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Article *in* Land Degradation & Development · June 2017

DOI: 10.1002/ldr.2949

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Received: 30 June 2017 | Revised: 6 November 2017 | Accepted: 16 March 2018
DOI: 10.1002/ldr.2949

RESEARCH ARTICLE

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Soil organic carbon recovery and coffee bean yield following bauxite mining

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Funding information
Fundação de Amparo à Pesquisa do Estado de Minas Gerais (FAPEMIG); Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES); Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq)

Abstract

Bauxite mining requires the removal of the vegetation and topsoil, thus causing considerable impacts on both natural and managed ecosystems. This is typically the case of agricultural activities across Minas Gerais, South-eastern Brazil, where bauxite mining often displaces pastures and coffee plantations. In this study, our objective was to assess the effects of chemical and organic fertilizations combined with cover crops on the re-establishment of coffee plantations following bauxite mining. The experiment consisted of a split-plot design which main plot received 4 types of fertilization: no fertilization, chemical fertilization (CF), poultry litter (PL), and CF + PL. In subplots, 4 cover crops were cultivated in between the rows of the coffee plantation, including: no cover crops, grass (*Brachiaria brizantha* [B]), legume (*Stylosanthes* spp. [S]), and B + S. We had 4 blocks as replicates. Organic and chemical fertilization (PL + CF) combined with cover crops (B + S) led to significant recovery of soil organic carbon (SOC), soil organic nitrogen (SON), and $KMnO_4$-oxidizable SOC. PL + CF and B + S also led to SOC increments of 14.5 g kg^{-1} soil (0–10-cm depth). Based on isotopic data (^{13}C), both cover crops, isolated or combined, contributed to the recovery of SOC. Over 3 consecutive harvests, coffee bean yield was consistently above 1,800 kg ha^{-1} under PL or PL + CF, except when B was the only cover crop. Managing fertilization and cover crops can determine the recovery of SOC, SON and the capacity of soil to sustain the re-establishment of coffee plantations following bauxite mining.

KEYWORDS

bauxite mining, coffee productivity, cover crops, soil organic carbon, soil reclamation

1 | INTRODUCTION

Brazil has a territory with great continental extension and notable geological diversity, including various mineral deposits. Among the Brazilian states, mining activities are of particular importance for Minas Gerais, where large extensions of land are mined for bauxite extraction (Associação Brasileira do Alumínio, 2017). Despite its undeniable socioeconomic relevance, bauxite mining is often associated with serious environmental impacts throughout the world, mostly in tropics and subtropics of South America, Africa, Oceania, and Asia (Pokhrel & Dubey, 2013). The most notorious impacts of bauxite mining include the removal of the covering vegetation and the topsoil (Daws et al., 2015; Shrestha & Lal, 2006). Consequently, wherever bauxite is extracted, the reclamation of soil after mining represents a considerable challenge (Li, 2006; Mensah, 2015; Silva, Corrêa, Doane, Pereira, & Horwath, 2013; Vickers, Gillespie, & Gravina, 2012). In this context, stockpiled topsoil can be used to accelerate the reclamation process (Macdonald et al., 2015). However, stockpiled topsoil often exhibits depletion of soil organic carbon (SOC) and poor structure, thus hampering the development of plants (Macdonald et al., 2015; Schwenke, Ayre, Mulligan, & Bell, 2000; Vickers et al., 2012). Considering the impact of mining and the challenges for soil reclamation, developing strategies to boost the recovery of areas affected by bauxite extraction is very important for both natural and managed lands. This is of particular interest for coffee plantations that are displaced by bauxite mining across the Atlantic Forest (Mata Atlântica) biome, which accounts for approximately 23% of the total coffee bean production in Minas Gerais, South-eastern Brazil (Companhia Nacional de Abastecimento, 2016).

Soil organic matter (SOM) is a key factor to be considered in studies evaluating the reclamation of degraded lands, particularly those affected by mining activities (Mukhopadhyay, Maiti, & Masto, 2014). This is because SOM is closely related to physical and chemical properties of soils and also vital for biological processes that are at the core of nutrient cycling in terrestrial ecosystems (Dignac et al., 2017; Tesfahunegn, 2016). Thus, rehabilitation techniques that favour the recovery of SOM contents are desirable and need to be evaluated before being integrated into programmes for reclamation of bauxite-mined areas. To achieve such a goal, the use of mineral fertilizers and/or its combination with organic amendments (e.g., animal manure) has been presented as a feasible option to restore soil fertility to allow land reclamation (Larney, Henry Janzen, & Olson, 2011; Macdonald et al., 2015). Animal manure, particularly, can be beneficial once such materials can provide a C source for microbes, which mineralize nutrients that ultimately boost plant growth (Larney & Angers, 2012; Schlegel, Assefa, Bond, Wetter, & Stone, 2015; Srinivasarao et al., 2014). Thus, considering that many challenges must be overcome to restore plant growth on mined soils, it can be expected that the use of fertilization and animal manure should at least help to restore nutrient availability during the early stages of reclamation.

Fertilizers and/or manure applications to highly degraded soils certainly increase the chances of re-establishing conditions suitable to plant growth (Pallavicini, Alday, & Martínez-Ruiz, 2015). The first immediate benefit of restoring the vegetation is to reduce erosion given that soil structure is severely impacted during the stripping and stockpiling of topsoil (Mensah, 2015). Among the main types of plants used in land reclamation, fast-growing grasses often improve soil structure and reduce run-off (Mandal et al., 2017). Additionally, legumes also can be valuable for the reclamation of degraded soils, particularly species capable of forming associations with N_2-fixing microorganisms (Chaer et al., 2011). Ultimately, the combination of high biomass production by grasses and N input by legumes should increase total soil C and N contents (Boldt-Burisch, Naeth, Schneider, & Hüttl, 2015; Wu, Liu, Tian, & Shi, 2016). If grasses and legumes are included in programmes of soil reclamation, their contribution to SOM can be assessed by using stable isotopes (e.g., ^{13}C). During the fixation of C in photosynthesis, C_3 plants (e.g., legumes) discriminate more against the heavier ^{13}C than do C_4 species (e.g., tropical grasses). For instance, SOM under C_4 plants would exhibit a $\delta^{13}C$ of approximately −14.00‰, whereas it would be only −28.00‰ under C_3 plants (Silva et al., 2013). Such information can be critical for detecting changes in SOM, particularly in short-term experiments.

Recovering SOM in highly weathered soils can be understood as the primary step towards the re-establishment of soil fertility after bauxite mining. However, even if SOM content and nutrient availability are restored after mining, it is desirable to assess the capacity of such soils to support the re-establishment of crops that are displaced during the mining procedure. Nevertheless, experimental determinations linking the recovery of SOM and the productivity of crops in areas undergoing reclamation following bauxite mining remain scarce. Thus, our objectives in this study were to evaluate changes in SOM and the re-establishment of coffee plantations on a bauxite-mined area. The short-term effect of the recovery of SOM on the capacity of soil to sustain crop productivity was determined by considering coffee bean yield over three successive harvests.

2 | MATERIALS AND METHODS

2.1 | Characterization of the study site

This research was conducted on an experimental station (21°01′58″S, 42°35′8″W) located within the Atlantic Forest (Mata Atlântica) biome in Minas Gerais state, South-eastern Brazil. In this area, the altitude is 850 m above the sea level and the climate is classified as Cwb according to the Köppen classification. The predominant soil was classified as a Typic Hapludox (Soil Survey Staff, 2014), which native vegetation has been previously cleared for cultivation of pastures and coffee plantations. These are among the main agricultural activities impacted by bauxite mining in the area. The extraction of bauxite was preceded by the stripping of the A and BA horizons of the soil (0–40 cm) and this material remained stockpiled in the area during the mining (approximately 15 months). Selected properties of the soil prior to bauxite mining (pre-mining) are given in Table 1. The disposal of stockpiled topsoil in the mined area is shown in Appendix S1 (Figure S1).

TABLE 1 Chemical and physical characteristics of original soil (0–20-cm layer) under coffee plantation (pre-mining) and the topsoil 6 months after land reconfiguration (post-mining)

Property	Pre-mining	Post-mining	Change
pH (H_2O)	5.6	5.1	−0.5
SOC (g kg^{-1} soil)	36.1	15.1	−21.0
SON (g kg^{-1} soil)	2.8	0.6	−2.2
C:N	12.9	25.2	+12.3
P (mg dm^{-3} soil)[a]	7.9	1.1	−6.8
K^+ ($cmol_c$ dm^{-3} soil)[a]	0.2	0.1	−0.1
Ca^{2+} ($cmol_c$ dm^{-3} soil)[b]	1.9	0.4	−1.5
Mg^{2+} ($cmol_c$ dm^{-3} soil)[b]	0.5	0.1	−0.4
Al^{3+} ($cmol_c$ dm^{-3} soil)[b]	0.1	0.1	0.0
ECEC ($cmol_c$ dm^{-3} soil)	2.7	0.7	−2.0
CEC ($cmol_c$ dm^{-3} soil)	9.9	4.5	−5.4
Clay (%)[c]	66.0	64.0	−2.0
Silt (%)[c]	14.7	7.0	−7.7
Sand (%)	19.2	29.0	+9.7
Bulk density (kg dm^{-3} soil)	0.8	1.2	+0.4

Note. pH (H_2O) soil-to-water ratio of 1:2.5. CEC = cation exchange capacity measured with 0.5 mol L^{-1} calcium acetate at pH 7.0; ECEC = effective cation exchange capacity (K^+ + Ca^{2+} + Mg^{2+} + Al^{3+}); SOC = soil organic carbon; SON = soil organic nitrogen.

[a]Extracted by Mehlich-1 (0.05 mol L^{-1} HCl + 0.025 mol L^{-1} H_2SO_4).

[b]Exchangeable Ca^{2+}, Mg^{2+}, and Al^{3+} extracted by 1 mol L^{-1} KCl soil extract.

[c]Determined by the pipette method following wet sieving to separate sand-sized particles.

After the mining was concluded, the stockpiled topsoil was used for land reconfiguration, which occurred in three steps: (a) BC and C horizons that were exposed during bauxite mining were stripped to 60-cm depth using a ripper pulled by a bulldozer; (b) the stockpiled topsoil was redistributed in the area building a layer approximately 20–40 cm thick; and (c) the reconfigured topsoil was subsequently stripped to 60-cm depth to reduce compaction and terraces were built to reduce erosion. Six months after land reconfiguration, soil samples were collected to characterize the reconfigured topsoil - post-mining (Table 1). A general timeline of all phases preceding bauxite mining and land reclamation stages is given in Appendix S1 (Figures S1–S3).

2.2 | Experimental design and cover crops management

Six months after the reconfiguration of topsoil was completed, the treatments were assigned to the experimental plots according to a split-plot design with fertilization types applied to the main plots and cover crops in subplots. The dimensions of the main plots were 28.0 m × 14.0 m (392 m^2), where the following fertilization types were applied: (a) a nonfertilized control (NF); (b) poultry litter (PL, at 50 Mg ha^{-1}); (c) chemical fertilization (CF), consisting of 8.0 Mg ha^{-1} of lime and 1.5 Mg ha^{-1} of rock phosphate; and (d) a combination of PL and CF (PL + CF). PL additions at 50 Mg ha^{-1} implied inputs of C, N, P, K, Ca, and Mg at 17,600.0, 1,210.9, 470.0, 1,157.7, 1,063.2, and 182.7 kg ha^{-1}, respectively. All fertilizers were randomly assigned to the plots in four replicates (16 plots in total) and mixed within the first 20 cm of topsoil. The coffee plantation (cultivar Red Catuaí, *Coffea arabica*, var. IAC 44) was re-established 3 months after the assignment of the fertilization types to the main plots. Within the rows, the distance between the coffee seedlings was 0.5 m, and the distance between the rows was 2.0 m, yielding a total of 10,000 coffee plants per hectare. Within each plot, we had 392 plants distributed over seven rows, which were disposed perpendicularly to the slope of the terrain. Coffee seedlings that died after the transplant were replaced within the same week. Topdressing fertilizations were added only for CF or PL + CF treatments as described in Appendix S1.

One month after the re-establishment of the coffee plantation, each main plot was subdivided into four subplots (14.0 m × 7.0 m, 98 m^2) where four cover crops were inserted including (a) a control with no cover crops (NCC); (b) grass *Brachiaria brizantha* (B); (c) legume, 80% *Stylosanthes capitata* and 20% *Stylosanthes macrocephala* (S); and (d) a combination of *Brachiaria* and *Stylosanthes* (B + S). For the treatments including only B or S, the amount of viable seeds sown was 25 and 2.5 kg ha^{-1}, respectively. For the B + S treatment, only half of the amount of seeds of both B and S was sown (12.5 and 1.5 kg ha^{-1}, respectively). The seeds were introduced into the first 2 cm of the topsoil and sown in a way to form four rows separated by 25 cm, covering the 1-m central section in between the coffee plant rows. For the treatment B + S, the cover crops also were introduced to form four lines in between the coffee plant rows, with B placed on the two central lines and S seeds sown on the outer lines closer to the coffee rows. Details on the distribution of coffee plants and cover crops can be found in Appendix S1 (Figures S1–S3).

Cover crops were managed by regular clippings once B or S plants reached approximately 60 cm in height. B plants were clipped to reduce their height down to 20–25 cm, and S plants were clipped to 10–15-cm height. During the first year, cover crops were clipped at 60, 126, 246, 309, and 364 days after the seeds were sown. The same intervals were used afterwards to have a minimum of five clippings per year. The fresh biomass produced was weighted in the field, and subsamples were taken and oven-dried in the laboratory under forced-air circulation (62 °C for 72 hr) to obtain the dry matter yield. After the clipping, the biomass produced by the cover crops was left as a mulching that was placed within the 50-cm section on both sides along the coffee plant rows. For the determination of dry mass yield of the cover crops, we only considered those located in between the five rows of coffee plants located at the centre of the main plots, and two external rows were discarded; thus, the sampled area for each subplot included 40 coffee plants (40 m^2).

2.3 | Soil sampling, characterization of organic matter, and stable isotope data

Soil samples were collected to a depth of 0–10-cm depth on and in between the rows of the coffee plants in two field campaigns. The first sampling occurred approximately 1.5 years (19 months; Table S1) after the coffee plants were replanted and the second after the third harvest of coffee beans (approximately 4.5 years after replanting). In total, eight subsamples (four subsamples from the coffee plants rows and another four collected in between the rows) were mixed in one composite sample for each subplot. The composite samples were air-dried, sieved through a 2-mm sieve, and submitted to chemical analysis. For the determination of total SOC and SON contents and $\delta^{13}C$ of SOM, the samples were submitted to ball-milling and subsequently analysed using an isotope ratio mass spectrometer with continuous flux (20-20, ANCA-GLS, Sercon, Crewe, UK). Tests in the field and in the laboratory using HCl did not indicate the presence of inorganic carbon in the soil evaluated, even in BC or C horizons. Operationally defined labile SOC was determined by oxidation with a $KMnO_4$ solution at 33 mmol L^{-1}.

Isotopic data were used to infer the contribution of C_4 and C_3 plants to total SOC during soil reclamation. *Stylosanthes* spp. and coffee plants (C_3) exhibited a $\delta^{13}C_{PDB}$ of −27.15‰ and −28.00‰, respectively, whereas *Brachiaria* (a C_4 plant) had a $\delta^{13}C_{PDB}$ of −13.00‰. On the basis of isotope data, we could not distinguish the contribution of coffee plants and *Stylosanthes* for SOC. Additionally, the soil sampled before the mining had a $\delta^{13}C_{PDB}$ of −21.585‰, and the PL had a $\delta^{13}C_{PDB}$ of −22.20‰. Consequently, the contribution of PL for SOC content could not be estimated based on isotope data. The contribution of C_4 plants for SOC was calculated as follows:

$$C_4\text{–SOC} = \frac{(\delta_t - \delta_c)}{(\delta_b - \delta_c)} \times 100,$$

where δ_t was the $\delta^{13}C$ of a given treatment, δ_c was the $\delta^{13}C$ in the control treatment with no cover crops, and δ_b was the $\delta^{13}C$ of *Brachiaria*. As such, by applying this formula and assuming that SOC under pure coffee plants would have a $\delta^{13}C$ of −28.00‰, the initial contribution of C_4 plants for SOC was approximately 42.8% (6 months after reconfiguration of topsoil). This was because the original coffee plantation was only 10 years old, which replaced *Brachiaria* pastures.

2.4 | Coffee bean productivity

Coffee productivity was evaluated three times, at 2.5, 3.5, and 4.5 years after the experiment began. The harvesting proceeded between May and June of each year (2013–2015), when at least 60% of the fruits had ripened. There was no selective harvesting of only ripen fruits. The productivity was assessed separately for each treatment and expressed as kilograms per hectare of processed coffee beans at 12% of moisture content.

2.5 | Statistics

Statistical analyses were run using Statistica STATSOFT® (Quest, Aliso Viejo, CA), and the graphs were prepared with Sigma Plot® 11 (San Jose, CA). The results were submitted to a two-way analysis of variance to test for the main effects of fertilization, cover crops, and their interactions. We set $p < .05$ as the significant level for differences among means.

TABLE 2 Annual shoot dry matter yield (Mg ha^{-1}) of cover crops as a function of fertilization types

Fertilization type	*Brachiaria* (B)	*Stylosanthes* (S)	B + S
No fertilization (NF)	0.4 Ca	0.4 Ba	1.8 Ba
Poultry litter (PL)	16.0 Ba	5.9 Ab	14.2 Aa
Chemical fertilizers (CF)	3.0 Ca	2.3 ABa	3.1 Ba
PL + CF	23.0 Aa	3.8 ABb	17.3 Aa

Note. Capital letters compare dry matter yield by a cover crop among fertilization types. For a given fertilization, lowercase letters compare the dry matter production among cover crops. Means followed by the same capital or lowercase letter do not differ according to Tukey's test ($p < .05$).

3 | RESULTS

The use of PL led to significant increments on the shoot dry matter production by the cover crops as compared to the NF treatment (Table 2). Unexpectedly, the productivity of the cover crops did not differ ($p < .05$) between CF and the NF control (Table 2). In the presence of PL + CF, the highest annual shoot biomass production for B was 23.0 Mg ha^{-1}. For S, however, the highest biomass productivity was 5.9 Mg ha^{-1} in the presence of PL and only 3.8 Mg ha^{-1} for PL + CF combination (Table 2). For B + S, the highest biomass yield was 14.2 and 17.3 Mg ha^{-1} for the plots fertilized with PL and PL + CF, respectively. The application of PL or PL + CF in combination with cover crops also led to a higher recovery of SOC and SON contents than CF-only applications (Figure 1a,b). Lower C:N ratio occurred for the treatments including PL as compared with the treatments including *Stylosanthes* (Figure 1c). Moreover, the amount of SOC oxidizable by $KMnO_4$ was mostly affected by PL but also increased with the introduction of the cover crops (Figure 1d). The lowest levels of SOC oxidizable by $KMnO_4$ were observed for the NF control or in the treatments including only CF. Similar results for SOC, SON, and $KMnO_4$-oxidizable C contents were observed 1.5 years after the coffee plantation was replanted (Table S1). Relative to this first campaign, both SOC and SON exhibited higher averages at 4.5 years (Figure 1).

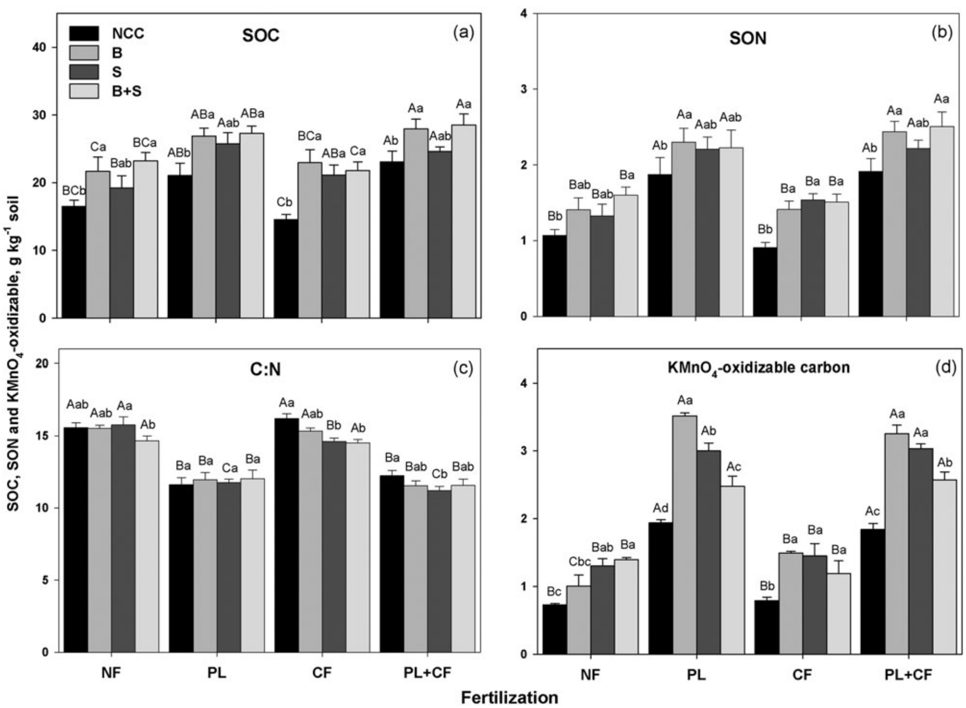

FIGURE 1 Soil organic carbon (SOC; a), soil organic nitrogen (SON; b), C:N ratio (c), and $KMnO_4$-oxidizable C (d) as affected by fertilization type, including no fertilization (NF), poultry litter (PL), chemical fertilizers (CF), and the combination of PL and CF (PL + CF) and different cover crops, including no cover crops (NCC), *Brachiaria* (B), *Stylosanthes* (S), and the combination of B and S (B + S). Capital letters compare means for a given cover crop among fertilizations; lowercase letters compare means for cover crops within a single fertilization. Means followed by the same capital or lowercase letter do not differ according to Tukey's test ($p < .05$). Vertical bars denote the standard error of the mean, $n = 4$

The means for $\delta^{13}C$ used for partitioning the contribution of C_3 and C_4 plants are given in Table S2. On the basis of these data, the contribution of C_4 plants for total SOC content under NCC was almost uniform among the fertilization types used (Figure 2a–d). In fact, as inferred from the NF group, in all NCC treatments, there was a net decrease on the C_4-SOC. Apparently, losses of C_4-SOC were minimized by growing B, S, or B + S, among which there was no significant variation on C_4-SOC (Figure 2a). Thus, although the C_4-SOC was reduced under NCC, it was at least preserved under cover crops (Figure 3a). Under PL, CF, or PL + CF, the contribution of B for SOC led to a significant increment on C_4-SOC (Figure 2b–d). When B was combined with PL, the total contribution of C_4 plants for SOC reached 72.6% (Figure 2b). Only for PL and CF the contribution of C_4-SOC was higher for B as compared with the B + S combination (Figure 2b,c). Whenever S was fertilized, there was a significant reduction on the contribution of C_4-SOC similar to that observed for the NCC treatment. These results indicate an increment in C_3-SOC rather net loss of C_4-SOC as observed for NCC (Figure 3). Relative to the reconfigured topsoil (post-mining, Table 2), PL or PL + CF led to increments in SOC content of 7.0 to 9.1 g kg^{-1} of soil, respectively (Figure 3b,d). Combined, PL + CF and B or B + S led to increments in SOC as high as 14.0 and 14.5 g kg^{-1} of soil, respectively (Figure 3d).

As observed for the cover crops, coffee bean yield (kg ha^{-1}) also was strongly affected by fertilization and the cover crops used over three successive harvests (Figure 4a–d; $p < .01$). For NF treatments, there was no recovery in coffee bean yield throughout the period evaluated (Figure 4a–d). Generally, coffee bean yield was favoured by CF, but still it was not as good as the productivity observed for PL throughout the 3-year evaluation. Nevertheless, even in the presence of PL, there was no recovery in coffee bean yield when B was used as cover crop (Figure 4d). Yet for B + S it was possible to achieve a compromise between SOC accrual (Figure 1), without reducing coffee bean yield (Figure 4).

4 | DISCUSSION

The most evident effects of the addition of PL at 50 Mg ha^{-1} (approximately 17.6 Mg ha^{-1} of C) included an increase in total SOC content (Figure 1a) and $KMnO_4$-oxidizable C (Figure 1d). Given that SOC is often included as a key parameter to infer on the recovery of soil degraded by mining activities (Mukhopadhyay et al., 2014), our results indicate that PL application was critical during the early stages of reclamation. These effects are particularly relevant when there are no cover crops in the rehabilitation (Figure 3b). Beyond increasing total SOC content, PL also appears to provide substrates that can boost biological processes, as inferred from the $KMnO_4$-oxidizable C (Hurisso et al., 2016). Importantly, PL applications led to inputs of

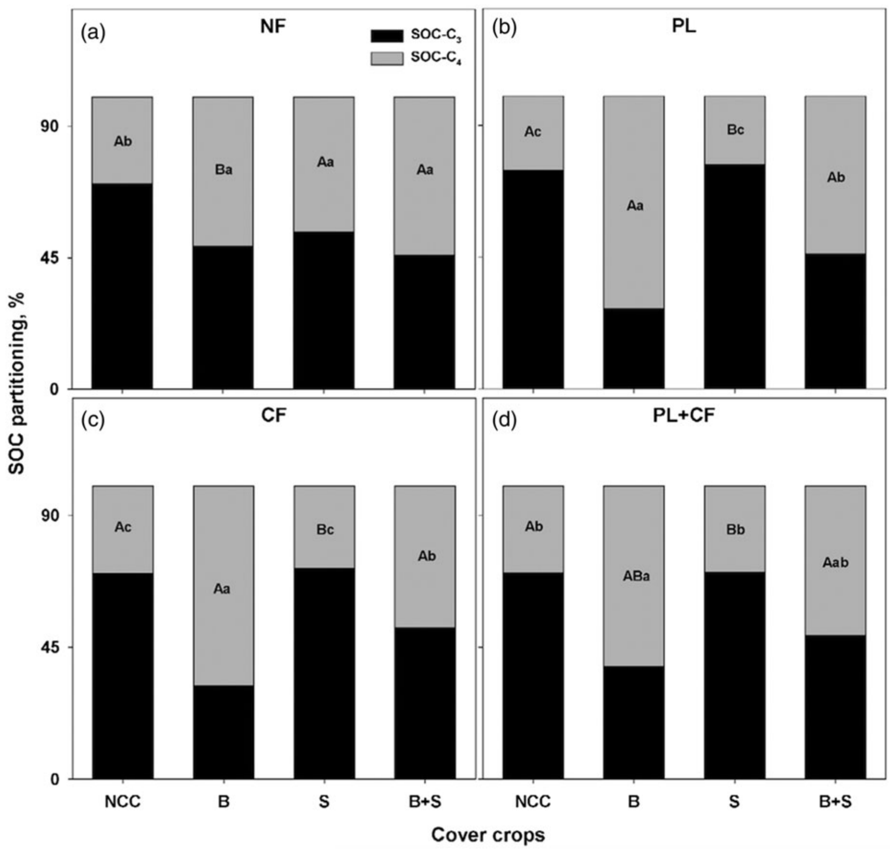

FIGURE 2 Partitioning of soil organic carbon (SOC) as derived from C_3 (SOC-C_3) or C_4 plants (SOC-C_4) as affected by growing no cover crops (NCC), *Brachiaria* (B), *Stylosanthes* (S), or *Brachiaria* + *Stylosanthes* (B + S) and applying (a) no fertilization (NF), (b) poultry litter (PL), (c) chemical fertilizers (CF), and (d) poultry litter + chemical fertilization (PL + CF). Capital letters compare means for a given cover crop among fertilizations; lowercase letters compare means for cover crops within a single fertilization. Means followed by the same capital or lowercase letter do not differ according to Tukey's test ($p < .05$). The baseline value for C_4-SOC was 42.8%

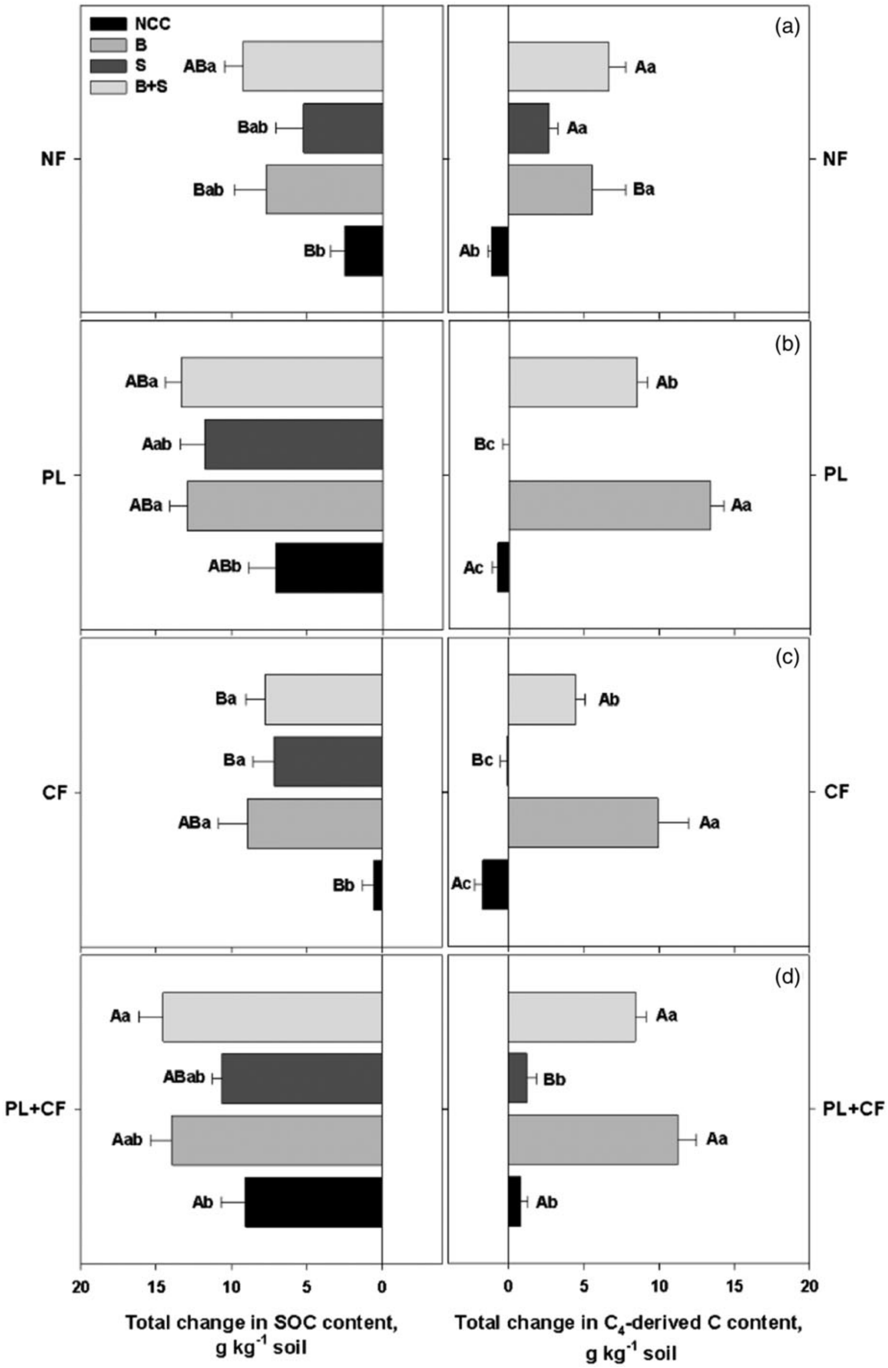

FIGURE 3 Total variation on soil organic carbon (SOC) and C_4-derived SOC content (both g C kg^{-1} soil) relative to the reconfigured topsoil (post-mining) as a function of growing no cover crops (NCC), *Brachiaria* (B), *Stylosanthes* (S), and *Brachiaria* + *Stylosanthes* (B + S) using (a) no fertilization (NF), (b) poultry litter (PL), (c) chemical fertilizers (CF), and (d) poultry litter + chemical fertilizers (PL + CF). Capital letters compare means for a given cover crop among fertilizations; lowercase letters compare means for cover crops within a single fertilization. Means followed by the same capital or lowercase letter do not differ according to Tukey's test ($p < .05$). Vertical bars denote the standard error of the mean, $n = 4$

1,211 kg ha^{-1} of N and 470 kg ha^{-1} of P, which are among the most limiting factors constraining land reclamation, particularly in tropical ecosystems (Chaer et al., 2011; Koch & Samsa, 2007; Mukhopadhyay et al., 2014). Larney et al. (2011) reported positive effects of one-time application of poultry litter (20 Mg ha^{-1}) on SOC content and crop productivity even after 18 years in highly degraded soils in temperate regions. For tropical soils, however, the residual effect of PL application may persist for a considerably shorter period. Following PL applications of 15 Mg ha^{-1} to a Brazilian Oxisol, only 15% and 18% of its initial N and P contents, respectively, were not released within the first year of application (Pitta et al., 2012). As we observed significant effects of PL on SOC and SON contents almost five years after the application, this could be due to the higher input of PL as compared with that reported by Pitta et al. (2012). Despite not being possible to infer on how long the effect of PL applications may persist in tropical soils, manure applications should help to overcome many challenges posed during the early phases of land reclamation, particularly restoring SOC and SON (Figure 1a,b). This would increase the probability of restoring the vegetation, which is among the most critical challenges faced during the reclamation of bauxite-mined soils (Orozco-Aceves, Tibbett, & Standish, 2017; Vickers et al., 2012).

The application of PL alone or combined with CF had a strong effect on the establishment of the cover crops (Table 2). Generally, these results corroborate previous research suggesting the use of manure to recover the vegetation in soils affected by mining (Larney & Angers, 2012). The addition of PL and increase of SOC content

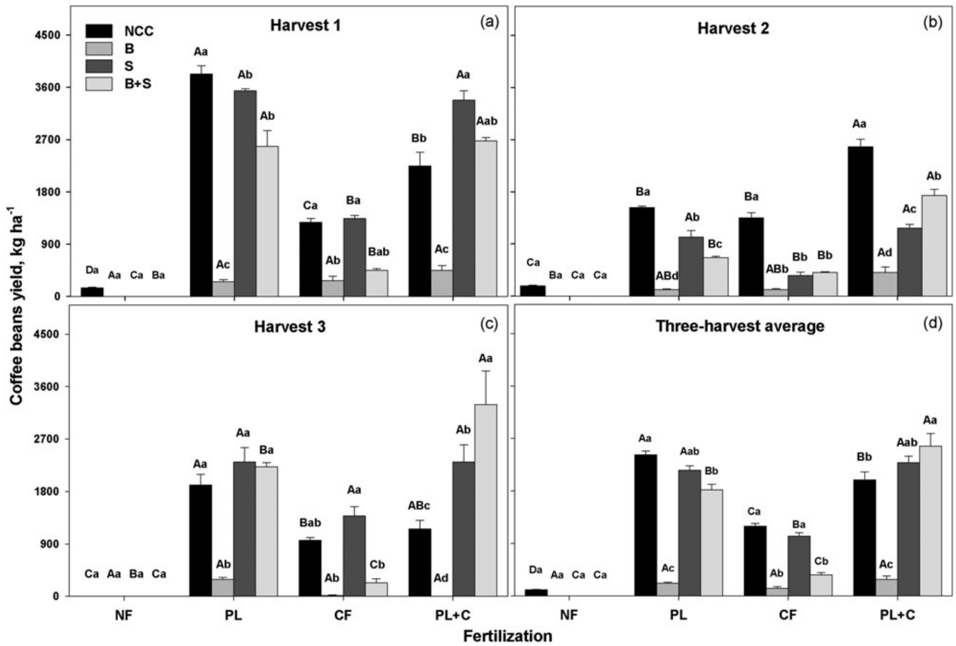

FIGURE 4 Coffee bean productivity (dry matter, kg ha^{-1}) as affected by growing no cover crops (NCC), *Brachiaria* (B), *Stylosanthes* (S), and *Brachiaria* + *Stylosanthes* (B + S) and fertilization over three successive harvests (a, b, c) and the average of the three harvests (d). Capital letters compare means for a given cover crop among fertilizations; lowercase letters compare means for cover crops within a single fertilization. Means followed by the same capital or lowercase letter do not differ according to Tukey's test ($p < .05$). NF: no fertilization; PL: poultry litter; CF: chemical fertilizers; PL + CF: poultry litter + chemical fertilizers. Vertical bars denote the standard error of the mean, $n = 4$

(Figure 1) probably increased the effective cation exchange capacity of the soil, as usually observed in tropical ecosystems (Sanchez & Logan, 1992). Indeed, the effective cation exchange capacity of the soil was reduced by approximately 2.0 $cmol_c$ kg^{-1} of soil after stockpiling and land reconfiguration (Table 1). This would help to explain why only CF inputs had a minor effect on productivity of cover crops (Table 2). When soil conditions allow the vegetation to be re-established, thereafter, the chances of the system being self-sustainable would be more feasible, particularly by keeping C inputs to soils to at least maintain SOC content (Tripathi, Singh, & Nathanail, 2014; Vickers et al., 2012). Establishing vegetation during land reclamation also reduces the transport of soil by erosion, which implies reduced losses of SOM (Mandal et al., 2017; Novara, Keesstra, Cerdà, Pereira, & Gristina, 2016). Accordingly, for the NCC treatment, there was a significant reduction in C_4-SOC, which losses were alleviated by growing cover crops (Figure 3a). The isotopic data also demonstrated direct contribution of B and S plants to increase SOC when these cover crops were fertilized (Figure 3a–d).

In principle, land rehabilitation should be based on (a) identifying characteristics of soil that are needed to restore its original condition/functionality and (b) determining the resources needed to achieve such a goal (Doley, Audet, & Mulligan, 2012). In our experiment, the combination of manure and cover crops had a major impact on the extent by which the original condition of the soil was restored and on its ability to sustain coffee production (Figure 4). Accordingly, the average coffee bean yield for the treatments receiving PL or PL + CF was consistently higher than 1,800 kg ha^{-1} over three successive harvests (Figure 4d). Such productivity is considerable, given that the average coffee bean yield is approximately 1,500–1,600 kg ha^{-1} across the Atlantic Forest biome (Companhia Nacional de Abastecimento, 2016). Importantly, in the presence of B alone, the productivity of coffee beans did not differ from the NF controls (Figure 4a–d), indicating a strong capacity of B to compete with coffee plants (Dias, Alves, & Dias, 2004). Thus, despite B being very efficient to recover SOC even in soils degraded by bauxite mining (Oliveira et al., 2017), this was not enough to guarantee the recovery of coffee bean yield. High SOM content without suppressing coffee bean productivity occurred in the presence of B + S (Figure 4a–d), in which B and S seeds were sown at a ratio of 12.5:1.5 kg ha^{-1}. Additionally, S plants can form associations with N_2-fixing microorganisms and, consequently, increase the availability of N to favour coffee bean yield (Mendonça, Lima, Guimarães, Moura, & Andrade, 2017). Although the short-term effect of fertilization and cover crops could be determined in our study, significant efforts are still required to provide insights on their long-term effects on SOM and coffee bean yield.

5 | CONCLUSIONS

The short-term effects of fertilization and cover crop types determined in our study highlight their potential for soil reclamation following bauxite mining. Combining PL and CF provided suitable conditions allowing the re-establishment of cover crops and the coffee plantation. However, coffee bean yield was as low as in the NF control when only *Brachiaria* was used as cover crop. Critically, when *Brachiaria* and *Stylosanthes* were combined, coffee bean yield was as high as when *Stylosanthes* was the only cover crop combined with PL or PL + CF. Weighting on the impacts of mining on the environment and inherent difficulties for land reclamation in bauxite-mined areas, our results indicate a strong potential of combining manure and cover crops to help speed up the rehabilitation of bauxite-mined soils.

ACKNOWLEDGMENTS

This research was funded by the Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq), Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES), and Fundação de Amparo à Pesquisa do Estado de Minas Gerais (FAPEMIG). The authors are also grateful to Votorantim Metais for providing the experimental area and the maintenance of the experimental plots. We also thank the anonymous reviewers for their valuable suggestions to correct and improve the manuscript.

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How to cite this article: Vilas Boas HF, Almeida LFJ, Teixeira RS, Souza IF, Silva IR. Soil organic carbon recovery and coffee bean yield following bauxite mining. *Land Degrad Dev*. 2018;29:1565–1573. https://doi.org/10.1002/ldr.2949