iForest
Biogeosciences and Forestry

Research Article
doi: 10.3832/ifor4756-018
vol. 18, pp. 344-349

Short-term recovery of fine root carbon stock is inhibited by skid trails in a humid tropical forest

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Impacts of logging on below-ground carbon stocks are less well understood than those on above-ground carbon stocks. Consequently, there is a sizeable knowledge gap regarding fine root recovery and their contribution to below-ground carbon stocks. The objective of this study was to quantify whether short-term recovery of fine root carbon stock occurred after harvesting operations. Three blocks each consisting of a single skid trail and an undisturbed old-growth forest (control) were utilized. Skid trails were heavily compacted by 12 tractor passes during the dry season. After nearly 3 years, 60 samples of fine root biomass (FRB) were collected, along with 60 additional soil samples for chemical analysis. Results showed that despite similar soil chemical properties between skid trails and controls, there was no apparent short-term recovery of FRB. Indeed, there was a 57.1% difference between fine root carbon stocking in skid trails at 1.0 Mg ha^{-1} compared to the undisturbed controls with 1.8 Mg ha^{-1}. These results indicate that the recovery of FRB and C stocks takes at least several years; as such, skid trails should be planned to minimize disturbance to the forest floor, which will help reduce impacts on below-ground carbon pools. More research is needed to ascertain when fine roots do recover, so that future assessments of below-ground carbon stocks can be accomplished with greater confidence.

Keywords: Amazon, Logging Impacts, Soil Compaction, Machinery Traffic, Ferralsol

Introduction

The world's forests are an immense carbon sink, with above- and below-ground stocks in tropical forests accounting for the majority of the global forest carbon sink (Pan et al. 2024). However, the tropical carbon sink is threatened by deforestation, drought, and fires (Qie et al. 2017, Yang et al. 2018). Human activities are largely responsible for impacts on the carbon sink through land-use changes for agriculture and forest degradation from logging (Gatti et al. 2021, Berenguer et al. 2014). Logging primarily affects above-ground carbon stocks through tree removal, especially at higher logging intensities, and these effects may persist for decades (Rozak et al. 2018, Stas et al. 2020). The impacts of logging on carbon pools are not limited to the above-ground carbon pool. Indeed, Chiti et al. (2016) found impacts on soil organic carbon 45 years after selection logging at a depth of 1 m in Ghana. The degradation of soil organic carbon is primarily driven by logging infrastructure, such as skid trails, log landings, and roads (Tchiofo Lontsi et al. 2019, Shabaga et al. 2017). Studies on the impacts of logging infrastructure in both temperate and tropical forests have consistently shown that increases in soil compaction are correlated with decreases in soil organic carbon (Naghdi et al. 2016, Tavankar et al. 2022, DeArmond et al. 2024a).

In addition to impacts on soil organic carbon, the forest site's capacity for carbon storage is diminished by the impoverishment of fine roots. This is because fine roots are an important contributor to soil organic matter accumulation and provide substantial soil C from root exudates and necromass (Germon et al. 2020, Zhao et al. 2024). Logged forests have been shown to have higher fine root turnover, accompanied by a greater increase in fine root debris to the soil organic matter pool, compared to unlogged forests (Riutta et al. 2021). However, after several decades, Da Silva et al. (2020) found no difference in fine root biomass between old-growth and logged forests in Malaysia. In other tropical forests, logged stands had higher FRB levels after 6 years in Cameroon and after 54 years in Ghana (Addo-Danso et al. 2018, Ibrahima et al. 2010).

Fine roots are mostly affected by logging, which compacts soil with logging machinery (Latterini et al. 2024, Jourgholami et al. 2021a). This is because fine root production occurs predominantly at soil depths of 2.5 to 10 cm (Cordeiro et al. 2020, Sciumbata et al. 2023), which is also where soil disturbance by construction and the use of skid trails and landings is substantial. In some cases, this soil degradation from logging has resulted in fine root impoverishment in skid trails for decades (DeArmond et al. 2023, Jourgholami et al. 2019).

As skid trails alone can cover over 20% of the logged area (DeArmond et al. 2021), damage to fine roots and their ability to sequester carbon can be considerable. The compacted soil environment of skid trails inhibits root growth due to increased soil strength, reduced macroporosity, and

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Received: Nov 07, 2024 - Accepted: May 26, 2025

Citation: DeArmond D, Freitas S, Lima AJN, Higuchi N (2025). Short-term recovery of fine root carbon stock is inhibited by skid trails in a humid tropical forest. iForest 18: 344-349. - doi: 10.3832/ifor4756-018 [online 2025-11-30]

Communicated by: Angelo Nolè

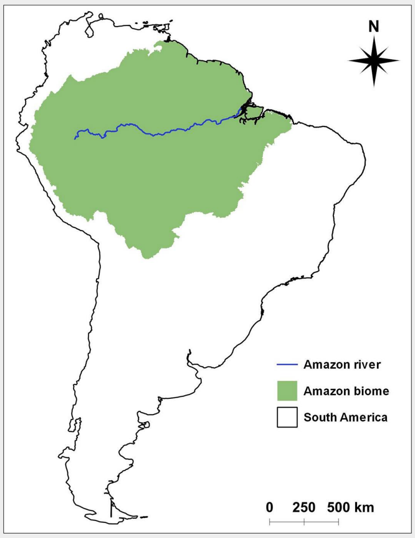

Fig. 1 - Location of the study site.

changes to soil chemical properties (Naghdi et al. 2016, Jourgholami et al. 2021a). Losses in macroporosity may lead to anaerobic soil conditions, resulting in reduced fine root production and biomass (Yaffar et al. 2023). Also, increased skidding traffic has been shown to reduce soil levels of vital nutrients necessary for fine root growth (Naghdi et al. 2016, Shabaga et al. 2017). In contrast, skid trails have been shown to have higher levels of Mg and Ca over time (Jourgholami et al. 2019, DeArmond et al. 2024b). Because skid trail compaction may alter soil chemistry, it is essential to evaluate soil chemical concentrations relative to FRB and their impacts on the recovery process. For example, studies have demonstrated that FRB is positively correlated with Ca and negatively correlated with Mg (Cavelier 1992, Swiatek & Pietrzykowski 2021). Soil compaction losses in phosphorus (P) could worsen in soils that are already low in available phosphorus, which is a limiting factor for fine root productivity in the Amazon. (Cunha et al. 2022). However, numerous studies have shown P accumulation in skid trails after a decade or more (Jourgholami et al. 2019, DeArmond et al. 2024b, Ebeling et al. 2017).

Given the critical role of fine roots in carbon stocks and net primary productivity (NPP) in lowland rainforests (Huasco et al. 2021), it is essential to understand when recovery occurs in degraded forest soils. This knowledge is crucial for properly assessing and calculating forest carbon stocks and NPP, especially in the compacted soils of logging infrastructure. Several studies have demonstrated an incomplete recovery of FRB in skid trails after 5-7 years (Jourgholami et al. 2021a, Miyamoto et al. 2024). In contrast, other studies have found no difference in fine root density or biomass even 7, 13, and 20 years after logging and compaction in skid trails (Ebeling et al. 2017, DeArmond et al. 2024b, Miyamoto et al. 2024), with the earliest reported recovery of FRB in Iranian skid trails after 5 years (Jourgholami et al. 2021a).

The recovery timeline of fine root biomass and fine root carbon stock in soils compacted by logging machinery remains uncertain. A recent meta-analysis on the effects of ground-based machinery on fine roots found no recovery trend in the increase of fine roots over time. In contrast, soil bulk density was reported to be highly correlated with fine root distribution (Latterini et al. 2024). Nonetheless, increases in root growth do not necessarily result in decreases in soil bulk density (Keller et al. 2021). This is evident in a recent study in the Amazon, which found that fine root biomass in skid trails with the highest bulk density was not different from that in undisturbed old-growth forest (DeArmond et al. 2024b). In this study, two hypotheses were tested: (i) soil chemical properties influence fine root biomass recovery in heavily compacted experimental skid trails, and (ii) in heavily compacted skid trails, fine root biomass and carbon stock do not recover in the short term.

Materials and methods

Study area

The study site is located in the Amazon biome (Fig. 1) in the state of Amazonas, Brazil, north of the capital city of Manaus (02° 38′ S, 60° 09′ W). According to the Köppen classification system, the area has a tropical climate (Af) with a mean temperature of 26 °C, and an annual precipitation of more than 2200 mm (Alvares et al. 2013). One month before sampling, site precipitation was 178 mm, and a week prior, 22 mm (Fig. 2). The topography consists of a plateau with a forest where soil has been classified as a Geric Ferralsol (Alumic, Hyperdystric, Clayic – Quesada et al. 2010). At this site, soil texture at the surface 5 cm is 68% clay, 21% silt, and 11% sand (DeArmond et al. 2024a).

Study design and sample collection

The experiment was established in 2021 to compare the impacts of increased logging traffic and seasonal differences in soil moisture on soil compaction. The initial study included three blocks, each with six treatments and a control. Treatments included skid trails with traffic intensities of 1, 3, and 12 machine cycles in both the wet and dry seasons. A machine cycle consisted of one ingress followed by the skid trail's subsequent egress. These differing machine cycles were meant to represent the various skid trail traffic intensities of logging operations: 1 - tertiary skid trails, 3 - secondary trails, and 12 - primary skid trails. In 2023, small-scale logging in the area reused most of the skid trails for log skidding. However, the dry season treatment consisting of 12 machine cycles, as well as the undisturbed controls, were not used in the small-scale logging. These unaffected trails and controls were preserved for the

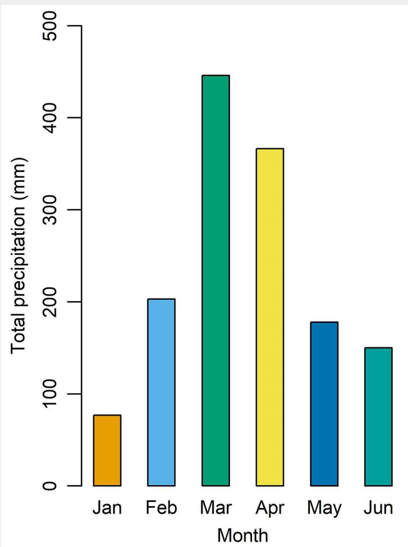

Fig. 2 - Total monthly precipitation at the study site.

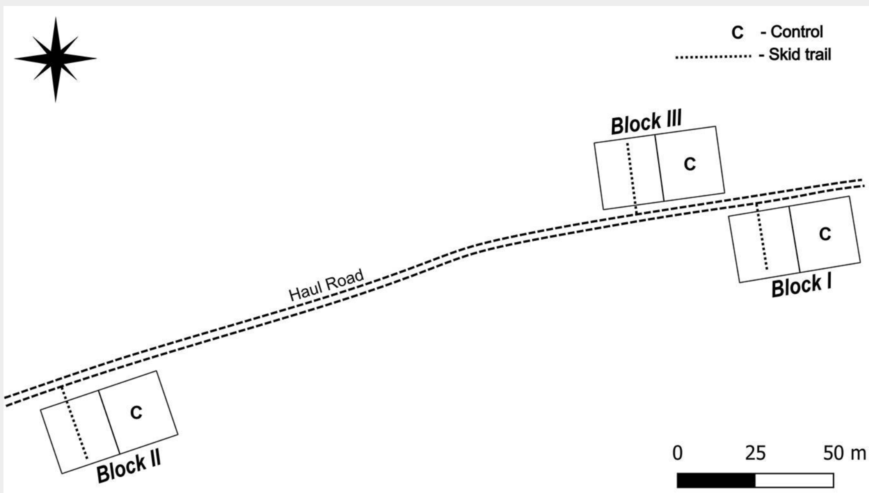

Fig. 3 – Sampling schema at the study site, which included three blocks, each having a treatment skid trail compacted by 12 machine cycles and a control (C).

present study (Fig. 3). In each of the three blocks, two sub-blocks were designated: a control replicate and a skid trail replicate. The dry-season skid trails with 12 machine cycles were previously compacted to a mean bulk density of 1.05 g cm^{-3}, representing a 28% increase over the undisturbed old-growth forest controls at 0.82 g cm^{-3} (DeArmond et al. 2024a).

At the end of June 2024, approximately 3 years after skid trail construction in the dry season, samples for soil chemical properties and fine root biomass (FRB) were collected. Before collecting the samples, a 25 m metric tape was stretched across each sub-block replicate, and a random number generator was used to select the sampling locations. Soil samples were collected in the mineral soil surface (0-5 cm) in skid trail tracks and undisturbed old-growth forest, after the litter layer and organic matter were gently scraped away. In each sub-block replicate, 10 samples for FRB and 10 samples for soil chemical properties were collected. For the skid trail sub-blocks, half the samples were taken from the right tracks and the other half from the left tracks. Samples were placed in sealable plastic bags before transport to the laboratory. In total, 60 samples for FRB (skid trails *n* = 30, controls *n* = 30) and 60 samples for soil chemical properties (skid trails *n* = 30, controls *n* = 30) were collected. The FRB samples were collected with steel sampling cores 5 cm in height, 100 cm^3. Adjacent to the FRB sample location, a 5 × 5 × 5 cm soil block was excavated for soil chemical analysis.

For FRB samples, soil was carefully washed away under running water using mesh screens to capture root tips and fragments. All fine roots < 2 mm were then dried for 72 h at 65 °C and weighed. Fine root C stocking was calculated as 45% of dry FRB (Huasco et al. 2021). Sampling for soil chemical properties, including pH, Ca^{2+}, Mg^{2+}, and Al^{3+}, was conducted at INPA's soil laboratory (*Laboratório Temático de Solos e Plantas* – LTSP). Soil pH was determined using 10 g of dry soil and 25 mL of distilled water, which was agitated for 1 minute. For exchangeable cations, 5 g of dry soil and 50 mL of a 1 mol L^{-1} KCl solution were used for a single extraction. Then Ca and Mg were determined by atomic absorption, and Al by titration. A more detailed description of soil chemical analysis can be found in Teixeira et al. (2017).

Tab. 1 - Mean values and standard deviations (±) for soil chemical properties and fine root biomass (< 2 mm) in controls and skid trails.

Variable	Controls	Skid trails	*F*	*P*
pH (H_2O)	4.201 ± 0.11	4.309 ± 0.12	6.349	0.065
Ca^{2+} ($cmol_c$ kg^{-1})	0.019 ± 0.02	0.026 ± 0.02	0.795	0.423
Mg^{2+} ($cmol_c$ kg^{-1})	0.074 ± 0.02	0.068 ± 0.02	0.586	0.487
Al^{3+} ($cmol_c$ kg^{-1})	1.973 ± 0.20	1.952 ± 0.29	0.025	0.883
Fine root biomass (g m^{-2})	409.0 ± 92.3	220.1 ± 99.9	67.158	0.001

Data analysis

All data were evaluated using a nested ANOVA because only differences between groups (treatment and control) were of interest, not the differences between subgroups (replicates), which were random (McDonald 2014). Respective replicates were nested in either the skid trail treatment (*n* = 3) or the control (*n* = 3). This approach was used because the data were balanced and the nesting structure was simple. Moreover, because the study was not conducted across different areas, there was no site-level random effect to consider. Additionally, Spearman's correlation coefficient (r_s) was used to evaluate the relationship between variables. The statistical software used was SPSS® Statistics ver. 29.0.2.0 (IBM, Armonk, NY, USA).

Results

Fine root biomass and soil chemical properties

When stratified into skid trails or controls, there were no correlations between fine root biomass (FRB) and soil chemical properties. However, when combined, there was a moderate negative correlation between pH and FRB (r_s = - 0.408, p = 0.001). Overall, soil chemical properties were similar across skid trails and controls (Tab. 1), although orange soil mottles were observed exclusively in the skid trails (Fig. 4). However, the range of pH values was slightly higher in the trails (4.05 - 4.65), compared to the controls (3.92 - 4.52 – Fig. 5A). Exchangeable aluminum had a greater range in the skid trails, 1.33 - 2.61 $cmol_c$ kg^{-1}, as opposed to 1.60 - 2.40 $cmol_c$ kg^{-1} in the controls (Fig. 5B). These two chemical properties, pH and Al^{3+}, where very strongly and negatively correlated in the skid trails (r_s = -0.809, *p* < 0.001), whereas in the

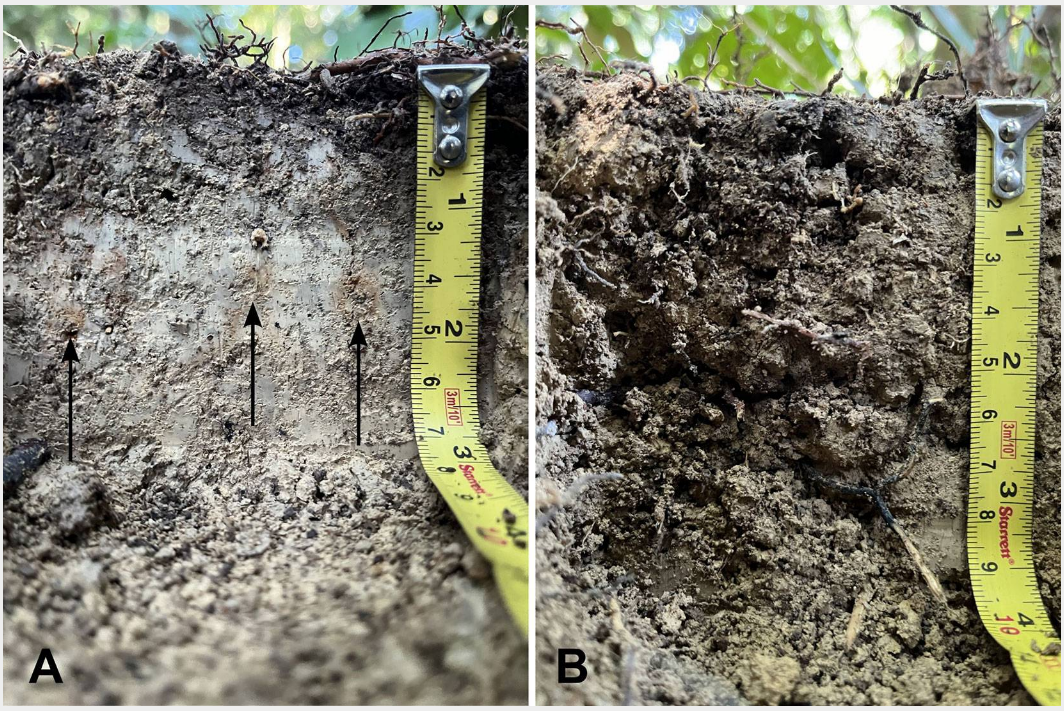

Fig. 4 - Soil profile of (A) skid trail soil with orange mottles and (B) undisturbed forest soil with extensive macroporosity.

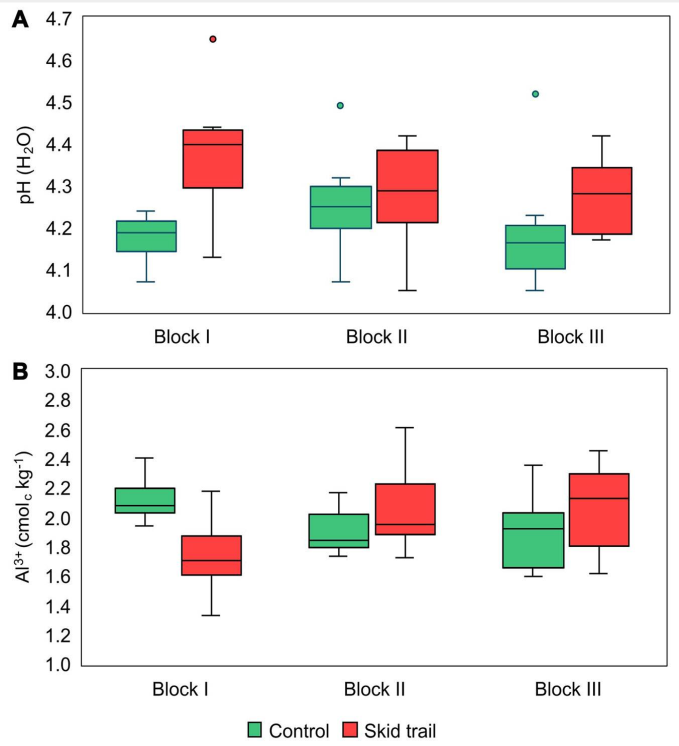

Fig. 5 - Box plots for (A) pH, (B) exchangeable Al. Outliers represented by infilled circles.

controls the relationship between the two properties was weak (r_s = -0.265, p = 0.156). However, there was no observable influence from soil chemical properties evaluated on FRB within the skid trails.

Short-term status of fine root biomass and carbon stocks

Fine root biomass (FRB) in the skid trails was substantially lower than in the controls (Tab. 1). This resulted in a difference of 57.1% between control and skid trail fine root carbon stock (Fig. 6), with a mean of 1.8 Mg ha^{-1} for the controls and 1.0 Mg ha^{-1} for the skid trails. In the skid trails, 76.7% of all samples were below the minimum sample value of 264.9 g m^{-2} detected in the controls, although in each of the three skid trail replicates, there were samples found near or above the control minimum, with a single skid trail sample of 607.5 g m^{-2}.

Discussion

Influence of soil chemical properties on fine root biomass

No influence of soil chemical properties on fine root biomass (FRB) was observed in the present study, therefore the first research hypothesis was not supported. Nevertheless, soil mottles were observed in the studied skid trails, which are indicative of fluctuations between reducing and oxidizing conditions (Jahn et al. 2006). Thus, there is evidence that the skid trails experience longer periods of soil saturation than the mottle-free controls. Soil mottling and other hydromorphic features have also been reported in compacted skid trails in Canada and Germany (McNabb & Startsev 2022, Klein-Raufhake et al. 2024). This is an issue for fine roots, as fine root productivity and biomass decline, along with increased mortality, under anaerobic soil conditions (Yaffar et al. 2023). Anaerobic soil conditions are caused by heavy machinery traffic in high-use skid trails, which destroys macropores (Naghdi et al. 2016). The loss of macropores is also an issue for fine roots, as roots prefer to grow in existing pores rather than to create new pores through bioturbation (Keller et al. 2021). Lastly, given that pH and exchangeable cations were similar in both skid trails and controls, it appears that the soil chemical properties evaluated did not influence differences in FRB.

Lack of recovery in the short-term for fine root biomass and carbon stocks

There was no observable short-term recovery of fine root biomass (FRB) in skid trails after almost 3 years, confirming the second research hypothesis. The single isolated and elevated FRB sample in the skid trails was likely due to uncompacted soil rather than recovery. The skid trail surfaces were not scraped clean with the tractor blade, leaving litter and large tree roots, which could have protected the mineral soil below. A lack of short-term recovery of fine roots in skid trail tracks has been observed in other regions, such as Germany, after 6 years (Ebeling et al. 2017). Nonetheless, in another short-term study in Iran, Jourgholami et al. (2021a) observed recovery of FRB in skid trails with a dense overhead canopy after 5 years, whereas FRB in skid trails in clearcuts and natural gaps remained impoverished. The absence of FRB recovery in the present study is not surprising, considering FRB turnover. In the Central Amazon, the average lifespan of FRB is 3.7 years (Cordeiro et al. 2020). As the presence of FRB is highly correlated with soil C stock (Cordeiro et al. 2024, Cusack & Turner 2021), more time is likely needed for soil C stocks to build up from several turnover cycles. This is because fine roots are a substantial contributor to soil organic matter (Lin & Zeng 2017). However, this process is seriously inhibited in highly compacted skid trails, as fine root presence is negatively correlated with increased soil compaction (Latterini et al. 2024). Studies have consistently demonstrated that root lengths, rooting depths, and root biomass are substantially reduced in skid trails (Cambi et al. 2017, Naghdi et al. 2016), which results in lower contributions to soil C stocks over time. Even after FRB recovery, soil organic carbon had not recovered in the same skid trails after 5 and 13 years (Jourgholami et al. 2021a, DeArmond et al. 2024b). In contrast, after 28 and 30 years of skid trail recovery, both FRB and soil C had recovered (Tavankar et al. 2021, DeArmond et al. 2023).

Due to the slow recovery process of FRB and carbon stocks, improving degraded skid trail soils would enhance carbon storage and sequestration potential. Generally, skid trails are left to recover naturally over time, which may take decades or longer (DeArmond et al. 2021). Nevertheless, several studies have shown that there are

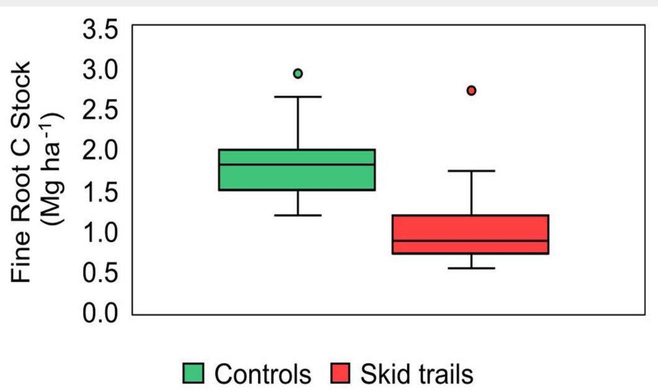

Fig. 6 - Box plots for fine root carbon stocks in undisturbed soil in controls and skid trails. Outliers are identified with infilled circles.

methods to increase fine root production in skid trails, with the added benefits of lower soil bulk density and greater soil C accumulation. After four years of recovery, trails treated with various leaf mulch revealed increased FRB and soil C compared to untreated trails (Jourgholami et al. 2021b). Another approach involved planting a pioneer species – *Alnus incana* – adjacent to skid trails, which lowered soil bulk density and increased fine root density in the skid trails after 8 years (Flores Fernández et al. 2019). As the skid trails in the present study will not receive any amelioration, the estimated recovery time for FRB and carbon stocks will likely exceed a decade, or approximately three fine root turnover cycles. However, this study is limited to a single area in the humid tropics, therefore care should be taken when extrapolating these results elsewhere.

Conclusion

In the tropical forests of Amazonia, skid trails are a vital component of logging operations. Nevertheless, their implementation and use directly affect the fine root carbon stock of the stand. This impact lasts for years in heavily impacted primary skid trails. Calculations of carbon stocking and net primary productivity need to account for reduced fine root capacity in logged stands. However, primary skid trails are just one part of a functioning skid trail system, which includes many more tertiary and secondary skid trails. Future research should consider differences in skid trail traffic intensity and their impacts on soil carbon stocks, net primary productivity, and recovery processes over time. Our results further emphasize the need to carefully plan skid trail systems in timber harvesting operations to protect the belowground carbon pool as much as possible.

Competing interests

The authors declare there are no competing interests.

Data availability

Data will be made available on request.

Acknowledgments

The authors would like to thank the CNPq - *Conselho Nacional de Desenvolvimento Científico e Tecnológico*, Capes, and Fapeam for grant funding. In addition, the authors would like to thank INCT - *Instituto Nacional de Ciência e Tecnologia Madeiras da Amazônia* and the PPG-CFT *Programa de Pós-Graduação em Ciências de Florestas Tropicais* for their scientific and financial support of the research project.

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