent Advances in Ecological Restoration. New York: Nova Science Publishers; 2020

Martins SV, Fonseca WS, Andrade CF, Barros RS, Paiva JM, Silva CH et al. Reflorestamento com mudas altas: uma inovação da restauração florestal na mineração de bauxita em Minas Gerais. In: Oliveira RJ, editor. Engenharia florestal: contribuições, análises e práticas em pesquisa. Guarujá: Editora Científica Digital; 2022. https://doi.org/10.37885/220308108

Melander B, Rasmussen IA, Olesen JE. Legacy effects of leguminous green manure crops on the weed seed bank in organic crop rotations. Agriculture, Ecosystems & Environment 2020; 302(16): 107078. https://doi.org/10.1016/j.agee.2020.107078

Melo CES, Sánchez LE. Evaluation of environmental rehabilitation practices in bauxite mining at the plateau of Poços de Caldas. REM-International Engineering Journal 2020; 73(2): 247-252. https://doi.org/10.1590/0370-44672019730131

Mendonça EDS, Lima PCD, Guimarães GP, Moura WDM, Andrade FV. Biological nitrogen fixation by legumes and N uptake by coffee plants. Revista Brasileira de Ciência do Solo 2017; 41(1): e0160178. https://doi.org/10.1590/18069657rbcs20160178

MME. Mineral Sector Bulletin. 7 nd ed. Brasília: Ministry of Mines and Energy and National Mining Agency; 2021.

Muller KE, Guinness J, Hecking M, Drinkwater LE. Estimating agronomically relevant symbiotic N fixation in green manure breeding programs. Crop Science 2021; 61(5): 3314-3330. https://doi.org/10.1002/csc2.20517

Narayanan M, Thangabalu R, Natarajan D, Kumarasamy S, Kandasamy S, Elfasakhany A et al. Reclamation competence of *Crotalaria juncea* with the amalgamation and influence of indigenous bacteria on a waste dump of bauxite mine. Chemosphere 2021; 279(19): e130632. https://doi.org/10.1016/j.chemosphere.2021.130632

Nascimento V, Arf O, Alves MC, de Souza EJ, da Silva PRT, Kaneko FH et al. Soil mechanical scarification increases the dry matter yield of cover crops under no-tillage. Idesia 2019; 37(4): 29-39. http://dx.doi.org/10.4067/S0718-34292019000400029

Neto JF, Franzluebbers AJ, Crusciol CAC, Rigon JPG, Calonego JC, Rosolem CA et al. Soil carbon and nitrogen fractions and physical attributes affected by soil acidity amendments under no-till on Oxisol in Brazil. Geoderma Regional 2021; 24(1): e00347. https://doi.org/10.1016/j.geodrs.2020.e00347

Oliveira KJ, de Lima JS, Ambrósio MMDQ, Neto FB, Chaves AP. Propriedades nutricionais e microbiológicas do solo influenciadas pela adubação verde. Revista de Ciências Agrárias 2017; 40(1): 23-33. https://doi.org/10.19084/RCA16010

Pacheco LP, Miguel ASDCS, Silva RGD, Souza EDD, Petter FA, Kappes C. Biomass yield in production systems of soybean sown in succession to annual crops and cover crops. Pesquisa Agropecuária Brasileira 2017; 52(8): 582-591. https://doi.org/10.1590/S0100-204X2017000800003

Prezotti LC, Guarçoni MA. Guia de interpretação de análise de solo e foliar. Vitória: Incaper; 2013.

R CORE TEAM. R: A Language and Environment for Statistical ComputingVienna, AustriaR Foundation for Statistical Computing, 2019. Available from: <https://www.r-project.org/>

Rastetter EB, Kling GW, Shaver GR, Crump BC, Gough L, Griffin KL. Ecosystem Recovery from Disturbance is Constrained by N Cycle Openness, Vegetation-Soil N Distribution, Form of N Losses, and the Balance Between Vegetation and Soil-Microbial Processes. Ecosystems 2020; 24(3): 667–685. https://doi.org/10.1007/s10021-020-00542-3

Reis LK, Guerra A, Colado MLZ, Borges FLG, Oliveira MDR, Gondim EX et al. Which spatial arrangement of green manure is able to reduce herbivory and invasion of exotic grasses in native species?. Ecological Applications 2019; 29(8): e02000. https://doi.org/10.1002/eap.2000

Ribeiro SS, Oliveira FDA, Ferreira GC, Santos DE, Cruz DC. Forest restoration evaluation through indicators in areas of bauxite mining. Floresta e Ambiente 2019; 26(3): e20170812 https://doi.org/10.1590/2179-8087.081217

Rocha RS, Monteiro VF, de Abreu LCPC, Fernandes APD, dos Santos CRC. Effects of the planting of legume species and soil conditions on the recovery of a sand and pebble mining area. Land Degradation & Development 2021; 32(4): 1695-1705. https://doi.org/10.1002/ldr.3805

Saldanha ECM, Silva-Júnior ML, Alves JDN, Mariano DC, Okumura RS. Consórcio milho e feijão-de-porco adubado com NPK no nordeste do Pará. Global Science and Technology 2017; 10(1): 20 – 28.

Santana JEDS, Leles PSDS, Resende ASD, Machado AFL, Ribeiro JG, Gomes RF. Grasses Control Strategies in Setting Restoration Stand of the Atlantic Forest. Floresta e Ambiente 2020, 27(2): e20190066 https://doi.org/10.1590/2179-8087.006619

Santos HG, Jacomine PKT, Anjos LHC, Oliveira VA, Lumbreras JF, Coelho MR et al. (2018). Sistema brasileiro de classificação de solos. Brasília: Embrapa; 2018

Silva AR, Collier LS, Flores RA, Santos VM, Barbosa JM. Soil fertility in agroforestry system with introduction of green manure. American-Eurasian Journal of Agriculture & Environmental Sciences 2015; 15(1): 29-35. https://doi.org/10.5829/IDOSI.AEJAES.2015.15.1.12477

Silva KA, Martins SV, Miranda Neto A, Demolinari RDA, Lopes AT. Restauração florestal de uma mina de bauxita: avaliação do desenvolvimento das espécies arbóreas plantadas. Floresta e Ambiente 2016; 23(3): 309-319. https://doi.org/10.1590/2179-8087.142515

Silva MF, Fernandes MMH, Fernandes C, da Silva AMR, Ferraudo AS, Coelho AP. Contribution of tillage systems and crop succession to soil structuring. Soil and Tillage Research 2021; 209(5): e104924. https://doi.org/10.1016/j.still.2020.104924

Silva JP, Teixeira RDS, da Silva IR, Soares EM, Lima AM. Decomposition and nutrient release from legume and non-legume residues in a tropical soil. European Journal of Soil Science 2022; 73(1): e13151.

Sellan G, Thompson J, Majalap N, Robert R, Brearley FQ. Impact of soil nitrogen availability and pH on tropical heath forest organic matter decomposition and decomposer activity. Pedobiologia 2020; 80(3): e150645. https://doi.org/10.1016/j.pedobi.2020.150645

Sharma P, Laor Y, Raviv M, Medina S, Saadi I, Krasnovsky A et al. Green manure as part of organic management cycle: Effects on changes in organic matter characteristics across the soil profile. Geoderma 2017; 305(21): 197-207. https://doi.org/10.1016/j.geoderma.2017.06.003

Soares JAH, de Souza ALT, Pestana LFA, Tanaka MO. Combined effects of soil fertility and vegetation structure on early decomposition of organic matter in a tropical riparian zone. Ecological Engineering 2020; 152(12): e105899. https://doi.org/10.1016/j.ecoleng.2020.105899

Soares MB, Tavanti RFR, Rigotti AR, de Lima JP, Freddi OS, Petter FA. Use of cover crops in the southern Amazon region: What is the impact on soil physical quality?. Geoderma 2021; 384(4): 114796. https://doi.org/10.1016/j.geoderma.2020.114796

Souza DC, Engel VL, de Mattos EC. Direct seeding to restore tropical seasonal forests: effects of green manure and hydrogel amendment on tree species performances and weed infestation. Restoration Ecology 2021; 29(1): e13277. https://doi.org/10.1111/rec.13277

Stuble KL, Fick SE, Young TP. Every restoration is unique: testing year effects and site effects as drivers of initial restoration trajectories. Journal of Applied Ecology 2017; 54(4): 1051-1057. https://doi.org/10.1111/1365-2664.12861

Subaedah S, Aladin A, Nirwana. Fertilization of nitrogen, phosphor and application of green manure of Crotalaria juncea in increasing yield of maize in marginal dry land. Agriculture and Agricultural Science Procedia 2016; 9(1): 20-25. https://doi.org/10.1016/j.aaspro.2016.02.114

Vásquez-Castro DC, Rodrigues RR, Meli P, Brancalion PHS, Silva RR, Couto HTZ. Preliminary results of using green manure species as a cost-effective option for forest restoration. Scientia Forestalis 2020; 48(127): e3374 https://doi.org/10.18671/scifor.v48n127.21

USGS. Mineral commodity summaries 2022 - Bauxite and Alumina. United States: US Geological Survey; 2022.

Yao Z, Zhang D, Liu N, Yao P, Zhao N, Li Y et al. Dynamics and sequestration potential of soil organic carbon and total nitrogen stocks of leguminous green manure-based cropping systems on the Loess Plateau of China. Soil and Tillage Research 2019; 191(7): 108-116. https://doi.org/10.1016/j.still.2019.03.022

Yao Z, Xu Q, Chen Y, Liu N, Li Y, Zhang S et al. Leguminous green manure enhances the soil organic nitrogen pool of cropland via disproportionate increase of nitrogen in particulate organic matter fractions. Catena 2021; 207(12): e105574. https://doi.org/10.1016/j.catena.2021.105574

Xavier FADS, Oliveira JIA, Silva MRD. Decomposition and nutrient release dynamics of shoot phytomass of cover crops in the Recôncavo Baiano. Revista Brasileira de Ciência do Solo 2017; 41(1): e0160103. https://doi.org/10.1590/18069657rbcs20160103

Villa PM, Martins SV, Pilocelli A, Kruschewsky GC, Dias AA, Nabeta FH. Attributes of stand-age-dependent forest determine technosol fertility of Atlantic forest re-growing on mining tailings in Mariana, Brazil. Journal of Forestry Research 2022; 33(1): 103-116