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Sewage sludge as a pedotechnomaterial for the recovery of soils compacted by heavy machinery on *Eucalyptus* commercial plantation

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ABSTRACT

Commercial forestry activities featuring heavy machinery and intensive traffic represent one of the most common degradation processes in infertile Tropical soils. This research aimed to evaluate the potential of sewage sludge (SS) as pedotechnomaterial (PTM) for soil recovery in strongly degraded Entisols with a human-induced, highly compacted densic horizon (A_d). The area was used as a lumber deposit and for related forestry activities for more than ten consecutive years. Soil recovery activities consisted of: *i)* SS increasing dose applications (2.5, 5.0, 10.0, 15.0, and 20.0 Mg ha^{-1}) in the surface mineral horizon, *vs* a control; and, *ii)* pioneer (Pn), secondary (Sc), and climax (Cx) native species plantation. Pioneer, Sc, and Cx were characterized by an increasing H and D trend as time went by, with Pn (H and D) > Sc > Cx. After three years, the highest SS dose (20 Mg ha^{-1}) provided the best performance in most investigated species. Soil treated with the highest SS dose showed increased SOM, total P, CEC, exchangeable Ca, total Fe, Mn, Cu, and Zn contents after 36 months. No soil nutrient deficiency, potentially toxic elements (PTE) soil pollution, or related hazards were observed. The principal factor analysis showed that SS positively effects soil-plant feedbacks and related behavior. Canonical correspondence analysis explained how soil physical-chemical parameters influenced the whole plant ecological succession over time: *i)* during the early stage of development, Pn and Sc species were mainly affected by soil pH (SS buffering effect); *ii)* after one year, Ca, Mn, and CEC strongly influenced D development of mainly Sc species, thus further developing the whole soil-plant system; *iii)* at the end of the experiment, SOM and several soil macro- and micronutrients greatly influenced more demanding Cx species. For the first time, this research demonstrated the SS efficiency as PTM in strongly degraded Tropical soils; a PTM strongly favoring soil and forest restoration.

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1. Introduction

Land degradation is a long-term loss of on-site and off-site terrestrial ecosystem goods and services from which humans strongly depend (Bossio et al., 2010). Soil is a fundamental part of an ecosystem, ensuring most of its functions and services, such as: *i*) food and water security (Koch et al., 2013); *ii*) climate regulation (McBratney et al., 2014); *iii*) major contributors to a wide range of ecosystem services (Dominati et al., 2010). Despite this, most of the world's soil resources are in only fair, poor, or very poor condition (Montanarella et al., 2016). FAO and ITPS (2015) estimated 33% of global land area as degraded, with forested areas accounting for approximately 47% of the global total degraded land.

Actions against forest soil degradation involve preventing its definitive loss in currently used or useable lands and/or rehabilitating degraded soils (Buondonno et al., 2018). Increasing carbon stocks should be emphasized for infertile tropical soils (Montanarella et al., 2016) because these regions produce most of the forest and agricultural commodities worldwide (Nogueira et al., 2018). Consequently, reduced carbon stocks must be avoided to ensure and increase socio-economic benefits at a worldwide level.

Interventions that decrease the soil organic matter (SOM) content in surface horizons of forest tropical soils, such as their use as permanent/transitional, intensively managed timberlands with intensive traffic by heavy machinery, represent among the most common degradation processes in these infertile areas (Tassinari et al., 2019). A decrease in SOM content has a detrimental role in fertility because these soils have little potential to release nutrients for plants, being characterized by highly weathered, leached, and acidic conditions with a high sand content (Abreu-Junior et al., 2020).

Recovery procedures are usually slow, expensive, and related to a low soil recovery capacity, usually featuring these infertile soils (Lal, 2015). Thus, several techniques have been proposed and adopted to recover degraded soils, with most combining mechanical practices to break compacted layers (densic A_d horizons) with soil amendments (Tassinari et al., 2019).

The use of sewage sludge (SS) in soils, mainly for crops that are not destined to direct feeding or, even better, for reforestation purposes, stands out as a promising alternative for the recovery of degraded areas (Abreu-Junior et al., 2017). Sewage sludge fully satisfies the criteria to be a pedotechnomaterial (PTM), which is defined as any organic/inorganic material having at least the following properties (Buondonno et al., 2013): *i*) environmental safety and admissibility by current laws in land restoration activities; *ii*) pedogenic potential, i.e., susceptibility to undergo weathering/pedogenization, support pedogenic processes, and sustain vegetal growth; and, *iii*) compatibility with the pedoclimatic environment of the site to be restored. Recently, the Brazilian government approved a Resolution, for the full admission of SS reuse in agriculture and forestry.

As a PTM, SS can favor nutrient release and vegetation absorption by re-establishing biological activity and physical-chemical soil properties (Guerrini et al., 2017). Interest in SS as PTM is also because of its organic composition and macro- and micronutrients essential to plants. Besides, SS application would: *i*) utilize an organic byproduct beneficially by avoiding its landfill disposal (Abreu-Junior et al., 2019); *ii*) reduce the use of mineral fertilizers and related socio-environmental costs (Sampaio et al., 2016); *iii*) improve the growth of forest plantations and conserve energy and natural resources (Florentino et al., 2019).

While SS reuse has been evaluated from several perspectives (Abreu-Junior et al., 2019), studies on its reuse in pedotechnique are still missing. Additionally, among problems to be investigated, those about the recovery of areas used as lumber deposits and involved in heavy machinery traffic for commercial forestry represent a still unsolved issue. Such areas are usually affected by severe soil surface organic/mineral horizon loss/truncation and compaction issues.

Brazil represents a paradigmatic example since it is the worldwide market leader with 9 million hectares of commercially planted forests (mainly concentrated in the southern part); *Eucalyptus* alone occupies 6.97 million hectares of this total area (IBÁ, 2020). Such leadership was reached thanks to an advanced pulp and paper industry that increased its skills and knowledge due to enormous money investments to satisfy the increasing worldwide demand for roundwood products. As planted forest surfaces increased, areas affected by degradation issues increased accordingly.

This study aimed to evaluate the potential of SS as PTM for the recovery of soil fertility in strongly degraded tropical Entisols. For more than ten consecutive years, the investigated soils were used as lumber deposits, thus involved in heavy machinery traffic for commercial *Eucalyptus* plantation activities. Consequently, they have been affected by: *i*) partial truncation and loss of both surface organic O and mineral A_p horizons now compacted into a densic one (A_d); *ii*) severe compaction issues to 50 cm soil depth. The area was recovered by using a pedotechnical protocol (Buondonno et al., 2018), i.e., by planting several native species (with different ecological function) and by applying increasing doses of SS (2.5, 5.0, 10.0, 15.0, and 20.0 Mg ha^{-1}) in comparison to a control. The experiment lasted three years by investigating both plant parameters and several soil physical-chemical properties at established times.

2. Material and methods

2.1. Study area

This study was carried out in Itatinga Municipality, São Paulo State, Brazil, in the experimental field at Suzano Bahia Sul Papel e Celulose Company (23° 18′ S and 48° 30' W; 636 m asl) (Fig. 1). Mean annual rainfall was 1635 mm and mean annual air temperature was 19.4 °C. According to the Köppen climate, the area can be classified as Cwa (mesothermal humid climate).

The area had been a lumber deposit for twelve years. This resulted in deep soil degradation, particularly the total or partial loss of both O and Ap surface horizons with their remnant part being characterized by a high degree of compaction. Consequently, these soils were not suitable for either productive (agriculture and forestry) or natural/conservation purposes due to the presence of a human-induced densic (A_d) compacted horizon.

2.2. Soil and sewage sludge characterization

Before the experiment started, a full pedological investigation was made according to the international method (Schoeneberger et al., 2012). The soil was classified as sandy, mixed, semiactive, Typic Quartzipsamment (family level; Soil Survey Staff, 2014) and was characterized by the following physical-chemical features: pH-$CaCl_2$ 4.4; a sand content of 90%, silt 1%, and clay 9%, thus being sandy in texture; soil organic matter (SOM) of 9 g kg^{-1}; total P of 4.3 mg kg^{-1}; cation-exchange capacity (CEC) of 28.3 mmol$_c$ kg^{-1}; H + Al of 23.0 mmol$_c$ kg^{-1}; K^+, Ca^{2+}, and Mg^{2+} of 0.4, 4.0, and 1.0 mmol$_c$ kg^{-1}, respectively; base saturation (BS) of 18%; potentially toxic elements (PTE) concentrations of 1.6 mg kg^{-1} for B, 4.6 mg kg^{-1} for Cu, 27.6 mg kg^{-1} for Fe, 0.6 mg kg^{-1} for Mn, and 0.1 mg kg^{-1} for Zn.

Sewage sludge came from the wastewater treatment plant of Jundiaí Municipality (São Paulo State). It uses a process consisting of a complete mix of aerated lagoons, followed by decantation for hygienization purposes. The main chemical features and PTE content are presented in Supplementary Material 1. In Brazil, SS agricultural/forestry reuse is regulated by the National Council of the Environment (Conselho Nacional do Meio Ambiente-CONAMA; CONAMA, 2020). In particular, the Brazilian government recently clarified that composted sewage sludge (CSS) can be assimilated to organic amendments/fertilizers without further restriction. Additionally, all observed parameters in applied SS are within ranges suggested by CONAMA for its safe use in agriculture.

2.3. Experimental design

The experiment started between the beginning of autumn (March) and middle of the winter season (August). The area was cleaned entirely by firstly removing the invasive species *Brachiaria decumbens* Stapf, and then a ripper was used to till to 50 cm soil depth and reduce soil compaction (Supplementary Material 2a).

The recovered area (*vide supra*) was then treated with five different SS increasing doses compared to a control, for a whole of 6 different treatments. In particular, SS doses were 2.5, 5.0, 10.0, 15.0, and 20.0 Mg ha^{-1}. Due to the low K content in the SS, KCl was applied (26 kg ha^{-1} as K_2O). Sewage sludge was mechanically distributed and incorporated along the planting line (Supplementary Material 2b).

In all the experimental areas a mixture of Brazilian autochthonous species was planted to recover the whole environment from an ecological point of view. They were selected based on their ecological function and following the natural ecological succession in the investigated environment. In particular, pioneers, secondary, and climax species were selected. For pioneers, Euphorbiaceae (*Croton floribundus* Spreng.) and Anacardiaceae (*Schinus terebinthifolius* Raddi) were planted to improve general physical-chemical pedosystem conditions, such as increasing SOM content, porosity, etc. while establishing more favorable conditions for higher demanding species that are characterized by a deeper and more complex root system. Secondary species, such as Fabaceae (*Anadenanthera colubrina* var. *cebil* (Griseb.) Altschul, *Peltophorum dubium* (Spreng.) Taub.), Meliaceae (*Cedrella fissilis* Vell.), and Malvaceae (*Guazuma ulmifolia* Lam.) were planted to further increase both SOM stock (Tapia-Coral et al., 2005) as well as macro (N, P, K) and micro (Ca) soil nutrients (Siddique et al., 2008). Additionally, such species are prone to recover infertile soils by fixing large amounts of atmospheric N and C through bacterial symbiosis (Joslin et al., 2011). Climaxes species, such as Fabaceae (*Copaifera langsdorffii* Desf., *Hymenaea courbaril* L.) and Lecythidaceae (*Cariniana estrellensis* (Raddi) Kuntze), were selected because they represent the final stage of ecological succession after full soil and environmental recovery. All of the species have already demonstrated their ability to promote both a significant and consistent increase in SOM, macro- and micronutrient stocks, thus being considered a tool to promote the recovery of degraded lands (Siqueira et al., 2020). All species were planted (Supplementary Material 2c, d) at their seedling stage.

Each of the six treatments consisted of square areas of 4 × 4 m in width and length (16 m^2 in terms of area) with four replications. Overall, 24 plots were investigated for a total area of 384 m^2. The experiment was conducted according to a completely randomized block design.

2.4. Soil and plant analysis

Soil samples were collected and analyzed 6, 12, 18, and 36 months after SS application. Samples from each plot were taken from the surface A_p horizon (0–0.20 m) over the line where SS/fertilizers were applied in 15 different randomized points to form a single composite sample.

Physical-chemical analyses were conducted on soil air-dried Ø < 2 mm, following the Brazilian official procedures (Raij et al., 2001). Soil pH-$CaCl_2$ and potential acidity (H + Al) were measured potentiometrically with a glass electrode in a soil/solution mixture of 1:2.5 1 N $CaCl_2$. SOM content was estimated by the Walkley-Black method. Total P through the NH_4Cl and HCl acid digestion method. CEC was determined via saturation with $BaCl_2$ at pH 8.2. Potassium, Ca, and Mg content by atomic absorption spectroscopy (AAS). Iron, B, Mn, Cu, and Zn concentrations by the DTPA method.

Plant height (H) and diameter (D) measurements were taken 6, 12, 18, and 36 months after SS application. In particular, plant H was measured from the stem's base to the apical bud, and the stem D was measured with a precision caliper.

2.5. Statistical analysis

Univariate and multivariate statistics were carried out using the software program R (RStudio, 2021).

Data were compared using ANOVA. Significant differences between mean values were determined using Tukey's post-hoc honest significant difference test with $p < 0.05$. Polynomial regression analysis was

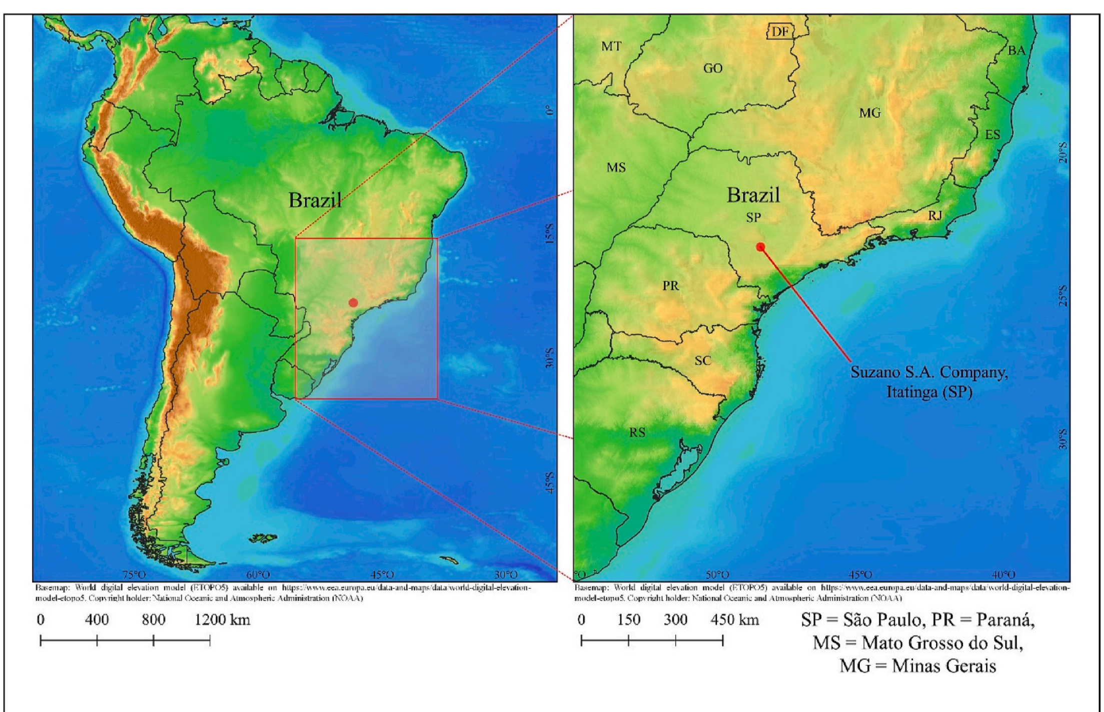


Fig. 1. Study area.

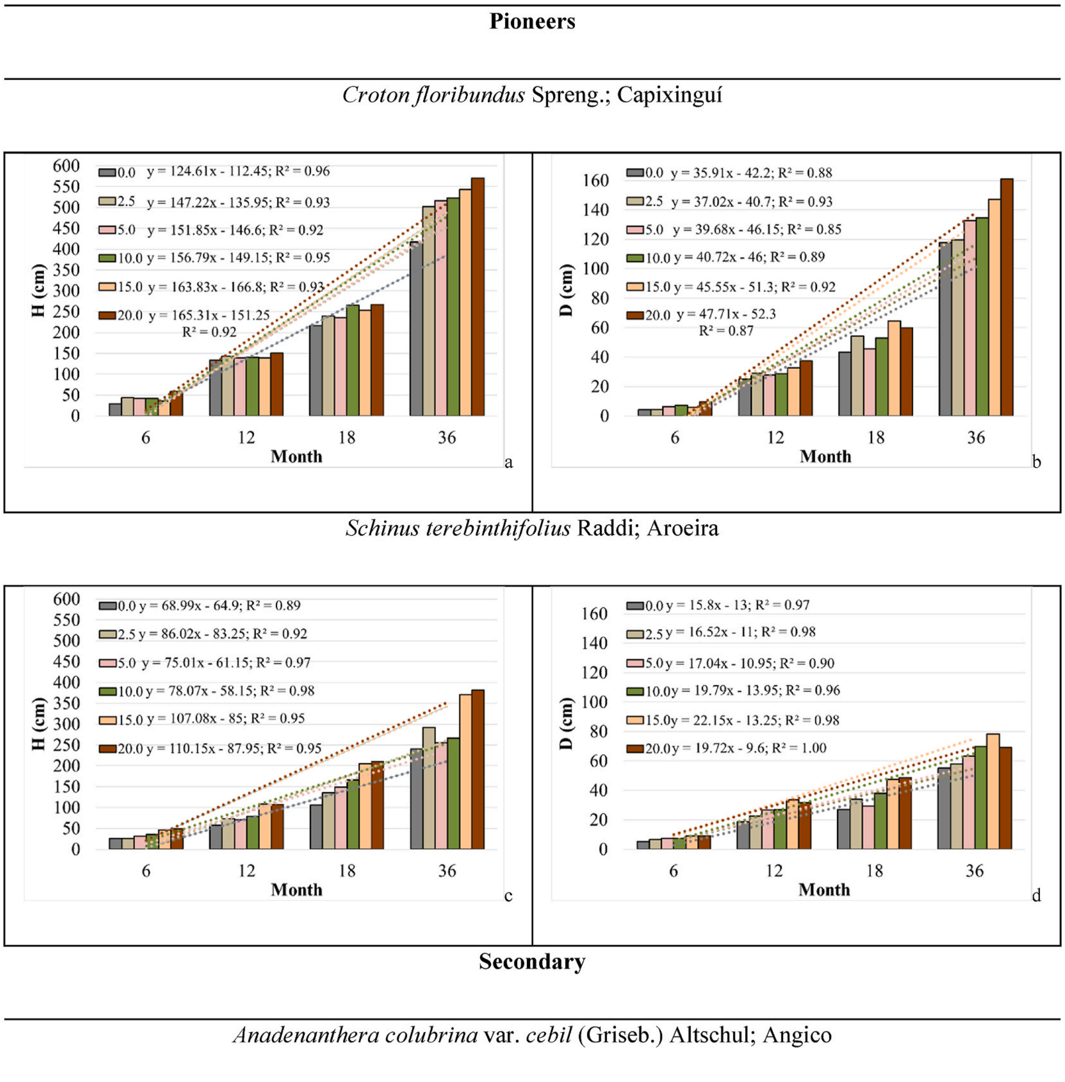


Fig. 2. Plant height (H) and diameter (D) along the whole investigated period and according to increasing SS doses for the whole investigated plant species (pioneers, secondary, and climax).

performed to study the responses to different SS doses for each period of sampling.

Before carrying out the CM and FA, the procedure proposed by Capra et al. (2014) was applied. In particular: *i*) dataset was tested to understand whether or not investigated variables have a normal distribution; *ii*) the raw data sets were Box–Cox transformed to approach normality; *iii*) a CM was performed on the Box–Cox transformed data; and, *iv*) FA was carried out based on the CM. Factor analysis (FA) was then used to explain the variation in a multivariate dataset with as few factors as possible. For facilitation of the interpretation of results, varimax rotation was used. Canonical correspondence analysis (CCA) was applied, as it represents one of the most reliable statistical tools for comparing different sets of variables (Capra et al., 2016). In the CCA, two main data matrices were used. The first (M1) was organized with rows containing the different treatments (six) along with the four investigated periods (for a total of 24 rows) and columns representing the soil's physical-chemical parameters and plant measurements. The second matrix (M2) contained the same rows, but the columns were associated with soil physical-chemical parameters and plant development data.

When reported, values indicate the mean ± standard error of the mean.

3. Results and discussion

3.1. Plant measurements

Fig. 2 shows both plant height (H) and diameter (D) along with the whole investigated period (6, 12, 18, and 36 months) and according to increasing SS doses (0.0, 2.5, 5.0, 10.0, 15.0, and 20.0 Mg ha^{-1}), for the whole investigated plant species (*vide supra*). They are shown following their role within the ecological successional groups, i.e., pioneers (Pn), secondaries (Sc), and climaxes (Cx) species.

Overall, all Pn, Sc, and Cx species showed an increasing trend of both H and D as time went by. In particular, Pn (Fig. 2a–d) showed more significant increases, followed by Sc (Fig. 2e-l) and Cx (Fig. 2m–r), respectively. This was expected since pioneer species play a pivotal ecological role in early soil colonization within ecological succession. Fast-growing species provide both soil protection while improving microclimatic conditions, thus enhancing soil conditions for the positive establishment of Sc and Cx species (Guerrini et al., 2017). Indeed, they can grow in poor soil conditions, providing substantial amounts of both SOM and macronutrients. Conversely, Cx species had the lower H and D increases since they are well-known as slow-growing species (Guerrini

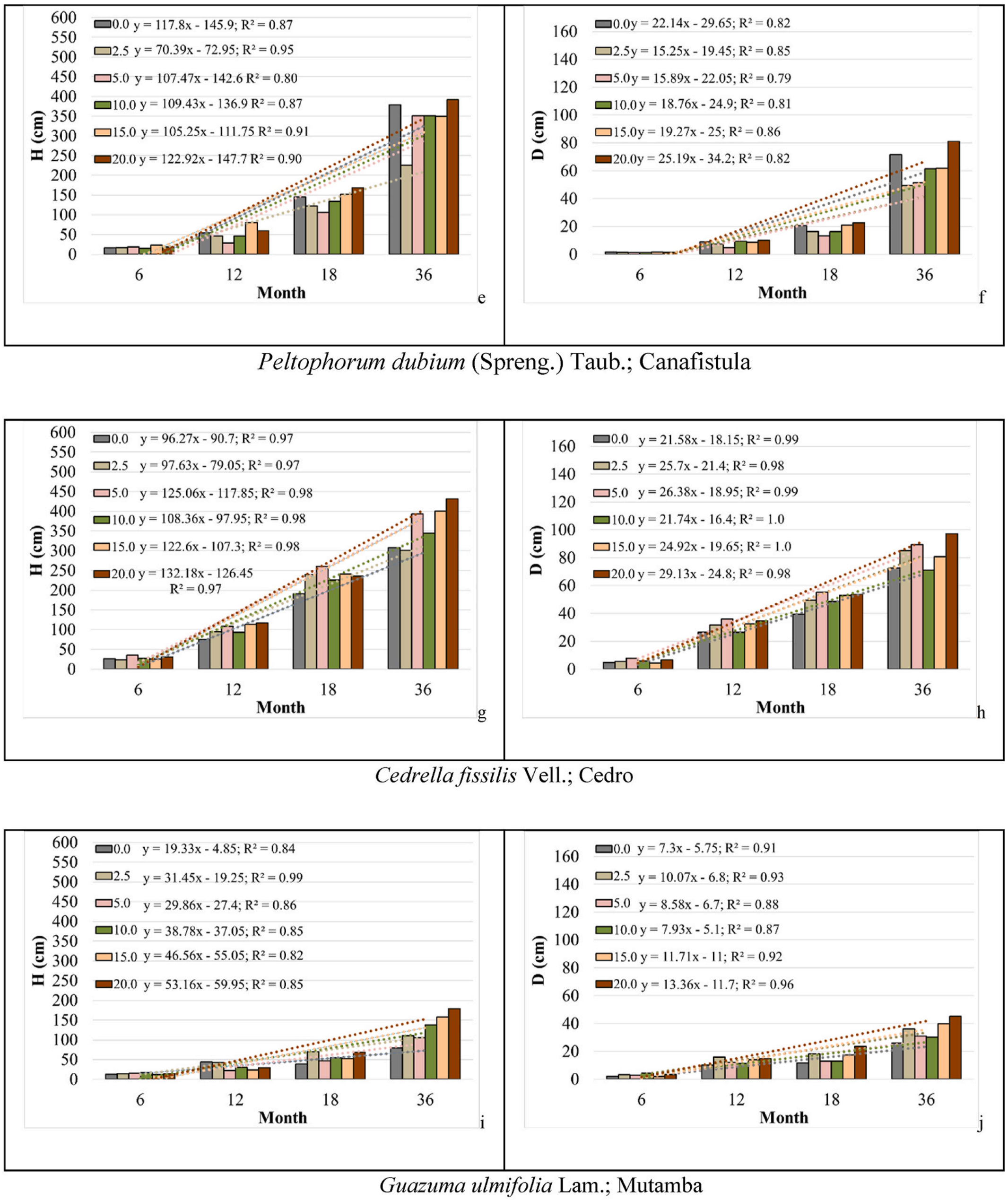


Fig. 2. (*continued*).

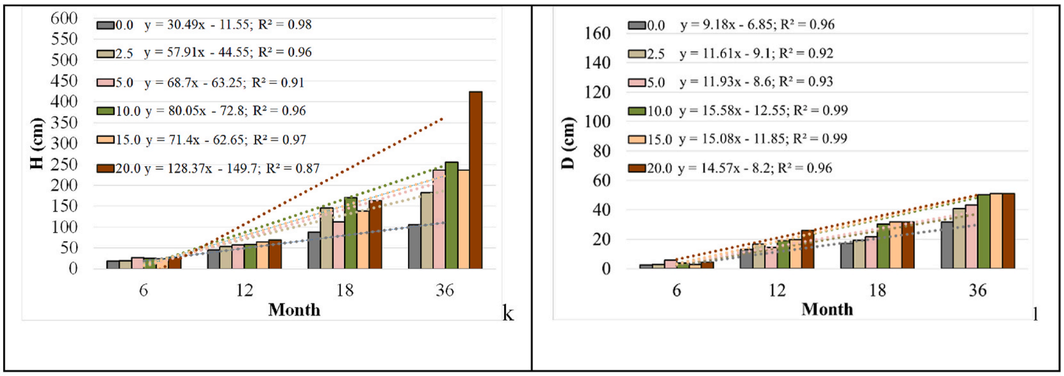
et al., 2017).

In terms of differences among investigated doses, the highest one (20 Mg ha^{-1}) provided the best performance in most investigated species; however, this was particularly true during the last period, i.e., after 36 months. This showed that SS efficiency in increasing H and D plant species is a strongly time-dependent factor; linear equations confirmed this, showing a high R^2 ranging from 0.71 to 1.00. This was observed in previous studies too. Florentino et al. (2019) argued that as time went by, SS amended/rehabilitated soils showed enhanced edaphic physical-chemical conditions due to SOM stabilization and related positive effects such as improved porosity, decreased bulk density, and increased macro- and micronutrients availability.

3.2. Soil features

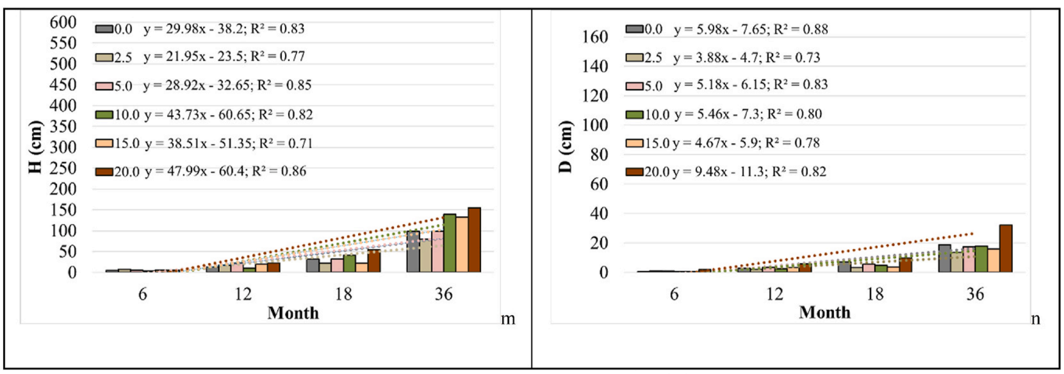
All investigated parameters will be discussed in terms of observed: *i*) ranges and mean values, compared with interpretation limits, for soil physical-chemical parameters and nutrients, most used for Tropical soils (Raij et al., 1997); *ii*) temporal trends and behavior according to SS applied doses. For potentially toxic elements (PTE), only a comparison with threshold values ruled by Brazilian laws, or reported in the literature, is presented.

The pH-$CaCl_2$ (Fig. 3a) ranged from extremely high (3.8) to high (4.6) acidic values, with a mean of 4.1 ± 0.0 (extremely high); all common values for tropical weathered soils (Nogueira et al., 2018). In terms of temporal trends, pH-$CaCl_2$ showed a significant decrease ($p < 0.05$) after 36 months only. Indeed, among 6, 12, and 18 months there were no significant differences in pH. Additionally, SS does not significantly influence soil pH. This could be related to the fact that while investigated degraded soils showed a strongly acidic pH, applied SS was characterized by a pH near moderate values (5.0). Additionally, applied SS were not treated with pH-corrective amendments. In previous

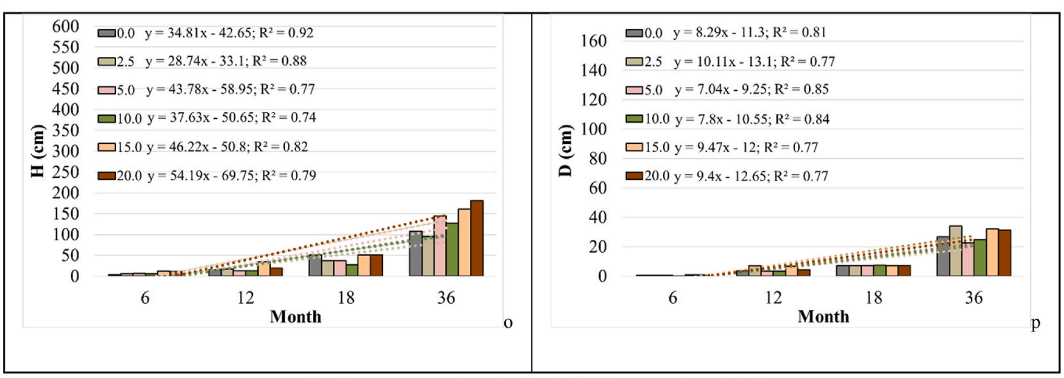


Climax

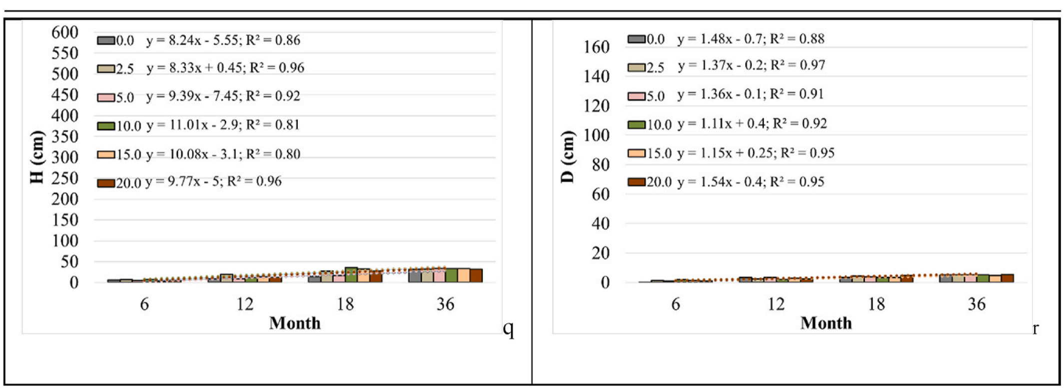
Copaifera langsdorffii Desf.; Copaiba



Hymenaea courbaril L.; Jatobá



Cariniana estrellensis (Raddi) Kuntze; Jequitibá



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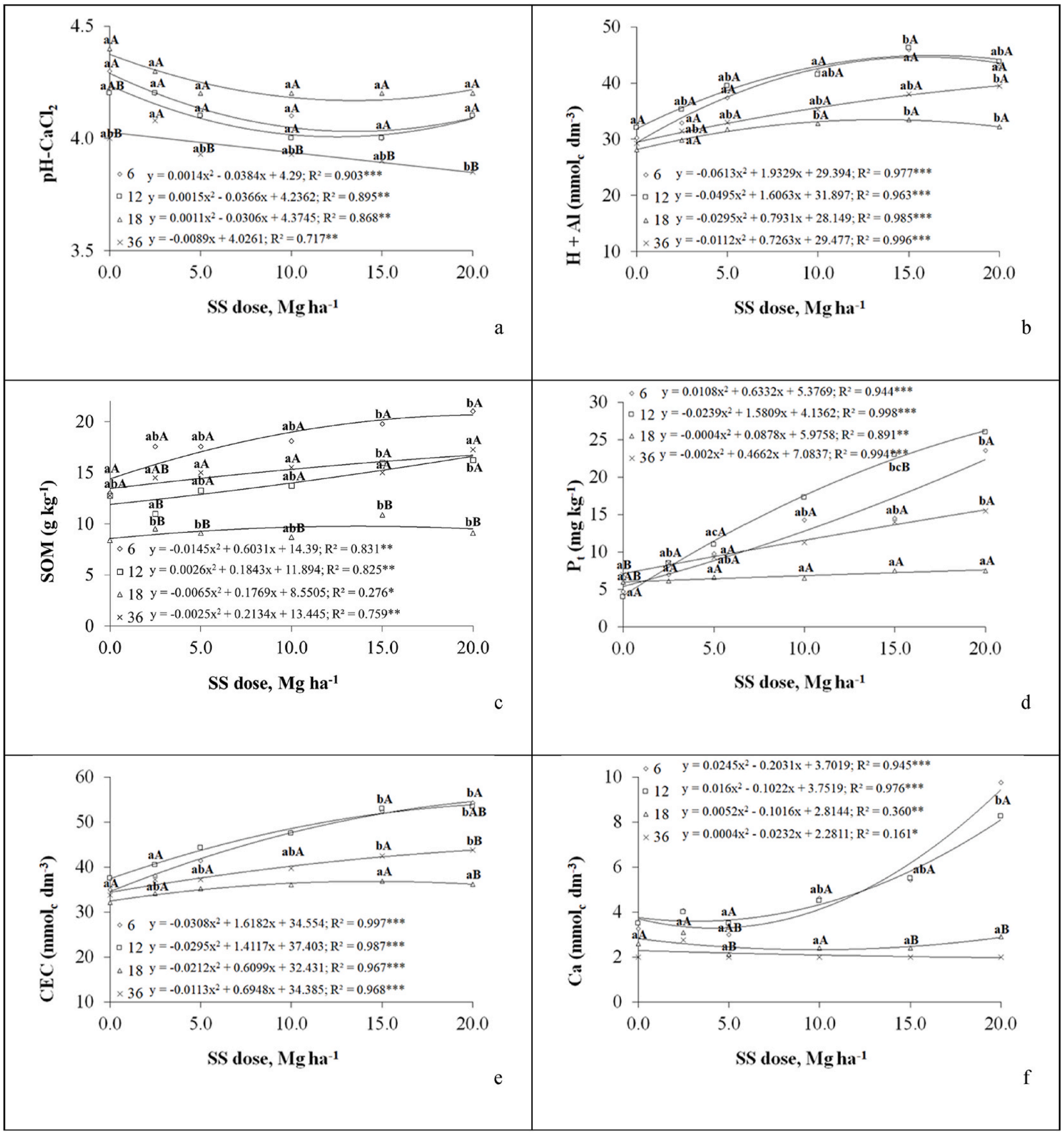

Fig. 3. Soil physical-chemical parameters along the whole investigated period and according to increasing SS doses. Different lowercase letters showed significant differences ($p < 0.05$) among SS doses along the same investigated month, while different capital letters are for significant differences ($p < 0.05$) for the same SS dose over time. $p <$ *0.05, **0.01, ***0.001.

studies, a decrease in soil pH *vs* increased SS applied doses were observed (Abreu-Junior et al., 2019; Guerrini et al., 2017), which was related to entirely different conditions in pH values of both treated soils and applied SS. In particular, SS often showed a pH lower than those observed in treated soils. In such conditions, an increase in SS applied soils is expected to reduce pH due to the presence of organic acids produced during the SOM microbiological decomposition and the nitrification reactions of ammonium nitrate already present in the sludge or produced by organic N mineralization (Bezerra et al., 2006). As expected, potential acidity (Fig. 3b) showed an opposite trend with increasing SS dose compared to soil pH, i.e., an inverse correlation. This confirms that SS applied doses do not influence soil acidity, while leaching processes are the main responsible for timely decreasing pH and, consequently, indirectly increasing acidic cations.

SOM ranged from 10.0 to 24.8 g kg^{-1}, with a mean of 15.6 ± 0.4 g kg^{-1}; these values agree with those expected for sandy soils. In terms of investigated periods, SOM (Fig. 3c) was significantly lower at the 18-month measurement compared to both earlier (6, 12 month) and later (36 month) measurements. In terms of SS increasing doses, no significant differences were observed among most of the investigated treatments. However, there is a clear trend towards an increase (R^2 ranging 0.759–0.831; $p < 0.01$) in SOM content at increasing SS doses, except for the 18th month. This is related to the fact that the 18th month corresponded to the summer period (February), when higher temperatures were recorded (data not reported), thus favoring SOM mineralization; conversely, during the 12th and 36th month, SOM either did not change or significantly increased since this period corresponded to the winter (August), where SOM humification processes prevail. Overall, soil treated with the highest sludge dose *vs* the control showed a significant SOM increase of 62% (6th month), 28% (12th month), 8% (18th month), and 35% (36th month).

Total P ranged from 3 to 34 mg kg^{-1} with a mean of 12.7 ± 0.9 mg kg^{-1}; most of the observed values are thus considered high (9–16 mg kg^{-1}) to extremely high (>16 mg kg^{-1}) for soils under forest cover (Raij et al., 1997). The Pt concentration (Fig. 3d) significantly increased in soils treated with 15.0 Mg ha^{-1} and in control during the 12 and 36th months, respectively. Conversely, its concentration significantly increased with increasing SS doses, except the 18th month. Other authors already observed such an increase in Pt concentration towards SS increasing doses (Florentino et al., 2019). This can be explained by the

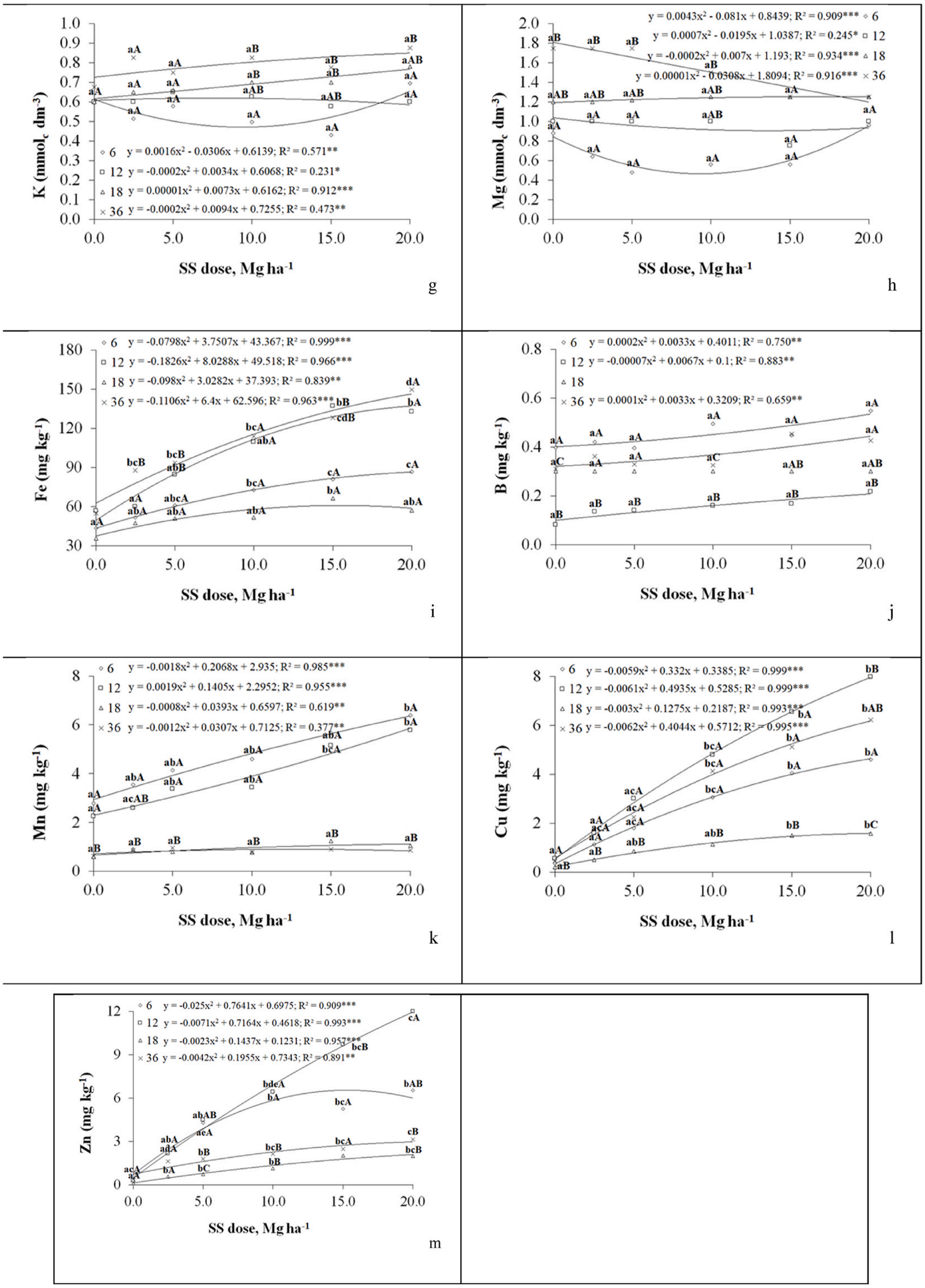

Fig. 3. (*continued*).

high amount in P content characterizing sewage sludge.

Cation-exchange capacity ranged between 30.0 and 68.7 mmol$_c$ dm^{-3}, with a mean of 43.3 ± 1.0 mmol$_c$ dm^{-3}, meaning a high CEC although a sandy weathered soil but in agreement with observed high SOM contents (*vide supra*). CEC (Fig. 3e) contents significantly increased starting from the 18th month through the end of the experiment (36th month), when the highest dose was applied (20.0 Mg ha^{-1}). From the SS dose viewpoint, an increase in CEC values at increasing SS doses was observed, except in the 18th month. As previously discussed, Pt's and CEC's tendency to decrease during the 18th month (summer season) seems as strongly related to climatic condition encouraging SOM degradation; this obviously brings consequences in terms of Pt and CEC soil contents too.

Exchangeable Ca, K, and Mg ranged between 2 and 15.2, 0.2–1.0, 0.0–2.0 with a mean of 4.0 ± 0.0, 0.6 ± 0.0, 1.1 ± 0.1, respectively, which correspond with medium (Ca), extremely low (K), and low values (Mg). Exchangeable cations (Ca^{2+}, K^+, Mg^{2+}; Fig. 3f–h) showed different behaviors when compared to each other. Calcium (Fig. 3f) showed higher concentrations during the first year (6–12 months) at the higher doses (15 and 20 Mg ha^{-1}); it showed significantly higher

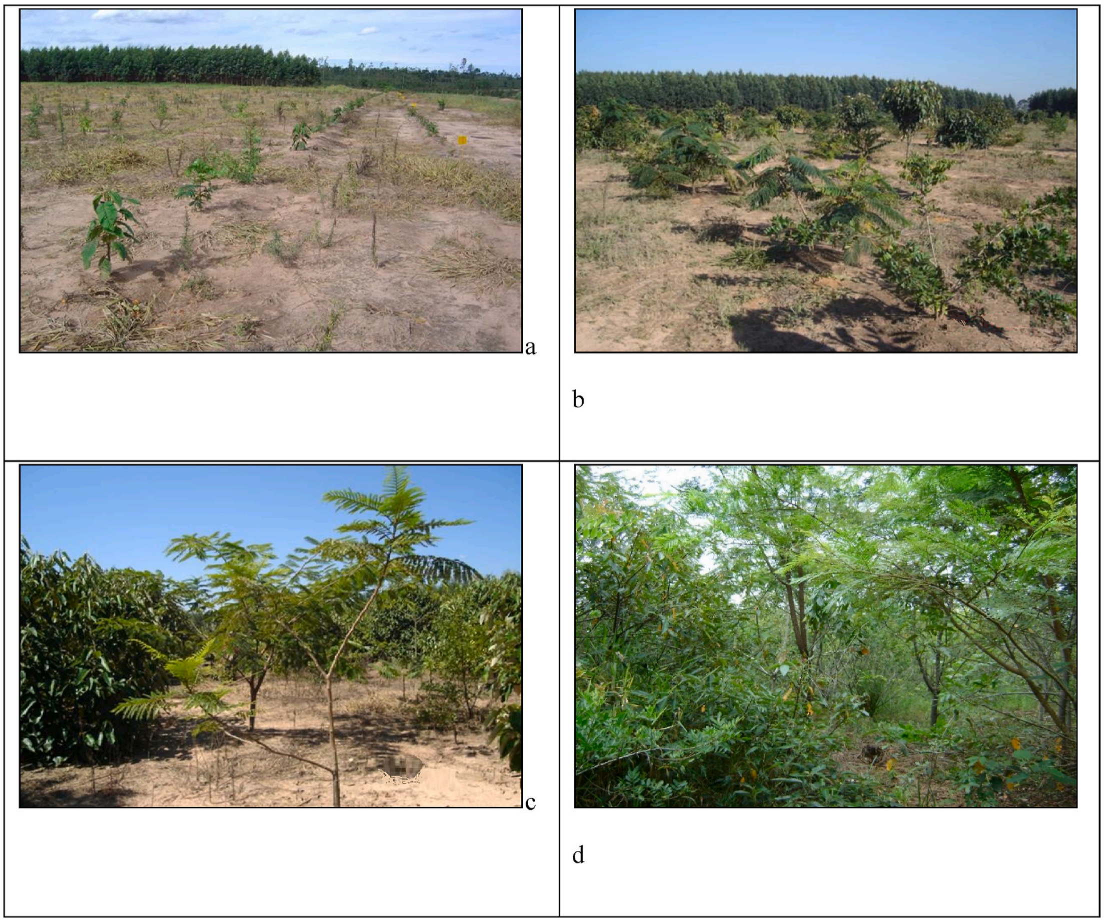

Fig. 4. Ecological succession along the investigated period (a: 6 months after SS application; b: 12 months; c: 18 months; d: 36 months) in soils treated with the highest SS doses (20 Mg ha^{-1}).

concentrations only at the highest SS dose (20 Mg ha^{-1}). Potassium (Fig. 3g) significantly increased from the 12th/18th to 36th month for all SS doses >10 Mg ha^{-1}; it did not show a significant increase at increasing SS doses. Magnesium (Fig. 3h) showed higher concentrations during the final investigated periods (18 and 36 months) for all lower SS doses (<10 Mg ha^{-1}); also, in this case, it did not show any increase with to SS dose. Previous studies have observed similar strong variability in exchangeable-cation behavior and concentration in SS-treated soils (Guerrini et al., 2017; Abreu-Junior et al., 2019; Prates et al., 2020). Explanations for this behavior include: *i*) competitive adsorption processes among cations towards soil organic and mineral colloidal fractions; *ii*) soil leaching processes; *iii*) kinetic aspects as a consequence of both (*i*) and (*ii*) (Guerrini et al., 2017).

Potentially toxic elements (PTE) showed different trends as expected by their different pedogeochemical behaviors and cycles. Iron ranged between 37.2 and 180.0 mg kg^{-1} with a mean of 81.4 ± 0.0 mg kg^{-1}, thus always reaching high Fe concentrations as usual in tropical strongly weathered soils (Nogueira et al., 2018). The highest iron concentrations were observed at the end of the experiment (36 months), with a clear tendency to increase with larger SS doses (Fig. 3i). Boron ranged between 0.0 and 0.7 mg kg^{-1} with a mean of 0.3 ± 0.0 mg kg^{-1}, meaning a medium B concentration in investigated soils. It showed a tendency towards an increase during the 12th month, without being influenced by SS increasing doses (Fig. 3j). Manganese ranged between 0.4 and 9.5 mg kg^{-1}, averaging 3.0 ± 0.2 mg kg^{-1}, thus reaching medium values. Soil Mn concentrations were significantly higher at 6 and 12 months since application compared to 18 and 36 months across all SS doses including control, and also trended higher with increasing SS dose during the early months (Fig. 3k). Copper ranged between 0.3 and 9.4 mg kg^{-1}, with a mean of 3.3 ± 0.3 mg kg^{-1}, thus reaching high values. It showed statistically lower values during the 18th month (similar to SOM, Pt, and CEC) and trended higher at increasing SS doses (Fig. 3l). Zinc ranged between 0.1 and 16.3 mg kg^{-1}, averaging 4.0 ± 0.4 mg kg^{-1}, thus reaching high contents. Zinc does not show a clear tendency during all the investigated periods, while it increased at increasing SS applied doses except for treatments at the 18th month (Fig. 3m).

Copper and Zn were also compared to quality reference values (QRV) ruled by CONAMA (2009) for soil pollutants, which indicate the concentration in natural background soils. QRV established for Cu (35 mg kg^{-1}) and Zn (60 mg kg^{-1}) are significantly greater than those detected

Table 1
Factor loadings of a factor analysis for investigated plant and soil parameters; extraction method: principal factor analysis (PFA); rotation method: varimax; bold loadings >0.6.
Green part = plant parameters (PN_ = pioneer species, SC_ = secondary species, CX_ = climax species, TS_ = total species (the mean among PN, SC, and CX), _H = height, _D = diameter); Light brown = soil physical-chemical parameters.

	F1	F2	F3
PN_H	**0.994**	0.050	0.043
PN_D	**0.995**	0.005	0.024
SC_H	**0.984**	0.082	0.069
SC_D	**0.996**	0.038	-0.026
CX_H	**0.978**	-0.004	0.157
CX_D	**0.973**	-0.005	0.120
TP_H	**0.992**	0.059	0.072
TP_D	**0.997**	0.019	0.012
pH	-0.578	**0.629**	-0.264
SOM	-0.141	**-0.704**	**0.622**
Pt	-0.044	**-0.969**	-0.017
CEC	-0.267	**-0.945**	0.075
Ca	-0.548	**-0.682**	-0.019
K	**0.870**	0.064	-0.029
Mg	**0.788**	0.305	-0.238
Fe	0.478	**-0.845**	-0.018
B	0.136	0.077	**0.929**
Mn	**-0.687**	**-0.698**	0.138
Cu	0.180	**-0.959**	-0.021
Zn	-0.283	**-0.917**	-0.117
Variance (%)	55	30	7
Cumulative variance (%)	55	85	92
Eigenvalues	11.002	6.100	1.372

Green part = plant parameters (PN_ = pioneer species, SC_ = secondary species, CX_ = climax species, TS_ = total species (the mean among PN, SC, and CX), _H = height, _D = diameter); Light brown = soil physical-chemical parameters.

in all the investigated treatments, meaning that these PTE concentrations were well below legal limits. Iron, B, and Mn are not ruled by law; however, observed concentrations were always within ranges reported for natural soils (Mn 7–100 mg kg^{-1}; B 42 mg kg^{-1}; Fe 1000–1500 mg kg^{-1}; Kabata-Pendias and Mukherjee, 2010). Overall, this clearly demonstrated that none of the investigated treatments created soil pollution issues or increased human health or ecological hazards by applying SS as a pedotechnomaterial.

In summary, results on plant and soils showed that: *i)* all investigated plants increased their H and D as time went by, thus showing a strongly time-dependent factor in agreement with their ecological role (Fig. 4a–d), i.e., Pn (H and D) > Sc > Cx; *ii)* higher H and D plants were mainly observed at the highest SS applied dose (20 Mg ha^{-1}) (Fig. 4a–d); *iii)* SS increased SOM, total P, CEC, exchangeable Ca, total Fe, Mn, Cu, and Zn at the highest SS applied dose (20 Mg ha^{-1}); *iv)* from a soil nutritional perspective, all investigated nutrients were within the optimal range expected for tropical forest soils and thus soil nutrient deficiencies were avoided, particularly for those treated with higher SS doses: *v)* PTE, even in soil treated with the highest SS doses, did not exceed QRV or values observed in natural soils worldwide, thus showing that SS was not responsible for soil pollution and related soil hazards.

3.3. Multivariate statistics

3.3.1. Principal factor analysis (PFA)

The PFA, after matrix rotation, extracted three main factors (Table 1). All of these were >1, therefore, they can be significantly grouped into a three-component model accounting for 92% of all explained data variation.

F1 (total variance 55%) extracted all plant parameters (H and D) of all ecological successional groups (pioneer, secondary, and climax), K, and Mg as all positively correlated; conversely, they were all inversely related to Mn. This factor showed that plant H and D increased in accordance with some pivotal soil macronutrients, specifically K and Mg. The negative correlation with Mn content was related to competitive aspects of kinetic soil nutrient uptake processes in plant roots, rather than an inverse correlation towards plant H and D (Florentino et al., 2019). For all these reasons, factor F1 underlined the pivotal role of soil K and Mg in plant development. F2 (30%) showed SOM, total P, CEC, Ca, and all micronutrients (B excluded) as positively concordant while negatively correlated with pH. Such a factor showed that at increasing SOM content (related to an increase in applied SS doses): *i)* total P increased since SOM represented its main source into the soil environment (Capra et al., 2014); *ii)* CEC increased as a consequence of increased colloidal fractions, thus increasing exchangeable Ca and positively charged micronutrients (Fe, Mn, Cu, and Zn); *iii)* at increasing SOM content there was a concomitant increase in H^+ release in soil solution as a consequence of SOM degradation processes, thereby decreasing pH values (Prates et al., 2020). Factor F2 can thus be interpreted as the key role of SOM in soil micronutrient and pH behavior. F3 explained only 7% of the total variance and was thus a less critical factor. It showed that SOM was directly correlated with B, being its main source in the soil environment; this relationship has been observed in other soils treated with SS (Guerrini et al., 2017).

Overall, PFA showed that the soil-plant system is strongly influenced by macronutrients (K and Mg), with SOM playing a pivotal role in their (and pH) behavior. Since SS was the primary source of SOM in the investigated system, it must be underlined that SS positively affects soil-plant feedbacks and related behavior.

3.3.2. Canonical correspondence analysis (CCA)

CCA showed a clear distribution pattern in terms of the investigated period (Fig. 5). In particular: *i)* measurements from the 6th (brown color) and 18th (green) months are mainly in II sector; *ii)* 12th (orange) month in I, while; *iii)* 36th (light red) month in III sector. As a matter of fact, the earliest investigated period (6th month) showed a completely opposite direction when compared with the last one (36th month); the 6 month period was more significantly influenced by soil pH, while the last period was influenced by SOM and both soil macro (K and Mg) and micronutrients (Cu and Fe). Such an outcome demonstrated that during the early stage of soil-plant feedback and species development, soil pH exerts a more significant influence, while as time went by, the other parameters (*vide supra*) increased their influence on both H and D plant development. This is also confirmed by the fact that D (one red triangle) and H (two red triangles) of pioneer species follow the pH direction on CCA, meaning that such soil parameters mainly influence them. A result that was also partially true for D of secondary species (one red asterisk) that appears also affected by basic exchangeable cations (Ca) and soil micronutrients (Mn).

Summarizing, CCA showed how soil physical-chemical parameters influenced plant ecological succession over time. Indeed: *i)* during the early stage of development (after 6 months), pioneer (mainly) and secondary species were affected by soil pH, with particular reference to the buffering effect exercised by SS addition, which created better conditions for plant growth in a strongly weathered, acidic soil; *ii)* at the end of the first year the soil-plant system further developed, with exchangeable cations (Ca) and micronutrients (Mn) together with CEC strongly influencing D development of mainly secondary species; *iii)* finally, at the end of the experiment, SOM and several soil macro and micronutrients greatly influenced both the D (one red hashtag) and H (two red hashtags) of more demanding climax species.

Overall, all previously reported outcomes, showed that the present research demonstrated, for the first time, that multiple positive effects can be achieved in sewage sludge reuse as pedotechnomaterial for the recovery of Entisols degraded by heavy-machinery traffic used in lumber deposits and the related forestry activities. Such positive effects were observed on the plant, soil, and whole soil-plant system feedback, thus favoring the progressive development of ecological succession on the site. A practical implication and an essential future perspective are that SS, used as PTM, can recover degraded soils and increase tree growth by

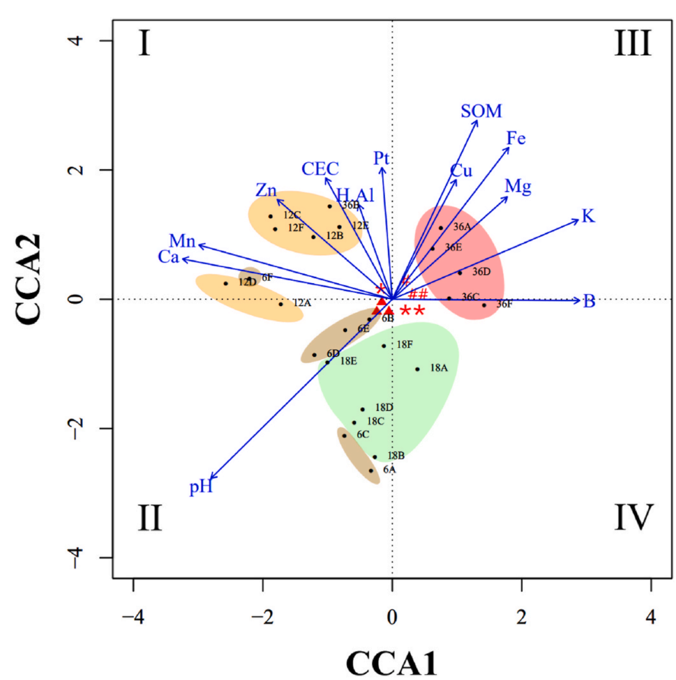

Fig. 5. Principal-component plots of canonical correspondence analyses (CCA). Red symbols: ▲ = Pn diameter, ▲▲ = Pn height; * = Sc diameter, ** = Sc height; # = Cx diameter, ## = Cx height. Blue arrows: soil physical-chemical parameters. Number + black letters: month (6, 12, 18, and 36) + SS dose (A: control; B: 2.5 Mg ha^{-1}; C: 5.0 Mg ha^{-1}; D: 10 Mg ha^{-1}; E: 15 Mg ha^{-1}; F: 20 Mg ha^{-1}).

rapidly closing the canopy in forest restoration programs.

4. Conclusions

All planted native species showed, with particular reference to the highest sewage sludge doses (20 Mg ha^{-1}), a significant time-dependent increasing trend of both height and diameter. By applying increasing SS doses into the investigated degraded Entisols: *i*) SOM, total P, CEC, exchangeable Ca, total Fe, Mn, Cu, and Zn significantly increased; *ii*) all nutrients were within the optimal range for tropical soils, thus avoiding soil nutrient deficiency; *iii*) PTE never exceeded quality reference values ruled by law or values featuring natural soils, and; *iv*) SS did not represent a hazard from a soil pollution viewpoint. Multivariate statistics showed that sewage sludge favored, with particular emphasis on highest applied doses, positive soil-plant feedbacks by increasing SOM and related micro and macronutrient contents. Sewage sludge production has tremendously increased worldwide, with landfill disposal representing the final destination in most cases. This is neither profitable nor an environment-friendly reuse approach and is responsible for increasing public awareness and relative socio-economic costs. For the first time, this research demonstrated that sewage sludge can be safely reused by providing several benefits while avoiding drawbacks in soil-forest recovery activities.

CRediT authorship contribution statement

Iraê Amaral Guerrini: Resources, Validation, Supervision, Project administration, Funding acquisition, Investigation, Writing – original draft. **Thalita Fernanda Sampaio:** Conceptualization, Methodology, Validation, Investigation. **Julio Cesar Bogiani:** Methodology, Validation. **Clarice Backes:** Investigation, Data curation. **Robert Boyd Harrison:** Investigation, Data curation. **Fernando Carvalho Oliveira:** Investigation, Data curation. **José Luis Gava:** Investigation, Data curation. **Rogério Carlos Traballi:** Conceptualization, Investigation. **Rodolfo Garuba de Menezes Mota:** Investigation, Data curation. **Ludmila Ribeiro Roder:** Investigation, Data curation, Writing – original draft, Writing – review & editing. **Eleonora Grilli:** Data curation, Software, Formal analysis. **Antonio Ganga:** Data curation, Software, Formal analysis, Writing – original draft, Writing – review & editing. **Jason Nathaniel James:** Writing – original draft, Writing – review & editing, Supervision. **Gian Franco Capra:** Validation, Visualization, Data curation, Formal analysis, Writing – original draft, Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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References

Abreu-Junior, C.H., Firme, L.P., Maldonado, C.A.B., Moraes Neto, S.P., Alves, M.C., Muraoka, T., Boaretto, A.E., Gava, J.L., He, Z., Nogueira, T.A.R., Capra, G.F., 2017. Fertilization using sewage sludge in unfertile tropical soils increased wood production in *Eucalyptus* plantations. J. Environ. Manag. 203, 51–58. https://doi.org/10.1016/j.jenvman.2017.07.074.

Abreu-Junior, C.H., Brossi, M.J.L., Monteiro, R.T., Cardoso, P.H.S., Mandu, T.S., Nogueira, T.H.R., Ganga, A., Filzmoser, P., Oliveira, F.C., Firme, L.P., He, Z., Capra, G.F., 2019. Effects of sewage sludge application on unfertile tropical soils evaluated by multiple approaches: a field experiment in a commercial *Eucalyptus* plantation. Sci. Total Environ. 655, 1457–1467. https://doi.org/10.1016/j.scitotenv.2018.11.334.

Abreu-Junior, C.H., de Oliveira, M.G., Silveira Cardoso, P.H., da Silva Mandu, T., Florentino, A.L., Carvalho Oliveira, F., dos Reis, J.V., Alcarde Alvares, C., Stape, J.L., Nogueira, T.A.R., Capra, G.F., He, Z., 2020. Sewage sludge application in *Eucalyptus urograndis* plantation: availability of phosphorus in soil and wood production. Front. Environ. Sci. 18, 1–14. https://doi.org/10.3389/fenvs.2020.00116.

Bezerra, F.B., Oliveira, M.A.C.L., Perez, D.V., Andrade, A.G., Meneguelli, N.A., 2006. Lodo de esgoto em revegetação de área degradada. Pesq. Agropec. Bras. 41, 469–476. https://doi.org/10.1590/S0100-204X2006000300014.

Bossio, D., Geheb, K., Critchley, W., 2010. Managing water by managing land: addressing land degradation to improve water productivity and rural livelihoods. Agric. Water Manag. 97, 536–542. https://doi.org/10.1016/j.agwat.2008.12.001.

Buondonno, A., Grilli, E., Capra, G.F., Glorioso, C., Langella, A., Leone, A.P., Leone, N., Odierna, P., Vacca, S., Vigliotti, R.C., 2013. Zeolitized tuffs in pedotechnique for the reclamation of abandoned quarries. A case study in the Campania region (Italy). J. Environ. Manag. 122, 25–30. https://doi.org/10.1016/j.jenvman.2013.02.013.

Buondonno, A., Capra, G.F., Di Palma, D., Grilli, E., Vigliotti, R.C., 2018. Pedotechnologies for the Environmental Reclamation of limestone quarries. A protocol proposal. Land Use Pol. 71, 230–244. https://doi.org/10.1016/j.landusepol.2017.12.002.

Capra, G.F., Coppola, E., Odierna, P., Grilli, E., Vacca, S., Buondonno, A., 2014. Occurrence and distribution of key potentially toxic elements (PTEs) in agricultural soils: a paradigmatic case study in an area affected by illegal landfills. J. Geochem. Explor. 145, 169–180. https://doi.org/10.1016/j.gexplo.2014.06.007.

Capra, G.F., Ganga, A., Filzmoser, P., Gaviano, C., Vacca, S., 2016. Combining place names and scientific knowledge on soil resources through an integrated ethnopedological approach. Catena 142, 89–101. https://doi.org/10.1016/j.catena.2016.03.003.

Conselho Nacional Do Meio Ambiente–CONAMA, 2009. Resolution No. 420 of December 28, 2009. Provides guiding values and criteria of soil quality for the presence of chemicals and establishes guidelines for environmental management of areas contaminated by these substances as a result of anthropogenic activities. Conselho Nacional Do Meio Ambiente. Brasília, Retrieved March 30th, 2021 from. http://www.mma.gov.br/port/conama/legiabre.cfm?codlegi0620.

Conselho Nacional Do Meio Ambiente—CONAMA, 2020. Resolution No. 498 of August 19, 2020. Defines Criteria and Procedures for the Production and Application of Biosolids in Soils, and Takes Other measures. Conselho Nacional Do Meio Ambiente. Brasília, Retrieved March 30th, 2021 from. https://www.in.gov.br/en/web/dou/-/resolucao-n-498-de-19-de-agosto-de-2020-273467970.

Dominati, E., Patterson, M., Mackay, A., 2010. A framework for classifying and quantifying the natural capital and ecosystem services of soils. Ecol. Econ. 69, 1858–1868. https://doi.org/10.1016/j.ecolecon.2010.05.002.

FAO, ITPS, 2015. Status of the World's Soil Resources (SWSR) – Main Report Food and Agriculture Organization of the United Nations and Intergovernmental Technical Panel on Soils, Rome, Italy. Retrieved March 30th, 2021 from. http://www.fao.org/3/i5199e/i5199e.pdf.

Florentino, A.L., Ferraz, A.V., Gonçalves, J.L.M., Asensio, V., Muraoka, T., Dias, C.T.S., Nogueira, T.A.R., Capra, G.F., Abreu-Junior, C.H., 2019. Long-term effects of residual sewage sludge application in tropical soils under *Eucalyptus* plantations. J. Clean. Prod. 220, 177–187. https://doi.org/10.1016/j.jclepro.2019.02.065.

Guerrini, I.A., Croce, C.G.G., Bueno, O.C., Jacon, C.P.R.P., Nogueira, T.A.R., Fernandes, D.M., Ganga, A., Capra, G.F., 2017. Composted sewage sludge and steel mill slag as potential amendments for urban soils involved in afforestation programs. Urban For. Urban Green. 22, 93–104. https://doi.org/10.1016/j.ufug.2017.01.015.

IBÁ–Industria Brasileira de Árvores, 2020. Report 2020. IBÁ, Brasília. Retrieved March 30th, 2021 from. https://iba.org/datafiles/publicacoes/relatorios/relatorio-iba-2020.pdf.

Joslin, A.H., Markewitz, D., Morris, L.A., Oliveira, F.D., Figueiredo, R.O., Kato, O.R., 2011. Five native tree species and manioc under slash-and-mulch agroforestry in the eastern Amazon of Brazil: plant growth and soil responses. Agrofor. Syst. 81, 1–14. https://doi.org/10.1007/s10457-010-9356-1.

Kabata-Pendias, A., Mukherjee, A.B., 2010. Trace Elements from Soil to Human, fourth ed. Springer, Berlin-New York.

Koch, A., McBratney, A., Adams, M., Field, D., Hill, R., Crawford, J., Minasny, B., Lal, R., Abbott, L., O'Donnell, A., Angers, D., Baldock, J., Barbier, E., Binkley, D., Parton, W., Wall, D.H., Bird, M., Bouma, J., Chenu, C., Flora, C.B., Goulding, K., Grunwald, S., Hempel, J., Jastrow, J., Lehmann, J., Lorenz, K., Morgan, C.L., Rice, C.W., Whitehead, D., Young, I., Zimmermann, M., 2013. Soil security: solving the global soil crisis. Glob. Policy J. 4, 434–441. https://doi.org/10.1111/1758-5899.12096.

Lal, R., 2015. Restoring soil quality to mitigate soil degradation. Sustainability 7 (5), 5875–5895. https://doi.org/10.3390/su7055875.

McBratney, A., Field, D.J., Koch, A., 2014. The dimensions of soil security. Geoderma 213, 203–213. https://doi.org/10.1016/j.geoderma.2013.08.013.

Montanarella, L., Pennock, D.J., McKenzie, N., Badraoui, M., Chude, V., Baptista, I., Mamo, T., Yemefack, M., Singh Aulakh, M., Yagi, K., Young Hong, S., Vijarnsorn, P., Zhang, G.-L., Arrouays, D., Black, H., Krasilnikov, P., Sobocká, J., Alegre, J., Henriquez, C.R., Mendonça-Santos, M.L., Taboada, M., Espinosa-Victoria, D., AlShankiti, A., AlaviPanah, S.K., Elsheikh, E.A.E.M., Hempel, J., Camps Arbestain, M., Nachtergaele, F., Vargas, R., 2016. World's soils are under threat. Soils 2, 79–82. https://doi.org/10.5194/soil-2-79-2016.

Nogueira, T.A.R., Abreu-Junior, C.H., Alleoni, L.R.F., He, Z., Soares, M.R., Vieira, C.S., Lessa, L.G.F., Capra, G.F., 2018. Background concentrations and quality reference values for some potentially toxic elements in soils of Sao Paulo State, Brazil. J. Environ. Manag. 221, 10–19. https://doi.org/10.1016/j.jenvman.2018.05.048.

Prates, A.R., Coscione, A.R., Teixeira Filho, M.C.M., Miranda, B.G., Arf, O., Abreu-Junior, C.H., Oliveira, F.C., Moreira, A., Galindo, F.S., Sartori, M.M.P., He, Z., Jani, A.D., Capra, G.F., Ganga, A., Nogueira, T.A.R., 2020. Composted sewage sludge enhances soybean production and agronomic performance in naturally infertile soils (cerrado region, Brazil). Agronomy 10, 1677. https://doi.org/10.3390/agronomy10111677.

Raij, van B., Cantarella, H., Quaggio, J.A., Furlani, A.M.C., 1997. Recomendações de Adubação e Calagem para o Estado de São Paulo, second ed. Instituto Agronômico, Campinas.

Raij, van B., Andrade, J.C., Cantarella, H., Guaggio, J.A., 2001. Análise Química Para Avaliação da Fertilidade de Solos Tropicais, first ed. Instituto Agronômico, Campinas.

RStudio, 2021. RStudio: Integrated Development Environment for R [Computer Software]. RStudio, Boston. Retrieved March 30th, 2021 from. https://www.rstudio.com/.

Sampaio, T.F., Guerrini, I.A., Otero, X.L., Vazquez, F.M., Bogiani, J.C., Oliveira, F.C., Gava, J.L., Ciol, M.A., Littke, K.M., Harrison, R.B., 2016. The impact of biosolid application on soil and native plants in a degraded Brazilian Atlantic Rainforest Soil. Water Air Soil Pollut. 227, 1–9. https://doi.org/10.1007/s11270-015-2689-7.

Schoeneberger, P.J., Wysocki, D.A., Benham, E.C., the Soil Survey Staff., 2012. Field Book for Describing and Sampling Soils. U.S. Gov. Print. Office, Washington, DC, version 3.0.

Siddique, I., Engel, V.L., Parrotta, J.A., Lamb, D., Nardoto, G.B., Ometto, J.P.H.B., Martinelli, L.A., Schmidt, S., 2008. Dominance of legume trees alters nutrient relations in mixed species forest restoration plantings within seven years. Biogeochemistry 88, 89–101. https://doi.org/10.1007/s10533-008-9196-5.

Siqueira, C.C.Z., Chiba, M.K., Moreira, R.S., Abdo, M.T.V.N., 2020. Carbon stocks of a degraded soil recovered with agroforestry systems. Agrofor. Syst. 94, 1059–1069. https://doi.org/10.1007/s10457-019-00470-9.

Soil Survey Staff, 2014. Keys to Soil Taxonomy, twelfth ed. USDA-Natural Resources Conservation Service, Washington, DC.

Tapia-Coral, S.C., Luizão, F.J., Wandelli, E., Fernandes, E.C.M., 2005. Carbon and nutrient stocks in the litter layer of agroforestry systems in central Amazonia, Brazil. Agrofor. Syst. 65, 33–42. https://doi.org/10.1007/s10457-004-5152-0.

Tassinari, D., de Carvalho Andrade, M.L., de Souza Dias Junior, M., Martins, R.P., Rocha, W.W., Sant'Anna Moreira, P., de Souza, P.Z.R., 2019. Soil compaction caused by harvesting, skidding and wood processing in eucalyptus forests on coarse-textured tropical soils. Soil Use Manag. 35, 400–411. https://doi.org/10.1111/sum.12509.