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IMPACTS AND RECOVERY AFTER SOIL COMPACTION FROM LOGGING MACHINERY IN CENTRAL AMAZONIA

DANIEL DE ARMOND

Manaus, Amazonas
Outubro, 2023

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IMPACTS AND RECOVERY AFTER SOIL COMPACTION FROM LOGGING MACHINERY IN CENTRAL AMAZONIA

Orientador: Adriano José Nogueira Lima

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ATA DE DEFESA PÚBLICA DE TESE DE DOUTORADO

Ata da Defesa REMOTA de **DANIEL DE ARMOND**, ocorrida no dia 13 de outubro de 2023, via plataforma de videoconferência Zoom.

Aos 13 dias de outubro de 2023, às 08h00 (horário de Manaus/AM), realizou-se a Defesa Pública de tese de **DANIEL DE ARMOND**, aluno do Programa de Pós-Graduação *Stricto sensu* em Ciências de Florestas Tropicais, intitulada "Impacts and recovery after soil compaction from logging machinery in Central Amazonia", sob a orientação do Dr. Adriano José Nogueira Lima (INPA), em conformidade com o Art. 52 do Regimento Geral da Pós-Graduação do Instituto Nacional de Pesquisas da Amazônia (MCTI/INPA) e Art. 67 do Regimento Interno do Programa de Pós-Graduação em Ciências de Florestas Tropicais, como parte das atividades para conclusão e obtenção do Título de Doutor(a) em Ciências de Florestas Tropicais. A **Banca Examinadora** foi constituída pelos seguintes membros: Sávio José Filgueiras Ferreira (INPA), Newton Paulo de Souza Falcão (INPA), Daniel Magnobosco Marra (Max-Planck-Institute for Biogeochemistry), Alberto Carlos Martins Pinto (UFAM), Fabiano Emmert (UFRA), e tendo como suplentes os seguintes membros: Bruno Oliva Gimenez (INPA) e Cacilda Adélia Sampaio de Souza (INPA). O Presidente da Banca Examinadora deu início à seção e informou os procedimentos do exame. O aluno fez uma exposição do seu estudo e ao término foi arguido oralmente pelos membros da Comissão. Após as arguições os membros da banca se reuniram para avaliação e chegaram ao seguinte parecer:

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Nada mais havendo a tratar, foi lavrada a presente Ata que, após lida e aprovada, foi assinada pela Coordenação:

A banca examinadora apresenta as seguintes sugestões: 1) considerar o título em função das considerações finais; 2) reforçar ou destacar que o estudo tem orientação para o sistema Celos (corte, pré-arraste e arraste). Além disso, a banca também sugere incorporar os resultados mais relevantes, ligar os capítulos e fechar em torno do tema central, fornecendo recomendações.

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Sinopse:

Estudou-se os impactos e a reabilitação do solo argiloso compactado pelas máquinas pesadas em florestas exploradas, localizadas na Amazônia Central. Aspectos como densidade do solo, resistência à penetração do solo, raízes finas e propriedades químicas do solo foram avaliados.

Palavras-chave: Exploração de madeira, trilhas de arraste, compactação do solo, Latossolo amarelo

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“A sower went out to sow his seed. And as he sowed, some fell by the wayside; and it was trampled down, and the birds of the air devoured it. Some fell on rock; and as soon as it sprang up, it withered away because it lacked moisture. And some fell among thorns, and the thorns sprang up with it and choked it. But others fell on good ground, sprang up, and yielded a crop a hundredfold.”

Luke 8:5-8 (NKJV)

Resumo

A cada ano, vastas áreas de floresta madura são derrubadas em toda a Amazônia. Muitas vezes, a madeira é extraída com máquinas pesadas, o que leva à compactação do solo. Atualmente, a maioria das pesquisas sobre este tema tem sido conduzida em florestas temperadas. Nos trópicos, há uma escassez geral de pesquisas sobre a compactação do solo induzida pela exploração madeireira, especialmente no bioma Amazônico. O objetivo deste trabalho foi quantificar os impactos iniciais e a posterior recuperação do solo revolvido por máquinas empregadas na extração de madeira na Amazônia Central. A amostragem ocorreu em trilhas de arraste, trilhas experimentais de trator, pátios de estocagem e controles não perturbados adjacentes em solo dominado por argila de baixa atividade. As trilhas experimentais foram estabelecidas com um trator de esteira D6 para testar as diferenças na compactação do solo entre as estações (por exemplo: chuvosa, seca) e a intensidade do tráfego (por exemplo: 1, 3, 12 ciclos de máquina). O tempo desde os eventos de compactação variou de menos de um ano a 1, 13, 19, 23, 26, 27 e 28 anos após a perturbação do solo. Amostras foram coletadas para os seguintes atributos: densidade do solo, resistência do solo à penetração, biomassa de raízes finas, serapilheira, nutrientes foliares (total N, P, K, Ca, Mg, Fe, Mn, Zn) e propriedades químicas do solo (total N, NH_4^+, NO_3^-, P disponível, K^+, Ca^{2+}, Mg^{2+}, Na^+, Fe^{2+}, Mn^{2+}, Zn^{2+}, Al^{3+}, carbono orgânico, pH, capacidade de troca catiônica, saturação de base, saturação de alumínio). Independentemente da estação, o primeiro ciclo da máquina causou o maior aumento na compactação do solo. Houve menos danos à macroporosidade na estação chuvosa, quando a água do solo estava acima da capacidade de campo. Um ano após a compactação, as propriedades químicas do solo da trilha do trator foram mais afetadas pela compactação pesada na estação chuvosa. A recuperação do solo ocorreu em aproximadamente 15 anos para a capacidade de troca catiônica, 20 anos para o carbono orgânico e 25 anos para a densidade. Aos 27 anos após a exploração, os pátios de estocagem ainda não haviam recuperado as propriedades físicas do solo e da biomassa de raízes finas em relação aos valores encontrados em floresta madura adjacente. Depois de 28 anos, o solo superficial recuperado em trilhas de arraste ainda era afetado pela camada de solo inferior compactado, o qual agia como um duripã. Estes resultados indicam que os impactos das máquinas madeireiras são imediatos e duradouros. Portanto, atividades de manejo florestal devem incorporar métodos e tecnologias que minimizem ao máximo a construção de infraestrutura madeireira, como trilhas de arraste e pátios de estocagem. A infraestrutura de exploração deve prever a manutenção e logística de áreas de exploração atual e futura.

Abstract

Each year, vast areas of old-growth tropical forest are logged throughout Amazonia. Often, the timber is extracted with heavy machinery, which inadvertently leads to soil compaction. Currently, the majority of research on this topic has been conducted in temperate forests. In the tropics, there is an overall scarcity of research on logging induced soil compaction, especially in the Amazon biome. Therefore, the aim of this work was to quantify the initial impacts and subsequent recovery of soil disturbed by logging machinery in the Central Amazon. Sampling occurred in skid trails, experimental tractor trails, log landings and adjacent undisturbed controls on soil dominated by low activity clay. The experimental trails were established with a D6 track-type tractor to test the differences in soil compaction between seasons (*e.g.*, wet, dry) and traffic intensity (*e.g.*, 1, 3, 12 machine cycles). Time since compaction events ranged from less than a year to 1, 13, 19, 23, 26, 27 and 28 years after soil disturbance. Samples were collected for the following attributes: soil bulk density, soil penetration resistance, fine root biomass, forest floor litter, foliar nutrients (total N, P, K, Ca, Mg, Fe, Mn, Zn) and soil chemical properties (total N, NH_4^+, NO_3^-, available P, K^+, Ca^{2+}, Mg^{2+}, Na^+, Fe^{2+}, Mn^{2+}, Zn^{2+}, Al^{3+}, organic C, pH, cation exchange capacity, base saturation, aluminum saturation). Regardless of season, the first machine cycle caused the greatest increase in soil compaction. There was less damage to macroporosity in the wet season when soil water was above field capacity. At 1 year after compaction, tractor trail soil chemical properties were most affected by heavy compaction in the wet season. Over time, soil recovery occurred at approximately 15 years for cation exchange capacity, 20 years for soil organic C and 25 years for soil bulk density. By 27 after logging, log landings still had not recovered the soil physical properties of fine root biomass encountered in adjacent undisturbed old-growth forest. After 28 years, recovered topsoil in skid trails was still affected by the compacted soil layer below that acted as a hardpan. These findings indicate that impacts from logging machinery are immediate and long-lasting. Therefore, the implications for forest management are to minimize to the greatest extent feasible the construction of logging infrastructure such as skid trails and log landings and plan their layout for future reuse.

Resumen

Todos los años, se talan vastas áreas de bosque tropical antiguo en toda la Amazonía. A menudo, la madera se extrae con maquinaria pesada, lo que inadvertidamente conduce a la compactación del suelo. Actualmente, la mayoría de las investigaciones sobre este tema se han realizado en bosques templados. En los trópicos, hay una escasez general de investigación sobre la compactación del suelo inducida por la tala, especialmente en el bioma amazónico. Por lo tanto, el objetivo de este trabajo fue cuantificar los impactos iniciales y la posterior recuperación de suelos perturbados por maquinaria maderera en la Amazonía Central. El muestreo se realizó en pistas de arrastre, pistas de tractores experimentales, patios de carga y controles adyacentes no perturbados en suelo dominado por arcilla de baja actividad. Los senderos experimentales se establecieron con un tractor de orugas D6 para probar las diferencias en la compactación del suelo entre las estaciones (p. ej., húmedo, seco) y la intensidad del tráfico (p. ej., 1, 3, 12 ciclos de máquina). El tiempo transcurrido desde los eventos de compactación varió desde menos de un año hasta 1, 13, 19, 23, 26, 27 y 28 años después de la perturbación del suelo. Se recolectaron muestras para los siguientes atributos: densidad aparente del suelo, resistencia a la penetración del suelo, biomasa de raíces finas, hojarasca del suelo forestal, nutrientes foliares (N, P, K, Ca, Mg, Fe, Mn, Zn totales) y propiedades químicas del suelo (N, NH_4^+, NO_3^-, P disponible, K^+, Ca^{2+}, Mg^{2+}, Na^+, Fe^{2+}, Mn^{2+}, Zn^{2+}, Al^{3+}, carbono orgánico, pH, capacidad de intercambio catiónico, saturación de bases, saturación de aluminio). Independientemente de la estación, el primer ciclo de la máquina provocó el mayor aumento en la compactación del suelo. Hubo menos daño a la macroporosidade en la estación húmeda cuando el agua del suelo estaba por encima de la capacidad de campo. Un año después de la compactación, las propiedades químicas del suelo de la pista de tractor se vieron más afectadas por la fuerte compactación en la estación húmeda. Con el tiempo, la recuperación del suelo ocurrió aproximadamente a los 15 años para la capacidad de intercambio catiónico, 20 años para el carbono orgánico del suelo y 25 años para la densidad aparente del suelo. 27 años después de la tala, los patios de carga aún no habían recuperado las propiedades físicas del suelo de la biomasa de raíces finas que se encuentran en bosques primarios adyacentes no perturbados. Después de 28 años, la capa superior del suelo recuperada en los senderos de arrastre todavía se veía afectada por la capa de suelo compactado debajo que actuaba como capa dura. Estos descubrimientos indican que los impactos de la maquinaria maderera son inmediatos y duraderos. Por lo tanto, las implicaciones para la gestión forestal son minimizar en la mayor medida posible la construcción de infraestructura maderera, como pistas de arrastre y desembarcaderos de troncos, y planificar su diseño para su futura reutilización.

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General Introduction

Alterations of soils physical, chemical and biological properties are pervasive issues in managed forests. The causes and effects of machinery induced soil compaction are well known, especially in temperate forests (Greacen and Sands, 1980; Worrell and Hampson, 1997; Nawaz et al., 2013; Cambi et al., 2015a, DeArmond et al., 2021). What is less known are the impacts, subsequent recovery processes, and the timescales at which they occur in tropical forests. Over the last five decades numerous studies have been conducted to determine the length of time required for soil recovery at a given site under specific conditions such as soil texture and traffic intensity (Dickerson, 1976; Froehlich et al., 1985; Jusoff, 1996; Brais, 2001; Ezzati et al., 2012). The results of many studies and experiments have considerable variation depending on the amount of machine traffic, soil type, climate and the region of logging operations. However, a common consensus is that soil compaction persists for decades, if not longer (DeArmond et al., 2019; Mohieddine et al., 2019; Sohrabi et al., 2020).

Research of soil recovery after compaction has been gaining increased attention and awareness in recent years. The resultant decrease in site-productivity should concern all those with a vested interest in the long-term viability of forested ecosystems. Although there is an increasing awareness of the mechanisms involved in the soil recovery process after logging operations, there is still a sizable gap in the understanding of these processes in tropical forests worldwide. Therefore, this work sought to contribute to the quantification of the impacts and recovery process of clay soils in the humid tropics, so that future assessments and management decisions can be made based on a more complete understanding of the factors involved.

The specific areas of investigation that are presented here include experimental machine operating trails, skid trails and log landings that range in age from less than a year up to 28 years in age. Logging infrastructure has been well defined for many decades. Landings are cleared areas in the forest where the vegetation and topsoil are scrapped off to make way for the inventory, stacking and loading of logs to be shipped to a sawmill (Simmons, 1951; Dykstra and Heinrich, 1996). Skid trails are paths through the forest that enable heavy machinery to drag logs from the stump to the landing (Simmons, 1951; Dykstra and Heinrich, 1996). Skid trails are classified by their use: primary which experience more than ten cycles, secondary from two to ten cycles, and tertiary with only a single machine cycle (Whitman et al. 1997; Medjibe et al. 2011; Behjou 2014). A cycle consists of one ingress into the skid trail followed by an egress with a “turn” of log or logs on the same trail. The skid trail is not only characterized by the amount of traffic usage but can also be stratified into the different areas impacted on the running surface of the trail. These being the areas directly below the tracks where machinery makes contact with soil and the areas between the tracks where the log or logs are dragged, as well as the areas on either side of the tracks. These aspects of the skid trail are important to differentiate and stratify, as the initial compaction and subsequent recovery can be quite different in each area (DeArmond et al., 2021).

Assessments of the recovery of logging compacted soils for the most part began in the 1970’s (Hatchell et al., 1970; Hatchell and Ralston, 1971; Mace, 1971; Dickerson, 1976; Holman et al., 1978). The principal measurement parameter used in these studies was soil bulk density. These studies were also all conducted in the temperate forest biome. However, in the 1980’s, research began to evaluate greater aspects of recovery in skid trails other than the soils physical properties, such as: soil microbiota, successional vegetation and biomass (Hatchell, 1981; Calais and Kirkpatrick, 1983; Dick et al., 1988). This decade is also when the emergence of studies in the humid tropics began (Gillman et al., 1985; Jusoff and Majid, 1986; Jusoff, 1988). Even though, studies on this topic have been ongoing throughout the world over the last 50 years, there are still very few studies in the humid tropics, especially in Amazonia. Throughout this period of research though, it becomes abundantly clear that primary skid trails do not recovery quickly, and that the limited cases of recovery are generally limited to lighter use skid trails, *e.g.* secondary, tertiary (Reisinger et al., 1992; Williamson and Neilsen, 2003; Rab, 2004; Zenner et al., 2007). The information on landing recovery up to this point is relatively scarce with a limited number of studies conducted (Hatchell and Ralston, 1971; Lockaby and Vidrine, 1984; Reisinger et al., 1992; Jusoff, 1996; DeArmond et al., 2022). Unfortunately, many of these early works only measured one parameter, usually bulk density, and recent studies have demonstrated that many times bulk density has recovered while other properties have not (Smith and Wass 1985; Vora 1988; Brais 2001; Williamson and Neilsen, 2003). Therefore, it is prudent to measure more than one parameter when trying to determine the status of a recovering soil, as one is likely not sufficient.

The importance of this research, recovery processes of skid trails and landings, is because of the vast areas within forests where logging operations occur every year. On average, skid trail disturbance in logged areas accounts from two to ten percent of ground disturbance on average (Christopher and Visser 2007; Sawyers et al. 2012; Medjibe et al. 2013; Jourgholami et al. 2014; Arevalo et al. 2016; de Carvalho et al. 2017). However, in some instances skid trails may cover over 20% of the logging area (Dyrness 1965; Cheatle 1991; Thompson et al. 2011; Aust et al. 2019). This is a considerable amount of area that is generally left to recover naturally. Consequently, skid trails and landings become areas of diminished site productivity in the form of reduced biomass and c ommercial volumes (Froehlich, 1979; Smith and Wass, 1979; Hatchell, 1981; Wert and Thomas, 1981; Helms and Hipkin, 1986). Furthermore, these areas may even be considered a source of pollution in the form of sediment transport (*e.g.*, erosion) and greenhouse gas emissions. For example, forest soils are generally a methane (CH_4) sink (Dörr et al., 1983; Schnell and King, 1994; Price et al., 2004; Hiltbrunner et al., 2012). Nevertheless, skid trail compaction impairs soil consumption of atmospheric CH_4 (Teepe et al., 2004; Frey et al. 2011; Hartmann et al., 2014; Warlo et al., 2019; Vantellingen et al., 2022). In some cases, primary skid trails have become a source for CH_4 emissions, whereas the tertiary skid trails remained a CH_4 sink (Frey et al., 2011). In Amazonia, log landings were found to be the largest contributor in CH_4 emissions compared to other logging infrastructure on both a clay and a sandy soil (Keller et al., 2005). Skid trails also increase nitrous oxide and carbon dioxide within the soil profile (Goutal et al., 2013; Fründ et al., 2016; Jankovský et al., 2018), which can sometimes persist for decades (Ebeling et al., 2016).

In this context, this work seeks to fill the extensive gaps that exist in the knowledge of the impacts and recovery of logging induced compaction in the humid forests of Amazonia. Currently, there only a few studies on logging impacts to soil in the Amazon basin (Mello-Ivo et al., 1996, 2006; Ferreira et al., 2001, 2002, 2006; Keller et al., 2005; Olander et al., 2005; Schack-Kirchner et al., 2007; Hirai, 2008; DeArmond, 2018; DeArmond et al., 2020, Trindade et al., 2021), and even fewer on the subsequent recovery (McNabb et al., 1997; DeArmond et al., 2019, 2023a, 2024). Therefore, the aim of this work was to establish a basis of knowledge in this area that can serve as a foundation for future research, while at the same time clarifying the processes of recovery that occurs in the clay soils and humid climate of Amazonia. This thesis is divided into five chapters, or research papers, in the following order addressing the following questions:

- *Chapter 1*: Should the prohibition of logging in the wet season, specifically skid trail use, be reevaluated by the regulating agencies?
- *Chapter 2*: What are the seasonal differences in soil chemical properties 1 year after compaction from logging machinery?
- *Chapter 3*: Are there any observable trends of recovery over a time span of 26 years for soil physical and chemical properties in Central Amazonian skid trails?
- *Chapter 4*: After 27 years of recovery, do the impacts to soil physical properties and fine root biomass remain in Central Amazonian log landings?
- *Chapter 5*: In skid trails with observed recovery of soil physical properties, what is the assessment of the recovery when evaluating other attributes such as soil chemical properties and fine root biomass after 28 years?

OBJECTIVES

General objective

To evaluate the impacts and recovery of clay soils after logging machinery induced compaction in the humid tropics.

Specific objectives

1) Determine if differences exist in the initial impacts to soil physical properties between wet and dry seasons after light, moderate and heavy machinery traffic;

2) Determine if there are beneficial impacts to soil chemical properties after compaction from heavy machinery, as well as an assessment of the detrimental impacts caused by increasing traffic and seasonal influence (moisture content);

3) Estimate the soil recovery rate of primary skid trails based on a chronosequence of 26 years;

4) Determine if soil physical properties in log landings recover within the same time interval as skid trails;

5) Determine if recovered topsoil in primary skid trails encountered by DeArmond et al. (2019) have undergone a complete recovery based on soil chemical properties and fine root biomass.

Chapter 1

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Support for reevaluation of policy prohibiting logging operations in the wet season of the Brazilian Amazon

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ABSTRACT

In the Brazilian Amazon, logging is primarily restricted to the driest months of the year by law. Even so, the dry season in the humid tropics is susceptible to considerable rain events, with rain occurring monthly. Therefore, an experiment was established in unentered Central Amazonian old-growth forest to compare skid trail use in the wet season, when logging operations are not permitted, as well as in the dry season. This was done to investigate the differences in soil compaction for the season closed to logging versus the season open to logging. A randomized complete block design (RCBD) was utilized with three blocks composed of seven sub-blocks each, which contained a control, 1, 3 and 12 tractor cycles in both the wet and dry seasons. A Caterpillar track-type tractor model D6D was used for experimental skid trail establishment. Regardless of season the initial machine cycle caused the greatest increase in soil bulk density (BD) and penetration resistance (PR), as well as the greatest decrease in macroporosity. In fact, the initial dry season cycle caused more severe compaction than the wet season. Nevertheless, after 3 cycles, increases to BD and PR were similar for both seasons, with the end result after 12 cycles nearly identical. To the contrary, macroporosity was substantially reduced in the dry season versus the wet season. Overall, the site impacts were similar in both seasons. Thus, skidding operations could be permissible during the wet season with similar impacts caused in the dry season.

Keywords: forest management, machine cycle, soil moisture, soil compaction, macroporosity, penetration resistance

1. Introduction

Skid trails are a vital component of the logging infrastructure in ground-based harvesting systems. Nevertheless, skid trails cause varying degrees of impacts that affect the forest ecosystem (Cambi *et al.*, 2015a). Some impacts such as canopy opening and forest floor disturbance from skid trail construction result in increased plant diversity (Wei *et al.*, 2015; Mercier *et al.*, 2019). Even so, exotic plants may also be introduced through skid trail systems (Veldman *et al.*, 2009). Moreover, the often-favorable increase in light incidence for commercial species, is usually outweighed by a reduction in germination, root penetration and seedling foliar nutrients because of soil compaction (Picchio *et al.*, 2019; Solgi *et al.*, 2019; Treasure *et al.*, 2019). These impacts to soil in skid trails are generally long-lasting and persist for several decades, with skid trail coverage of the harvest area generally less than 10% in the tropics (DeArmond *et al.*, 2021). In the Central Amazon, a systematic planning of skid trails and the use of a winch to pull logs to the skid trails reduced ground disturbance to less than 3% (de Graaf and van Eldik, 2011). Additionally, forest regulations aim to reduce environmental impacts by reducing skid trail coverage of the logging site, as well as prescribing operational limitations for heavy machinery use.

A common approach to lessen the initial impacts from skid trail construction and use, is to limit operations to drier conditions. This is because increased soil moisture content is generally correlated with increased compaction (McNabb *et al.*, 2001; Cambi *et al.*, 2015a; Allman *et al.*, 2022). Numerous studies have attempted to quantify if tracked versus wheeled machines can lessen the impact on soils with elevated moisture (Jusoff, 1991; Cambi *et al.*, 2015b; D'Acqui *et al.*, 2020). These studies found that regardless of the differences between machinery type, moisture had the greater impact on soil compaction than machine differences. In the Amazon, Schack-Kirchner *et al.* (2007) determined that irrespective of wet or dry conditions the trend of increasing compaction with depth was similar. When soil moisture is high, the damage predominantly comes from soil displacement (Williamson and Neilsen, 2000). This is because rut formation increases with increasing soil moisture and traffic due to the lower bearing capacity of the soil (Jourgholami and Majnounian, 2011; Riggert *et al.*, 2019; Sadeghi *et al.*, 2022). However, despite a soil's moisture content, severe damage to many soils occurs in the first few passes by heavy machinery (McNabb *et al.*, 2001; Naghdi *et al.*, 2016a; Tavankar *et al.*, 2021a).

In the Brazilian Amazon, forest management is directed by the National Forest Code, which was initially established in 1934, and subsequently replaced in 1965, which was again replaced in 2012 by the current forest code (Brasil, 1934; Brasil 1965 Brasil 2012). The new forest code is general in nature and identifies areas of permanent protection such as areas adjacent to watercourses and steep slopes, as well as minimum forest cover to be maintained throughout managed portions of the forested biomes. In addition, the minimum information necessary to be included in submitted sustainable forest management plans is listed in the new forest code. The National Ministry of the Environment (IBAMA), guided by the forest code, dictate to Amazonas state ministries more specific matters of forest management such as cutting intensity, and operational restrictions for the rainy season (*i.e.*, wet season) (CONAMA, 2009). In the state of Amazonas, the environmental ministry established the restriction period (*i.e.*, no timber felling, skidding or log hauling) usually from December 15th to May 15th of the following year. Although, depending on the local conditions of the sub-region the overseeing agency IPAAM can make allowances (CEMAAM, 2018) or even extend beyond the restriction period, depending on site conditions (IPAAM, 2022). At the federal level, logging operations in forest concessions are restricted from 16th of December to 14th of May of the following year (IBAMA, 2015).

In this context, the present study sought to investigate differences in compaction caused by logging machinery in experimental skid trails for the wet and dry seasons. The intent of this study was to test the relevance of wet season restrictions dictated by law, as there is precipitation year-round, even in the dry season. Thus, the objective of this study was to determine if the current policy that prohibits logging for approximately half the year should be reassessed based on experimental data that compares soil impacts between seasons.

2. Material and methods

2.1. Study site

The study site (2° 38’ 25” S, 60º 09” W) is in the Amazon forest, located to the north of Manaus, state of Amazonas, Brazil (Fig. 1). The regional climate was classified as tropical without a dry season (Af) with all months receiving precipitation above ≥ 60 mm and an annual mean temperature of above 26° C, according to the Köppen classification system (Alvares *et al.*, 2013). Although there is not a technical dry season by the aforementioned classification system, from June to November conditions are generally drier in Central Amazonia, which is also why logging operations are permitted. Thus, the driest six months of the year, typically June through November, will be considered the dry season for the purposes of this research, which is entirely within the legally mandated operational period that is approximately between 15th of May to the 15th of December (Table 1). In the wet season the experimental skid trails were established on May 5, 2021, and in the dry season on September 28, 2021 (Fig. 2). The precipitation accumulated the week before skid trail establishment in the wet season was 93 mm with no rainless days and in the dry season 37 mm with 3 rainless days. Within the 24-hour period surrounding skid trail establishment gravimetric water content was determined from the controls in each block and then converted to volumetric water content. On site recorded precipitation data demonstrates an annual amount of greater than 2300 mm (Higuchi *et al.*, 2011). According to a previous forest inventory, there were in the research area 632 ± 46 trees ha^{-1}, a basal area of 29.1 ± 4.4 m^2 ha^{-1} (Marra et al., 2014). The site soil is classified as a Geric Ferralsol (Alumic, Hyperdystric, Clayic) (Quesada *et al.*, 2010). Kaolinite dominates the clay fraction with a small quantity of gibbsite (Chauvel, 1982). Ferralsols in the region are acidic, with low bulk densities, and low base saturation (Ferreira *et al.*, 2002; Trindade *et al.*, 2021). A description of the site texture and organic matter was determined from soil samples taken from the controls in each block of the present study (Table 2).

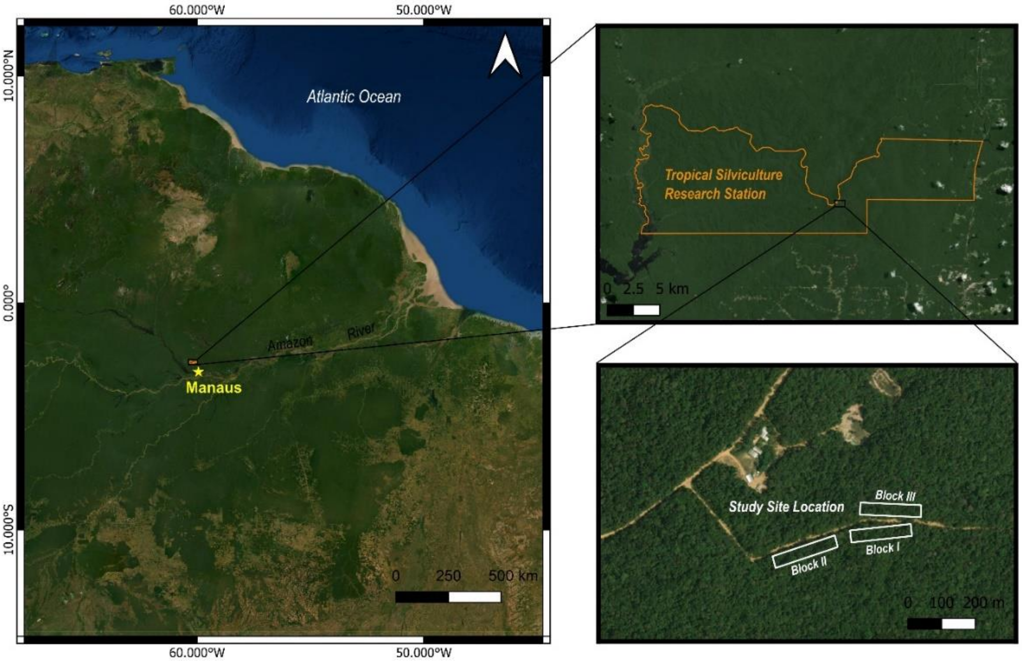

Fig. 1 Location of study site north of the capital city of Manaus in the state of Amazonas, Brazil.

Table 1. Precipitation accumulated in the study area during the approximate six month wet and dry seasons (*i.e.*, logging season) for the years 2014 - 2021.

Wet Season Year†	Precipitation (mm) December - May	Months of precipitation > 100 mm	Dry Season Year†	Precipitation (mm) June - November	Months of precipitation > 100 mm
2013-2014	2114	6	2014	1040	5
2014-2015	1897	6	2015	588	3
2015-2016	1248	4	2016	869	5
2016-2017	1584	6	2017	938	5
2017-2018	1632	6	2018	1055	5
2018-2019	1768	6	2019	1265	6
2019-2020	1519	6	2020	984	4
2020-2021	2080	6	2021	1164	6

†In 2015, an extreme drought occurred (Jiménez-Muñoz *et al.*, 2016).

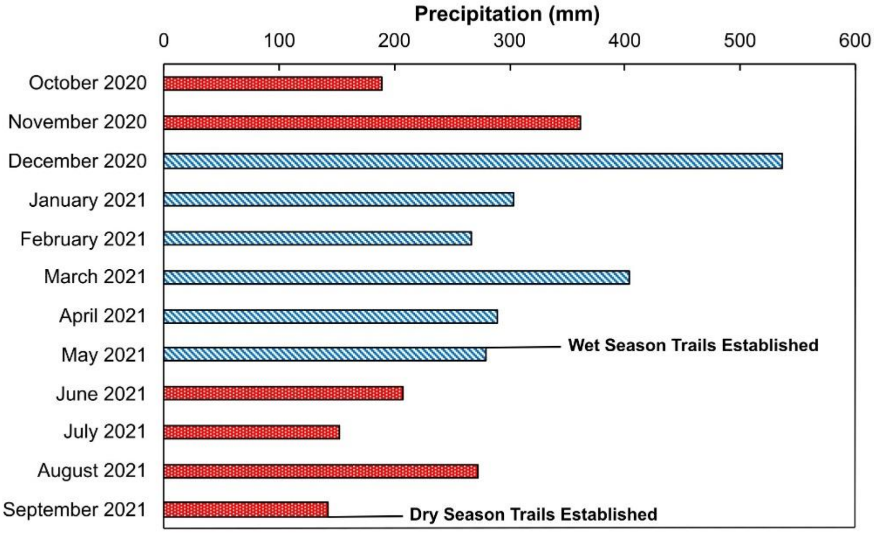

Fig. 2 Study site precipitation with date of the establishment of experimental trails in the wet and dry seasons.

Table 2. Soil physical characteristics determined from controls (*n* = 3). Values are the mean of all samples taken for a given depth (*n* = 9) followed by the standard deviation.

	Soil depth	
Soil characteristic	0-5 cm	5-10 cm
Sand (g kg^{-1})	108 ± 11.4	100 ± 9.52
Silt (g kg^{-1})	213 ± 48.6	159 ± 22.5
Clay (g kg^{-1})	679 ± 48.9	741 ± 20.9
Organic matter (g kg^{-1})	56.07 ± 4.57	34.04 ± 3.99

2.2. Experimental design

A randomized complete block design (RCBD) was utilized as the basis for this experiment. Seven treatments were randomly allocated to each of three blocks (Fig. 3). These treatments were designated as wet season skid trails and dry season skid trails, as well as a control. Each season was further divided into a traffic intensity of 1 cycle, 3 cycles and 12 cycles. A cycle consisted of a single ingress and egress for the experimental skid trails. The intent was to represent the various intensities of traffic that could be experienced in skid trails used in logging operations, as skid trails can generally be divided into primary (> 10 cycles), secondary (2-10 cycles) and tertiary (1 cycle) skid trails (DeArmond et al., 2021). Prior to skid trail establishment, small diameter trees (< 25 cm in diameter 1.3 m above the ground) were cut manually with chainsaws. All cut material was then removed by hand and scattered ≥ 2 m out of the skid trail locations. All experimental skid trails were established with the same Caterpillar track-type tractor model D6D with an operating weight of 13,150 kg. The tractor tracks had a shoe width of 450 mm and a grouser height of 4 mm. A cycle was considered as an ingress and egress of the tractor. The tractor operator was not permitted to deviate the tractor from the traveled path (*i.e.*, no off tracking), nor was the operator allowed to lower the blade. The experimental skid trails for each season were completed in a day and without precipitation.

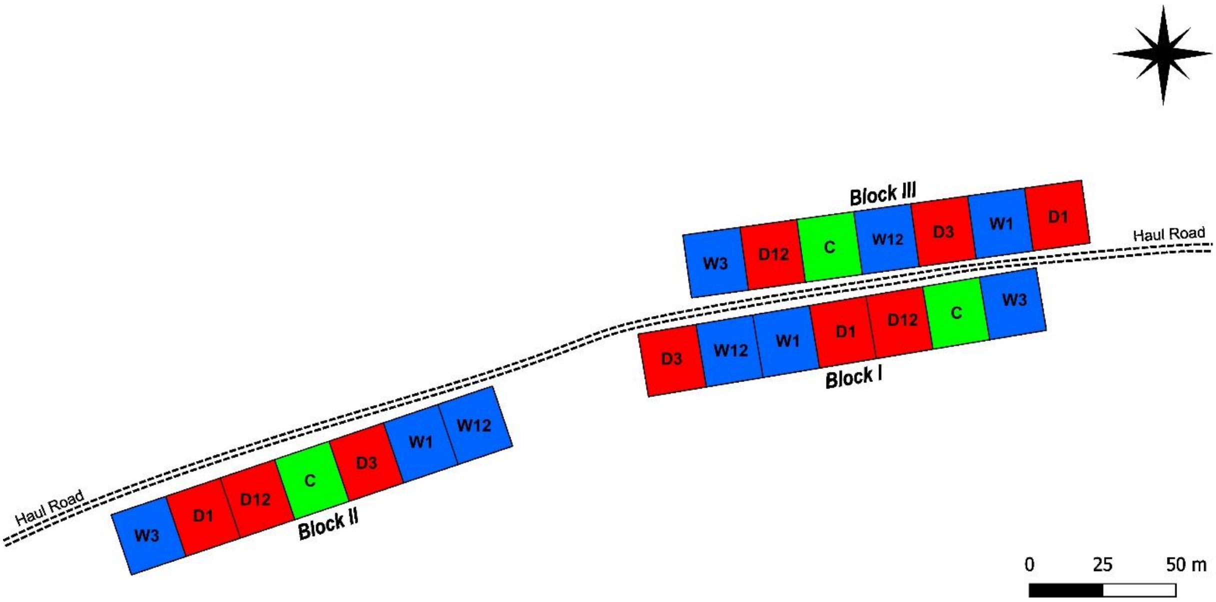

Fig. 3 Experimental design which consisted of three blocks with seven sub-blocks. Each sub-block was designated as one of the following: an undisturbed control (C), wet season 1 cycle (W1), wet season 3 cycles (W3), wet season 12 cycles (W12), dry season 1 cycle (D1), dry season 3 cycles (D3) dry season 12 cycles (D12).

2.3. Sample collection

Total samples that were collected were as follows: soil bulk density (*n* = 420), soil penetration resistance (*n* = 1,630) and macroporosity (*n* = 126). Soil surface disturbance (*i.e.*, tracks) measurements (n = 180) were also randomly made for all experimental skid trails with a ruler placed in the bottom of the track or rut to measure the sidewall height in cm. Rut formation was only encountered where the tractor traversed abandoned leafcutter ant mounds and were assessed separately. For soil bulk density (BD), a 100 cm^3 steel core that was 5 cm in height and diameter was utilized. The collection of BD samples was also used to determine gravimetric water content and the subsequent calculation of volumetric water content (VWC) as well. Soil penetration resistance (PR) was determined with a Stolf impact penetrometer with a 30° angle cone. The PR data was collected in measurement of drop distance and later converted with an Excel spreadsheet into 5 cm depths (Stolf *et al.*, 2014). In addition, samples for macroporosity (> 50 µm in diameter) were collected in a 100 cm^3 steel core that was 5 cm in height and width. The samples for macroporosity were maintained covered in a steel core and transported to the *Embrapa Amazônia Ocidental* soil physics laboratory (LASP) located near Manaus, Brazil. Blocks of soil approximately 5x5x5 cm were collected for the determination of soil texture and organic matter for a given depth from the control treatments, and taken to INPA's soil laboratory (*Laboratório Temático de Solos e Plantas* – LTSP).

2.4. Laboratory analysis

The samples for BD were weighed wet and then dried at 105°C for a minimum of 24 hours and then reweighed dry, which enabled the calculation of BD and VWC according to Brady and Weil (1999):

$$BD = \frac{a}{b} \quad (1) \qquad \theta_m = \frac{c}{a} \quad (2) \qquad \theta_v = BD * \theta_m \quad (3)$$

Where BD is soil bulk density (g cm^{-3}), a is weight of oven dry soil (g), b is total sample volume (cm^3); θ_m is water mass, c is sample water content (g) prior to drying; θ_v is soil volumetric water content (cm^3 cm^{-3}).

The collection of PR data occurred on different days at different soil moisture contents. As PR is highly affected by soil moisture (Smith *et al.*, 1997a), all PR data was adjusted to a common water content. In this case, the common water content that was used was field capacity, as determined by Ferreira *et al.* (2002) in a prior study of the surrounding area. The adjustment of PR data was conducted according to the formula proposed by Vaz *et al.* (2011):

$$PR = \exp\left(a + b^{*}\rho_b + c^{*}\theta_v\right) \qquad (4)$$

Where PR is soil penetration resistance (MPa), ρ_b is bulk density (g cm^{-3}), θ_v is volumetric water content (cm^3 cm^{-3}) and a, b, c are fitting parameters determined through non-linear regression.

Macroporosity was determined after microporosity was first calculated in an *Eijkelkamp* sandbox for pF-determination. Calculations were made according to Teixeira *et al.* (2017):

$$Mi = \frac{(a-b)}{c} \qquad (5) \qquad\qquad Ma = (Pt - Mi) \qquad (6)$$

Where Mi is microporosity (cm^3 cm^{-3}), a is wet soil mass (g) at a water tension of 6 kPa, b is soil mass dried at 105°C for a minimum of 24 hours and c is total sample volume (cm^3) of steel core cylinder, in this case 100 cm^3; Ma is macroporosity (cm^3 cm^{-3}), Pt is total porosity (cm^3 cm^{-3}).

For soil texture and organic matter determination, soil samples were air-dried prior to passing through a 2 mm sieve and removal of organic debris. The Walkley-Black method was used to determine soil organic carbon and the subsequent determination of organic matter with the Van Bemmelen factor of 1.724.

2.5. Statistical analysis

Statistical analysis was prefaced by the evaluation of approximate normality with a combination of the Shapiro-Wilk test, histograms and Q-Q plots. Independent variables were block and treatments. The interaction of block was excluded from the model, as it was not of interest. Dependent variables were soil bulk density, penetration resistance and porosity (macro, micro and total). Comparison of treatments was conducted with a General Linear Model (ANOVA). This was followed by a post hoc Tukey’s honest significance difference test (HSD). All data were analyzed using IBM Corp. SPSS Statistics for Windows, Version 28.0 (Armonk, NY: IBM Corp).

3. Results

3.1. Soil moisture and soil surface

There was a difference between wet and dry seasons for soil moisture in the upper soil depth of 0-5 cm. The soil moisture at the time of establishment for the wet season skid trails was 0.463 cm^3 cm^{-3}, whereas for the dry season skid trails it was 0.395 cm^3 cm^{-3}. This was a difference in soil moisture of 15.9% (t_{20} = 3.928, p = <0.001). In the lower depth of 5-10 cm, there was not a sizeable difference in soil moisture, 7.1%, between seasons (t_{20} = 1.890, p = 0.073). The dry season moisture content of 0.420 cm^3 cm^{-3} was only slightly different from the wet season at 0.451 cm^3 cm^{-3}.

3.2. Soil surface

Surface soil disturbance caused by the tractor tracks was minimal for both seasons (Table 3). Even so, when the tractor traversed abandoned and vegetated leafcutter ant mounds, rut formation did occur in both seasons. However, these areas of rut formation were more accentuated for the wet season.

Table 3. Surface soil changes from tractor cycles.

Season[a]	Cycle	Track depth (cm)	Rut depth (cm)[b]
Wet	1	< 1	11
	3	< 2	15
	12	< 4	19
Dry	1	< 1	3
	3	< 2	6
	12	< 3	11

[a]Post-hoc analysis revealed no statistical differences in track depth between seasons and the same cycle. [b]Rut depths displayed for descriptive purposes, as only a few were encountered when the tractor traversed an abandoned leafcutter ant mound.

3.3. Soil Bulk Density

Changes in soil bulk density (BD) were considerable between treatments (Fig. 4) for the upper depth interval of 0-5 cm ($F_{6,\,201}$ = 41.183, p = <0.001), as well as the lower depth interval of 5-10 cm ($F_{6,\,201}$ = 51.272, p = <0.001). The greatest increase in BD was caused in the first machine cycle regardless of season or depth, although the compaction was greater in the dry season than the wet for the initial tractor cycle (Table 4). From the first to the third machine cycle, increases to BD were substantially lower, except for the lower depth in the in the wet season. In fact, for the 5-10 cm depth interval, the BD for the third cycle in the wet season was the same as the BD for the first cycle in the dry season at 1.10 g cm^{-3}. After the third machine cycle, increases to BD until the twelfth cycle were minimal at less than 3% for all depths and both seasons. Moreover, even though the first machine cycle in the wet season was lower than the first cycle of the dry season, by the twelfth cycle there were only subtle differences between seasons for BD.

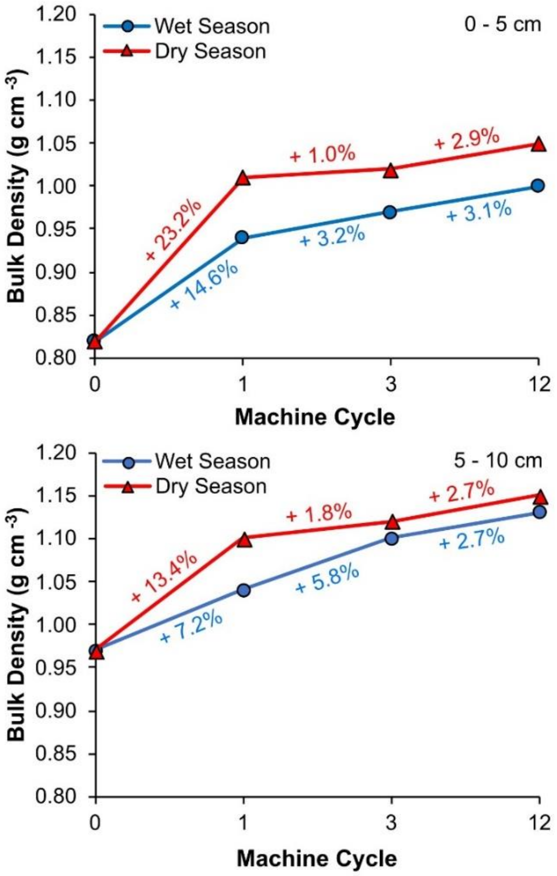

Fig. 4 Soil bulk density (g cm^{-3}) means with percent increase between each mean for both seasons in two depths at 0-5 cm and 5-10 cm.

Table 4. Mean soil bulk density values followed by the standard deviation (±). Differences according to Tukey's HSD test ($\alpha = 0.05$) are designated with different letters per a given row.

Soil Depth (cm)	Bulk Density (g cm^{-3})						
		Wet Season			Dry Season		
	Control	1 Cycle	3 Cycles	12 Cycles	1 Cycle	3 Cycles	12 Cycles
0-5	0.82 ± 0.08^{a}	0.93 ± 0.07^{b}	0.99 ± 0.06^{c}	1.00 ± 0.07^{cd}	1.01 ± 0.06^{cd}	1.02 ± 0.05^{cd}	1.05 ± 0.07^{d}
5-10	0.97 ± 0.08^{a}	1.04 ± 0.04^{b}	1.10 ± 0.05^{c}	1.13 ± 0.04^{cd}	1.10 ± 0.04^{c}	1.12 ± 0.03^{cd}	1.15 ± 0.05^{d}

3.4. Soil Penetration Resistance

The non-linear regression output resulted in the following fitting parameters for the 0-5 cm depth ($n = 210$): a = 0.070, b = 1.519, c = -2.484; and for the 5-10 cm depth ($n = 210$): a = 0.274, b = 1.648, c = -3.069. Prior to adjustment to a common water content, the unadjusted soil penetration resistance (PR) data demonstrated a lack of a consistent trend. This was due to the difference in water content at the time of sample collection that ranged from 0.446 $cm^3\ cm^{-3}$ to 0.550 $cm^3\ cm^{-3}$. The effect of this difference can be seen in the uncorrected data between the third and twelfth tractor cycle in the wet season for the upper depth. Although the twelfth cycle was more compacted than the third (Table 4), the PR was lower for the twelfth than the third machine cycle (Table 5). This was because the mean water content for the third cycle was 0.520 cm^{3} cm^{-3} at the time of sample collection, whereas for the twelfth machine cycle the mean water content was 0.550 cm^{3} cm^{-3}. However, after the adjustment to a common water content, field capacity in this case, a logically increasing trend can be observed. In addition, the values for PR were also adjusted to another common water content, the wilting point, for the studied soils (Table 5). Although, the soil of this area may not often dry to the wilting point, it also most certainly will not stay at field capacity. Therefore, it is important to remain cognizant that the PR will increase when the soil undergoes drier conditions.

Table 5. The mean penetration resistance (PR) values followed by the standard deviation (±) for a given treatment is presented by season and traffic intensity. The PR data is displayed for three categories: 1) prior to adjustment to a common water content ($\theta_{uncorrected}$), 2) after adjustment to field capacity (θ_{10}) and 3) after adjustment to the wilting point (θ_{1500}). Statistical analysis conducted solely for data corrected to field capacity. Significant differences according to Tukey's HSD test (α = 0.05) are designated with different letters per a given row.

Soil Depth (cm)	Volumetric Water Content (θ)†	Penetration Resistance (MPa)			
			Wet Season		
		Control	1 Cycle	3 Cycles	12 Cycles
0-5	$\theta_{uncorrected}$	1.06 ± 0.27	1.13 ± 0.21	1.58 ± 0.47	1.21 ± 0.35
	θ_{10}	1.22 ± 0.14^{a}	1.44 ± 0.15^{b}	1.58 ± 0.15^{c}	1.61 ± 0.17^{cd}
	θ_{1500}	1.64 ± 0.19	1.94 ± 0.20	2.13 ± 0.20	2.17 ± 0.23
5-10	$\theta_{uncorrected}$	1.62 ± 0.34	1.63 ± 0.22	2.11 ± 0.42	1.91 ± 0.41
	θ_{10}	1.59 ± 0.20^{a}	1.79 ± 0.12^{b}	1.98 ± 0.16^{c}	2.08 ± 0.14^{cd}
	θ_{1500}	2.10 ± 0.26	2.36 ± 0.16	2.61 ± 0.21	2.74 ± 0.18
			Dry Season		
0-5	$\theta_{uncorrected}$	1.06 ± 0.27	1.23 ± 0.21	1.29 ± 0.25	1.52 ± 0.25
	θ_{10}	1.22 ± 0.14^{a}	1.63 ± 0.15^{cd}	1.66 ± 0.14^{cd}	1.73 ± 0.18^{d}
	θ_{1500}	1.64 ± 0.19	2.20 ± 0.21	2.24 ± 0.19	2.33 ± 0.24
5-10	$\theta_{uncorrected}$	1.62 ± 0.34	1.59 ± 0.23	1.66 ± 0.26	2.01 ± 0.33
	θ_{10}	1.59 ± 0.20^{a}	1.97 ± 0.12^{c}	2.03 ± 0.11^{c}	2.14 ± 0.16^{d}
	θ_{1500}	2.10 ± 0.26	2.60 ± 0.16	2.68 ± 0.14	2.83 ± 0.21

†In the upper soil depth, the values used for θ_{10} and θ_{1500} were 0.45 and 0.33, respectively, and in the lower depth the values used for θ_{10} and θ_{1500} were 0.46 and 0.37, respectively. Both field capacity and the wilting point values employed were means derived from Ferreira *et al.* (2002).

After data adjustment to a common water content (field capacity), increases to soil penetration resistance (PR) were appreciable between treatments for the upper depth interval of 0-5 cm ($F_{6,\,201}$ = 35.938, p = <0.001), as well as the lower depth interval of 5-10 cm ($F_{6, 201} = 49.785$, $p = <0.001$). Similar to BD, the greatest increase to PR came after the initial machine cycle (Fig. 5). However, on a percent basis the increases to PR were proportionately higher than that of BD, although they both tended to follow the same trend. There were two notable differences to this trend. The first difference was the increase to PR ($p = 0.013$) between the initial and third machine cycles in the wet season for the upper depth (Table 5). The other notable difference was the increase to PR ($p = 0.042$) between the third and twelfth cycles in the dry season for the lower depth. While the twelfth machine cycle resulted in higher PR during the dry season than the wet season, these differences were inconsequential.

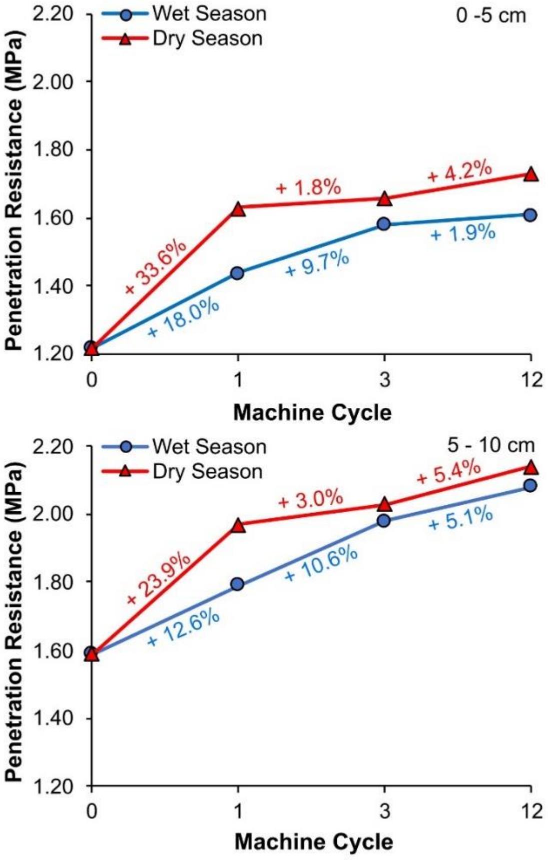

Fig. 5 Soil penetration resistance (MPa) means with percent increase between each mean for both seasons in two depths at 0-5 cm and 5-10 cm.

3.5. Soil Porosity

There were differences in soil porosity for macropores between treatments for the upper depth interval of 0-5 cm ($F_{6, 54} = 33.352$, $p = <0.001$), as well as the lower depth interval of 5-10 cm ($F_{6, 54} = 17.657$, $p = <0.001$). The decrease in macroporosity was severe irrespective of depth or season with a reduction of 60-80% (Fig. 6). In the upper depth interval, the initial machine cycle in the dry season experienced a loss of macroporosity twice that of the wet season first cycle (Table 6). In fact, in this depth the only consequential difference in macroporosity was between the first machine cycle in the wet season and the twelfth machine cycle in the dry season (*p* = 0.003). For the lower depth interval, the dry season twelfth machine cycle resulted in a substantial reduction in macropores to 1.1%, especially when compared to the wet seasons first (*p* = 0.021) and third cycles (*p* = 0.004).

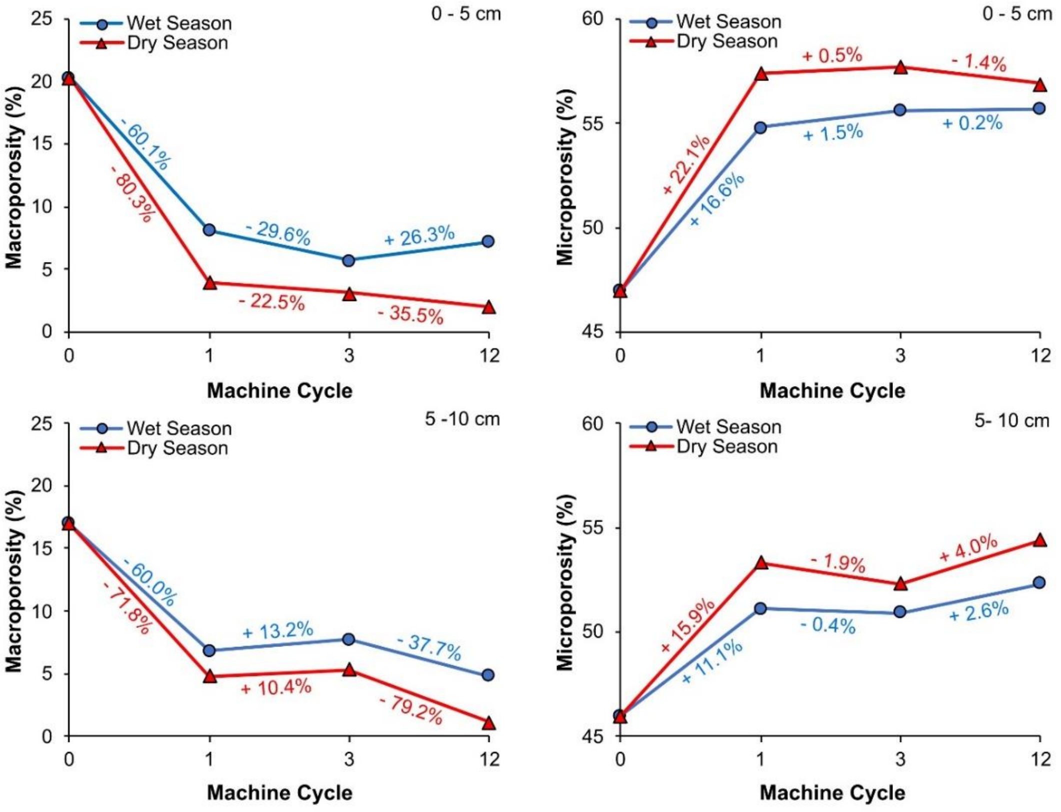

Fig. 6 Soil porosity (%) means with percent increase between each mean for both seasons in two depths at 0-5 cm and 5-10 cm.

Increases in microporosity were slight for all machine cycle treatments in the upper depth interval of 0-5 cm ($F_{6,54}$ = 17.020, *p* = <0.001) and the lower depth interval of 5-10 cm ($F_{6,54}$ = 17.987, *p* = <0.001). To the contrary of macroporosity, microporosity increased 11-22% (Fig. 6). Microporosity in the upper depth interval did not differ much between machine cycle treatments (Table 6). In the lower depth interval, the trend in microporosity followed macroporosity with differences in porosity limited to the wet season first and third machine cycles when compared to the twelfth cycle in the dry season.

Table 6. The mean porosity values followed by the standard deviation (±) for each treatment and depth interval. Macropores are defined as having pore diameters greater than 50 µm with micropores having pore diameters less than 50 µm. Significant differences between treatments determined by Tukey's HSD test ($\alpha = 0.05$) and are designated with different letters per a given row.

Soil Depth (cm)	Pore Space	Porosity (%)			
			Wet Season		
		Control	1 Cycle	3 Cycles	12 Cycles
0-5	Macropores	20.3 ± 3.4^{a}	8.1 ± 4.3^{b}	5.7 ± 3.0^{bc}	7.2 ± 4.3^{b}
	Micropores	47.0 ± 3.2^{a}	54.8 ± 3.5^{b}	55.6 ± 2.1^{b}	55.7 ± 2.5^{b}
	Total pores	67.3 ± 2.3^{a}	62.9 ± 2.6^{b}	61.2 ± 2.0^{bc}	62.9 ± 3.1^{b}
5-10	Macropores	17.0 ± 3.6^{a}	6.8 ± 1.9^{b}	7.7 ± 5.7^{b}	4.8 ± 2.4^{bc}
	Micropores	46.0 ± 1.3^{a}	51.1 ± 1.2^{b}	50.9 ± 3.0^{b}	52.3 ± 1.1^{bc}
	Total pores	63.0 ± 2.6^{a}	57.9 ± 1.6^{b}	58.6 ± 3.0^{b}	57.1 ± 2.0^{b}
			Dry Season		
0-5	Macropores	20.3 ± 3.4^{a}	4.0 ± 2.7^{bc}	3.1 ± 2.3^{c}	2.0 ± 1.4^{c}
	Micropores	47.0 ± 3.2^{a}	57.4 ± 2.7^{b}	57.7 ± 2.1^{b}	56.9 ± 2.2^{b}
	Total pores	67.3 ± 2.3^{a}	61.4 ± 2.1^{bc}	60.8 ± 1.6^{bc}	58.9 ± 2.0^{c}
5-10	Macropores	17.0 ± 3.6^{a}	4.8 ± 4.3^{bc}	5.3 ± 3.8^{bc}	1.1 ± 1.5^{c}
	Micropores	46.0 ± 1.3^{a}	53.3 ± 2.8^{bc}	52.3 ± 2.0^{bc}	54.4 ± 1.7^{c}
	Total pores	63.0 ± 2.6^{a}	58.1 ± 2.0^{b}	57.6 ± 2.1^{b}	55.5 ± 1.9^{b}

[†] In the upper soil depth, the values used for θ_{10} and θ_{1500} were 0.45 and 0.33, respectively, and in the lower depth the values used for θ_{10} and θ_{1500} were 0.46 and 0.37, respectively. Both field capacity and the wilting point values employed were means derived from Ferreira *et al.* (2002).

Total porosity differed between treatments in the upper depth interval 0-5 cm ($F_{6, 54} = 11.963$, $p = <0.001$) and the lower depth interval of 5-10 cm ($F_{6, 54} = 9.882$, $p = <0.001$). Total porosity was always lower than the controls for both depths and seasons (Table 6). In the upper depth interval, total porosity was lowest for the twelfth machine cycle in the dry season, and in trafficked soils this difference was greatest when compared to the initial wet season machine cycle ($p = 0.008$). After the initial decrease in total porosity occurred, there was only negligible decreases between skid trails.

4. Discussion

4.1. Soil moisture

As expected, the soil moisture at the time of wet season skid trail establishment was higher compared to the dry season. Even so, the dry season soil moisture was still elevated and just below the value determined for field capacity, whereas the wet season soil moisture was slightly above field capacity. This was not surprising, as every month in the dry season of 2021 experienced monthly precipitation above 100 mm. In fact, even the severe drought of 2015 had 3 of 6 months with precipitation above 100 cm in the dry season. This indicates that substantial rain events are to be expected during the logging season. With increased moisture there is generally increased soil compaction, although this is only to a critical point whereafter the potential for compaction decreases (Williamson and Neilsen, 2000; Nawaz *et al.*, 2013; Cambi *et al.*, 2015a). Furthermore, fine-textured soils with non-expansive clays tend to compact to the same degree regardless of the soil moisture at the time of compaction (Froehlich and McNabb, 1984). Nevertheless, Tavares Filho *et al.* (2005) developed compaction curves for a similar Ferralsol and determined that the greatest compaction was at a matric potential of -32 kPa. Moreover, Marques *et al.* (2004) found that for another Ferralsol near Manaus, the volumetric water content at a matric potential of 30 kPa (*i.e.*, field capacity) was 0.399 m^3 m^{-3}. Therefore, the dry season skid trail establishment occurred at field capacity under conditions more favorable for increased compaction even though the soil was drier than for the wet season skid trail establishment.

4.2. Soil surface

The soil surface experienced only slight track formation regardless of the season or cycle, whereas rut formation was limited to abandoned leafcutter ant mounds. This was probably because of the retention of the topsoil and organic layer, which consisted of an extensive root network. This is similar to other results encountered in Amazonia. For example, in a study where skid trails were constructed in the Central Amazon near field capacity by blading off the topsoil, track formation was 4 cm in depth after one D6 track-type tractor cycle (DeArmond *et al.*, 2020). Also in the Amazon, Schaak-Kirchner *et al.* (2007) observed 7 cm depth ruts after a single cycle of a laden rubber-tired skidder. So, it is possible that leaving the topsoil and organic layer intact could assist in reducing rutting. In fact, the only ruts encountered in the present study were when the tractor traversed one of the few leafcutter ant mounds present. As it is difficult to avoid wet conditions that are predisposed to rutting in the humid tropics, it is best to limit machinery to skid trails and limit operations when deep rutting occurs (Jourgholami and Majnounian, 2011). Moreover, if rut formation occurs, the appropriate use of water diversion structures has been shown to reduce rut depth, as well as assist in the recovery process (Jourgholami *et al.*, 2018).

4.3. Soil Bulk Density

The increases to bulk density (BD) in the surface soil were found to be in accordance with numerous other studies on the subject, namely the first machine cycle causes the greatest increase in terms of BD (Williamson and Neilsen, 2000; Naghdi *et al.*, 2016a; DeArmond *et al.*, 2020; Tavankar *et al.*, 2021a). However, during the wet season in the lower depth of 5-10 cm, large and significant increases to BD continued until the third cycle. McNabb *et al.* (2001), also found that in boreal forest soils the majority of compaction occurred by the third cycle. This is what the present study encountered in tropical forest soil irrespective of season or depth. Overall, between the third and twelfth cycles the small increases to BD were similar. The one key difference, although not statistically different in all cases, was that the wet season BD values generally did not reach the dry season BD values. This can be attributed to the elevated soil moisture in the wet season. In the wet season, the soil was above field capacity, which means the macropores had not fully drained (Brady and Weil, 1999). Moreover, in clay soils compaction can be impeded by the drainage rate (Greacen and Sands, 1980). Therefore, the elevated moisture content in the wet season skid trails was above the critical moisture content for maximum compaction, which resulted in lower BD values. Although the BD increases from logging machinery tend to be lower in very wet soil, there is greater soil plasticity which leads to displacement and rutting (Wiliiamson and Neilsen, 2000; Ampoorter *et al.*, 2010; Cambi *et al.*, 2015a). In addition, the surface 5 cm did not reach the same high level of BD as the lower 5-10 cm depth. Mello-Ivo and Ross (2006) also encountered this pattern in skid trail BD in area skid trails after logging and attributed this to the effects of higher organic material in the soil surface.

4.4. Soil Penetration Resistance

The results of this study demonstrate that it is imperative to adjust soil penetration resistance (PR) to a common water content, especially when comparing different seasons (*i.e.*, soil moisture contents). This is because PR increases with increasing BD, but also decreases with increasing water content (Smith *et al.*, 1997a; Nawaz *et al.*, 2013). For this reason, prior to adjustment, PR data did not demonstrate a consistent trend because of the variation in soil moisture content, which somewhat obscured the impact of BD. Furthermore, even if all measurements of PR had been taken on the same day, soil moisture would still vary due to the effect compaction has on impeding water percolation. The differences in drainage could lead to microsite differences in PR within the same site or even within the same skid trail.

In both the wet and dry seasons, PR increased at a greater rate than BD in terms of percent, which has also been observed in other studies (Ampoorter *et al.*, 2007; DeArmond *et al.*, 2020). Still, PR has also been shown to diminish at a faster rate than BD in chronosequence studies of soil recovery after compaction (Jusoff, 1996; Sohrabi *et al.*, 2019, 2020; Tavankar *et al.*, 2021a). Thus, growth limiting conditions were reached quicker for PR than BD. For PR, 2 to 2.5 MPa is considered the level where root elongation and tree growth are reduced, whereas for BD over 1.25 g cm^{-3} in heavy clay soils is considered restrictive (Greacen and Sands, 1980; Reichert *et al.*, 2003; Bengough *et al.*, 2011). Therefore, after 3 cycles in the lower depth of 5-10 cm, PR was potentially more limiting to plant growth at 2 MPa than was BD at approximately 1.10 g cm^{-3}, when values were adjusted to field capacity. To the contrary, the upper depth of 0-5 cm never reached what would be considered growth restrictive levels of PR. This is probably because the organic rich topsoil was retained in the experimental skid trails and not scraped off with the blade of the tractor. Although organic matter affects PR to a smaller degree in soils with a high clay content (Smith *et al.*, 1997a), organic matter may contribute to a soil being more resistant to compaction (Nawaz *et al.*, 2013; Cambi *et al.*, 2015a). Therefore, it is expected that the soil organic matter had an indirect impact on lowering PR through the overall effect on BD.

4.5. Soil Porosity

A drastic reduction in macroporosity of over 90% occurred in both seasons, similar to what Bottinelli *et al.* (2014a) encountered in a Neoluvisol in France. In fact, after the first cycle in both seasons air-filled porosity fell below 10%, which is considered the minimum threshold for root growth and survival (Greacen and Sands, 1980; Reichert *et al.*, 2003). For a fine-textured Cambisol in Germany, Klaes *et al.* (2016) found that it took 5 machine cycles to fall below this threshold. Furthermore, even though there was macroporosity left after soil compaction in the experimental skid trails of the present study, these macropores are likely smaller, discontinuous and horizontally parallel to the surface, as has been found in numerous other studies (*e.g.*, Bullock *et al.*, 1985; Alaui *et al.*, 2011; Feng *et al.*, 2020). McNabb *et al.* (2001) speculated that these remaining macropores are from air trapped in voids within the compacted soil. Macroporosity in skid trails is further impeded under wet conditions. For example, Hansson *et al.* (2019) found that after machine traffic, up to 82% of the wet season had less than 10% air-filled porosity in the wheel tracks. Consequently, even though there was higher soil moisture in the experimental skid trails that could benefit for root growth, the macropores were filled with water which inhibits root growth due to insufficient oxygen supply (Greacen and Sands, 1980). Moreover, it has been shown that in skid trails, the lower porosity in combination with higher moisture due to soil compaction led to reduced CH_4 uptake and increased N_2O emissions (Hartmann *et al.*, 2014; Warlo *et al.*, 2019; Vantellingen *et al.*, 2021, 2022).

5. Conclusion

The prohibition of timber harvesting during the wet season is based on the premise that increased site damage occurs during this period. However, logging operations are multifaceted (*e.g.*, timber felling, skidding, log hauling) and the various components should be assessed separately based on their potential impact to the logging site or operator safety. In the present study, greater compaction from logging machinery was encountered in the dry season, although overall damage to soil in the experimental skid trails was relatively the same regardless of season. As skid trails are considered part of the permanent logging infrastructure to be used in future logging operations, the differences in compaction between wet and dry seasons was inconsequential. Nevertheless, this experiment occurred on level terrain and any skidding operations in the wet season would need to take into consideration potential impacts of sloped topography. This is due to the track and rut formation observed in the wet season trails, which could concentrate overland flow of water that could cause erosion or sediment transport into a waterbody. Therefore, wet season skidding operations may require seasonal restrictions such as cessation of operations during heavy rain events, as well as construction of water breaks after skid trail use. Considering this, if prudence is exercised, the responsible agencies that oversee timber harvesting operations in the Brazilian Amazon could indeed permit log skidding operations in the rainy season.

Chapter 2

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Logging machinery traffic has greatest influence on soil chemical properties in the Amazonian rainy season

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ABSTRACT

In the forests of Amazonia, each year previously unentered stands are logged, which usually results in some degree of soil compaction. Consequently, the soil chemical properties in compacted areas are altered. The aim of this study was to determine how these changes may help or hinder site recovery in the context of seasonal variation and increased levels of compaction. To investigate these changes an experiment was established in the Central Amazon. This consisted of tractor trails compacted at three incrementally increasing traffic intensities of 1, 3 and 12 machine cycles in the wet and dry seasons. Results revealed that elevated moisture in the wet season combined with heavy compaction from 12 machine cycles had the greatest impact on soil chemical properties. This was indicated by diminished total N, organic C, available P, cation exchange capacity, as well as elevated NH_4^+ and Fe^{2+}. Nevertheless, heavy compaction in the wet season led to lower Al^{3+} and higher base saturation, which could be beneficial for future site recovery.

***Keywords*:** skid trails, forest management, ammonium, nitrate, tropical forest

Introduction

The unintended consequences of soil compaction from logging machinery are vast. Many of these impacts to soil, such as increased bulk density, decreased macroporosity and reduced infiltration are well known (Cambi *et al.*, 2015a; Froehlich and McNabb, 1984). Conversely, the effects of logging compaction on soil chemical properties have received far less attention. Even so, recent research has revealed that increased machine traffic in skid trails diminished concentrations of organic C, total N, P and K (Naghdi *et al.*, 2016b; Picchio *et al.*, 2019; Solgi *et al.*, 2019). To the contrary compacted skid trails and landings often contain elevated levels of Ca and Mg (Mello Ivo *et al.*, 1996; Thiofo Lontsi *et al.*, 2019). One aspect of this area of research that has garnered little attention, is the seasonal influence on soil chemical properties in skid trails and landings. A study by Shabaga *et al.* (2017), demonstrated that seasonal changes resulted in substantial differences for nitrate levels in skid trail ruts. Furthermore, Blumfield *et al.* (2005) found that compaction from machine traffic had little effect on N mineralization or nitrification, whereas there were distinct seasonal differences for N mineralization. Consequently, for a greater understanding of fluctuations in soil nutrient and chemical concentrations in compacted soil to be ascertained, measurements of more than a single season or at least divergent moisture contents are necessary.

The importance of investigating soil chemical properties after the impacts from logging induced compaction are at least twofold. First, site productivity is vital for sustainable timber harvesting. Studies have shown that skid trails substantially alter seedling germination, morphology and architecture, as well as overall survival (Naghdi *et al.*, 2016b; Picchio *et al.*, 2019; Solgi *et al.*, 2019). Also, many of the nutrients necessary for plant growth such as phosphorus and nitrogen are deficient in skid trails a decade or more after logging (Ilintsev *et al.*, 2018; McNabb *et al.*, 1997; Sohrabi *et al.*, 2022), although Ebeling *et al.* (2017) actually encountered increased phosphatase activity in the soil of machine operating wheel tracks after more than 30 years. Second, skid trails and landings are sometimes a point source of pollution. For example, de Wit *et al.* (2014) found elevated levels of ammonium, nitrate and phosphorus in streams after timber harvesting in boreal forest. As elevated levels of these nutrients can be detrimental to ecosystem health (Weil and Brady, 2017), it is important to understand the impacts caused by logging infrastructure (*e.g.*, skid trails, landings) to the environment. Additionally, depending on various factors within skid trails, such as redox potential, and soil moisture, chemical changes in the soil may result in elevated emissions of CO_2, N_2O and CH_4 (Hartmann *et al.*, 2014; Vantellingen and Thomas, 2021).

In this context, the objective of this paper was to determine if there are substantial differences in soil chemical properties between wet and dry seasons after logging machinery traffic on heavy clay soils. Therefore, answers to the following questions were sought: 1. What are the impacts from machinery compaction to soil chemical properties for each season? 2. How does increased compaction from machine traffic alter these impacts?

Material and Methods

Study site

The compaction experiment was established north of the capital city, Manaus, located in the state of Amazonas, Brazil (2° 38'S, 60º 09'W) (Fig. 1). The climate is considered tropical (Af) under the Köppen classification system, without a dry season and with an average temperature above 26 °C (Alvares *et al.*, 2013). On site annual precipitation varies between 2350 and 2700 mm (Higuchi *et al.*, 2011). Though there is not a technical dry season under the Köppen classification system, the driest six months of the year in the Central Amazon, June through November (Lopes *et al.*, 2016), will be considered the dry season for the purposes of this research. In the year preceding the final sample collection, there was a total of 2665 mm, or 868 mm in dry season months and 1797 in wet season months (Fig. 2). The humid tropical forest of the area has an overall stand density 593 ± 28 trees ha^{-1} and basal area of 27.7 ± 2.1 m^{2} ha^{-1}, whereas on the plateaus where the experiment was conducted the values are slightly higher with 632 ± 46 trees ha^{-1} and basal area of 29.1 ± 4.4 m^{2} ha^{-1} (Marra *et al.*, 2014). The soil of the site was previously classified as a Geric Ferralsol (Alumic, Hyperdystric, Clayic) (Quesada *et al.*, 2010). Generally, the clay fraction in the Amazon region is dominated by non-expansive kaolinite (Ito and Wagai, 2017). Site texture is dominated by the clay fraction (Table 1) and soil is acidic (Table 2).

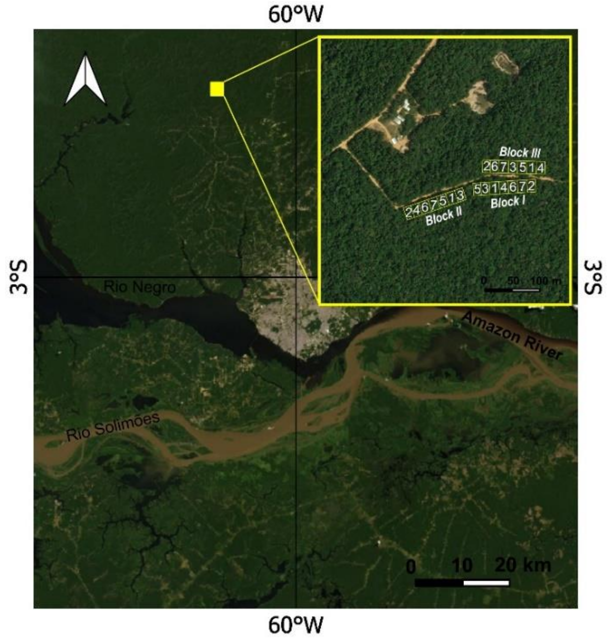

Fig. 1. General location map showing experiment location and setup. Each block consists of seven sub-blocks designated as the following: 1 – wet season, one machine cycle; 2 – wet season, three machine cycles; 3 – wet season, twelve machine cycles; 4 – dry season, one machine cycle; 5 – dry season, three machine cycles; 6 – dry season, twelve machine cycles; 7 – control.

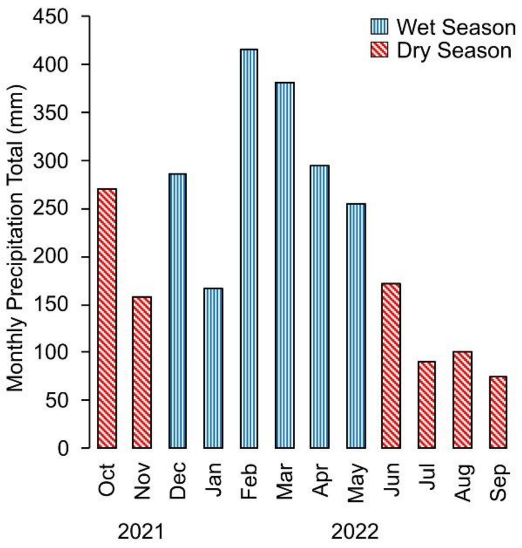

Fig. 2. Monthly precipitation totals acquired from onsite rain gauge.

Table 1. Site soil texture data. Particle size fractions are as follows: sand 2 – 0.05 mm, silt 0.05 – 0.002 mm and clay < 0.002 mm. Data derived from DeArmond *et al.* (2023b).

Soil depth (cm)	Particle size distribution (%)		
	Clay	Silt	Sand
0 - 5	68	21	11
5-10	74	16	10

Table 2. Soil chemical characteristics determined from controls (*n* = 3) one year prior to the current study. Values are the mean of all samples taken for a given depth (*n* = 9) followed by the standard deviation(±) in parenthesis.

Soil characteristic	Soil depth 0-5 cm	 5-10 cm
pH (H_2O)	4.28 (0.09)	4.41 (0.07)
Cation Exchange Capacity ($cmol_c\ kg^{-1}$)	11.04 (1.20)	7.02 (0.70)
Base saturation (%)	2.15 (0.30)	2.03 (0.29)
Aluminum saturation (%)	88.45 (1.57)	90.22 (1.32)
Organic carbon ($g\ kg^{-1}$)	32.52 (2.65)	19.74 (2.32)
Total nitrogen ($g\ kg^{-1}$)	2.66 (0.13)	1.79 (0.11)
Available P ($mg\ kg^{-1}$)	0.96 (0.48)	0.48 (0.23)
Exchangeable Ca ($cmol_c\ kg^{-1}$)	0.04 (0.00)	0.03 (0.01)
Exchangeable Mg ($cmol_c\ kg^{-1}$)	0.08 (0.01)	0.04 (0.01)
Exchangeable K ($cmol_c\ kg^{-1}$)	0.05 (0.01)	0.03 (0.01)
Exchangeable Na ($cmol_c\ kg^{-1}$)	0.06 (0.01)	0.05 (0.01)
Exchangeable Al ($cmol_c\ kg^{-1}$)	1.82 (0.18)	1.31 (0.09)

Sampling design and sample collection

In 2021, an experiment was established to determine the impacts from soil compaction caused by skid trails used in Amazonian logging operations. A randomized complete block design (RCBD) was chosen to analyze various traffic intensities (*i.e.*, treatments), as well as seasonal influence. The experimental design consisted of three blocks 105 m in width X 20 m in length each consisting of seven sub-blocks 15 m in width X 20 m in length. Each block had an undisturbed control, with three traffic intensities of 1 cycle, 3 cycles and 12 cycles implemented in both the wet and dry season. These traffic intensities were selected to represent those found in many logging operations: primary skid trails (>10 machine cycles), secondary skid trails (2-10 machine cycles) and tertiary skid trails (1 machine cycle) (DeArmond et al., 2021). A single cycle consisted of an ingress and egress of the machine operating trail. Each trail was 15-20 m in length, straight without curves. The wet season trails were established on May 5, 2021 and the dry season trails on September 28, 2021. The machine used was a Caterpillar D6D direct drive track-type tractor with an operating weight of 13,150 kg. Shoe width of the tracks was 450 mm with a grouser height of 4 mm. Two machine operators were used, one for each season. No off tracking or lowering of the blade was permitted, so the litter layer of approximately 2-3 cm in thickness, as well as tree roots were maintained in the trails. For each season, trail establishment was completed in the day of commencement. Prior to machine traffic all trees with a diameter at breast height of < 25 cm were felled, sectioned and removed by hand. All slash was also removed. Thus, the machine operating trails were established on leaves and an intact O-horizon. The machine operating trails were compacted from 13-28% (Table 3).

Table 3. Means for studied soil in control and compacted trails at a depth of 0-5 cm. Different upper-case letters signify differences in means ($p < 0.05$) between seasons for a single column. Different lower-case letters within a season (i.e., same row) represent differences in means ($p < 0.05$). ANOVA data derived from DeArmond *et al.* (2023b).

	Soil Bulk Density (g cm^{-3})			
		Machine Cycles		
Season	Control	1	3	12
Wet	0.82a	0.93Ab	0.99c	1.00c
Dry	0.82a	1.01Bb	1.02b	1.05c

One year after trail establishment, samples were collected in the first week of May (*n* = 60) and October (*n* = 60) 2022. One year was selected so that all trails could experience the complete seasonal changes that occur throughout the year such as wetting, drying and litterfall. In each sub-block, five soil samples were randomly taken from the surface 0-5 cm in controls and tractor ruts in the machinery trails. All samples were blocks approximately 5 X 5 X 5 cm in size. Once collected, blocks were placed in a cooler with ice until they could be placed in the field camp freezer. Samples were then transported frozen in coolers to the laboratory for analysis.

Laboratory analysis

The gravimetric method was used in the determination of water content. Soil samples of 10 g were dried for 24 hours at 105° C. All soil chemical properties were determined at the National Institute for Research in the Amazon (INPA) soil laboratory. Soil pH was determined with 10 g of soil shaken for an hour in 25 ml of distilled water (1:2.5 proportion) and after a minimum of 30 minutes read with an automatic probe (Teixeira *et al.*, 2017). The Walkley-Black method was used for soil organic carbon (Walkley and Black, 1934). The Kjeldahl method was used to determine total nitrogen (Bremner, 1960). A Perkin Elmer 1100B Atomic Absorption Spectrometer was utilized for the determination of Ca^{2+} and Mg^{2+} after extraction with KCl (1 mol L^{-1}), whereas available P, K^{+}, Na^{+}, were extracted with an Mehlich-1 solution (HCl 0.05 mol L^{-1} + H_2SO_4 0.125 mol L^{-1}) (Teixeira *et al.*, 2017). To determine exchangeable Al^{3+} and H^{+} an extraction with calcium acetate (0.05 mol L^{-1} at pH of 7.0) was used followed by titration. For available phosphorus, colorimetry in a molybdate blue ascorbic acid solution of 3% was used and then determined in a Shimadzu UV mini 1240 spectrophotometer (UV-120-01; $\lambda = 660$ nm). Ammonium and nitrate were determined through colorimetric determination (Anderson and Ingram, 1993).

Data analysis

All data were evaluated for normality with the Shapiro-Wilks test, and homogeneity of variances were evaluated with Levene’s test prior to proceeding with the analysis. Due to data non-normality and heterogeneity of variances, the non-parametric Kruskal-Wallis test was chosen and utilized. Only differences between treatments were of interest and not differences between blocks. For each soil chemical property, treatment distributions were compared. Pairwise comparisons were considered significant with a p-value < 0.05, after a Bonferroni correction for multiple tests. All data were analyzed with the software package *SPSS* Statistics for Windows, Version 28.0 (Armonk, NY: IBM Corp).

Results

Soil moisture

The highest and lowest mean moisture content throughout the study site was encountered in the controls (Table 3). All distributions between seasons for each location were different ($p < 0.05$), but there were no distributional differences between successive levels of compaction within a season. The greatest percent difference for soil moisture between seasons was 50.7% for the wet season in the controls, with the narrowest being 27.7% for tractor trails with 12 machine cycles.

Table 4. Soil moisture content (%) for controls and machine traffic. Each value is the mean (n = 15) for a given location followed by the standard deviation (±) in parenthesis.

	Soil Moisture (%)			
		Machine Cycles		
Season	Control	1	3	12
Wet	66.3 (8.67)	60.4 (5.98)	63.0 (8.26)	55.1 (6.42)
Dry	39.5 (1.60)	42.2 (2.21)	42.5 (5.54)	41.7 (4.39)

Soil chemical properties

The dry season presented elevated pH values for the controls, 1st and 3rd machine cycles, but not the 12th cycle (Table 4). These increases in the dry season were substantially higher when pH measurements were determined in H_2O. The effect of compaction on pH was only apparent at the 12th machine cycle in the wet season ($p < 0.001$). When compared to the control, cation exchange capacity and exchangeable acidity were also only affected by compaction after the 12th machine cycle in the wet season ($p = 0.019$) and ($p = 0.010$), respectively. Regardless of season, increased compaction tended to contribute to increased base saturation and lower levels of exchangeable aluminum. Overall, distributions of soil chemical properties were little affected by compaction in the dry season. To the contrary, the combination of heavy compaction with increased soil moisture in the wet season resulted in many differences in soil chemical property distributions.

Table 5. Descriptions for soil chemical properties and comparisons for season, control and machine cycle. Mean values followed by standard deviations (±) in parenthesis are for descriptive purposes only. Results for Kruskal-Wallis significant differences between distributions are described with letters. Different upper-case letters signify differences in distributions ($p < 0.05$) between seasons for a single column and a given chemical concentration. Different lower-case letters within a season (*i.e.*, same row) represent differences in distributions ($p < 0.05$) between values for a given chemical concentration.

Soil Chemical Concentration	Season	Control	Machine Cycles		
			1	3	12
$\mathrm{pH_{H2O}}$	Wet	3.95 (0.16) Aa	3.96 (0.11) Aa	3.81 (0.91) Aa	4.79 (0.52) Ab
	Dry	4.56 (0.07) Ba	4.54 (0.23) Ba	4.55 (0.19) Ba	4.74 (0.32) Aa
$\mathrm{pH_{KCL}}$	Wet	3.66 (0.11) Aa	3.76 (0.07) Aa	3.65 (0.09) Aa	3.99 (0.15) Ab
	Dry	3.80 (0.08) Aa	3.81 (0.15) Aa	3.81 (0.14) Ba	3.90 (0.17) Aa
C.E.C. (cmol$_c$ kg^{-1})	Wet	12.0 (1.13) Aa	10.3 (1.10) Aab	12.7 (1.89) Aa	9.60 (2.05) Ab
	Dry	10.7 (1.65) Aa	10.8 (1.56) Aa	12.2 (2.77) Aa	11.1 (2.37) Aa
T.E.B. (cmol$_c$ kg^{-1})	Wet	0.27 (0.05) Aab	0.23 (0.05) Aa	0.25 (0.05) Aa	0.52 (0.27) Ab
	Dry	0.35 (0.08) Aa	0.30 (0.07) Aa	0.38 (0.13) Ba	0.40 (0.14) Aa
$H^+ + Al^{3+}$ (cmol$_c$ kg^{-1})	Wet	11.7 (1.14) Aab	10.1 (1.09) Aac	12.5 (1.86) Ab	9.11 (2.15) Ac
	Dry	10.3 (1.63) Aa	10.5 (1.59) Aa	11.8 (2.76) Aa	10.7 (2.37) Aa
Al^{3+} (cmol$_c$ kg^{-1})	Wet	2.21 (0.28) Aa	1.91 (0.22) Aa	2.38 (0.31) Aa	1.31 (0.54) Aa
	Dry	0.81 (0.10) Ba	0.77 (0.14) Ba	0.78 (0.14) Ba	0.72 (0.25) Aa
Base Saturation (%)	Wet	2.28 (0.45) Aa	2.21 (0.54) Aa	1.96 (0.32) Aa	5.88 (3.51) Ab
	Dry	3.37 (0.84) Ba	2.92 (1.16) Aa	3.19 (1.24) Ba	3.71 (1.62) Aa
Al. Saturation (%)	Wet	88.9 (2.24) Aa	89.4 (2.48) Aa	90.5 (1.69) Aa	69.1 (18.1) Ab
	Dry	69.8 (5.50) Ba	71.3 (8.46) Ba	67.5 (7.73) Ba	63.9 (13.2) Aa

Note: Probability data for pairwise comparisons in this table can be found in Tables S1 and S2, Supplementary File, Appendix A.

Total N, organic C, NH_4^+ and NO_3^-

There were no seasonal differences between the controls for total N. In fact, the only seasonal difference for total N was between trails with 12 machine cycles ($p = 0.006$). Also, distributions for compaction and total N only differed in the wet season (Fig. 3a). The pattern across season and machine cycle for organic C was similar to total N, with the only seasonal difference in distributions being in trails after 12 machine cycles ($p = 0.008$). The 12th machine cycle for the wet season also had the lowest sample value for organic C at 15.7 g kg^{-1} (Fig. 3b). Overall, for controls and machine cycles the range of means for organic C was higher in the dry season at 36.5 – 41.7 g kg^{-1} than the wet season at 25.9 – 33.7 g kg^{-1}. Notably, the highest mean organic C in both seasons was encountered after the 3rd machine cycle, and not the 1st or 12th.

In the dry season, distributions of ammonium were similar for the control and all machine cycles. Additionally, dry season NH_4^+ was always higher than in the wet season, except for the 12th machine cycle in the wet season, which was no different than the dry season distributions (Fig. 3d). For the wet season, the NH_4^+ distribution in the most compacted trails was greater than that of the control (p = <0.001), and the 1st (p = 0.003) and 3rd (p = 0.004) machine cycles. Also, the highest mean NH_4^+ concentrations for each season were always in the trails with the greatest compaction (*i.e.*, 12 machine cycles). However, this difference for NH_4^+ was most pronounced in the wet season, with a mean of 8.72 mg kg^{-1} for the 12th machine cycle, which was 102-115% greater than the control and other machine cycles in the wet season. Distributions of nitrate were substantially higher in the dry season than the wet season (Fig. 3c). The narrowest distribution and lowest minimum values for NO_3^- were in the wet season trails with 12 machine cycles, but this was not different than the control (p = 0.512). For the most part, NO_3^- was only affected by season and not compaction, whereas NH_4^+ was affected mostly by season, but also the combination of season and heavy compaction.

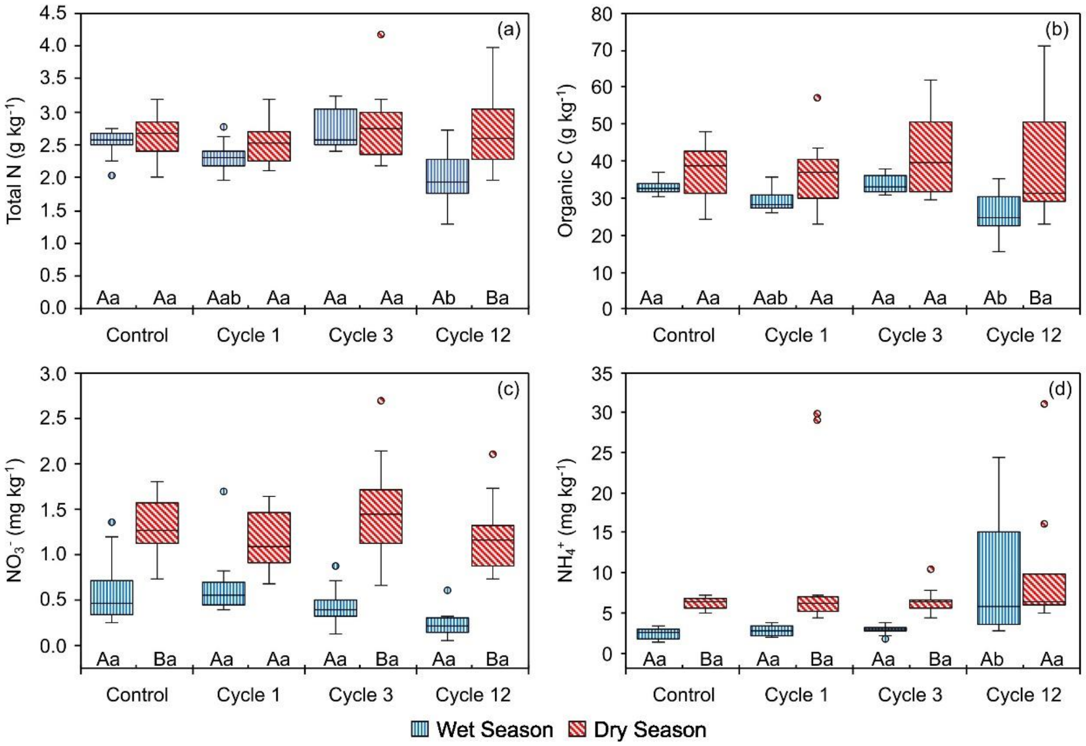

Fig. 3. Box plot data including medians, upper and lower quartiles, and outliers (circle outside of box) for (a) total N, (b) organic carbon, (c) nitrate and (d) ammonium. Differences for machine cycle compaction within a single designated with different lowercase letters. Seasonal differences between controls or between cycles of the same intensity designated with different uppercase letters. Different letters represent differences at the α = 0.05 level. *Note*: Probability data for pairwise comparisons in this figure can be found in Tables S3 and S4, Supplementary File, Appendix A.

Soil Ca^{2+}, Mg^{2+}, available P, Na^{+}, K^{+} and Fe^{2+}

Distributions for two macronutrients were affected by heavy compaction and in only one season (Fig. 4). Both Ca^{2+} and Mg^{2+} had increased concentration levels in the wet season trails with 12 machine cycles. To the contrary, the distribution for the 12th cycle in the wet season for available P was much lower than that of the dry season ($p < 0.001$). In fact, the wet season median value of 0.69 mg kg^{-1} was substantially lower than the dry season at 1.62 mg kg^{-1}. The macronutrient potassium was predominately affected by season. This was only in the controls and after 1 to 3 machine cycles, although after 12 machine cycles distributions were not different between seasons ($p = 0.701$). Sodium distributions were impacted by light compaction after the 1st machine cycle in both seasons, whereas Fe^{2+} only had differences after the 12th machine cycle, also for both seasons.

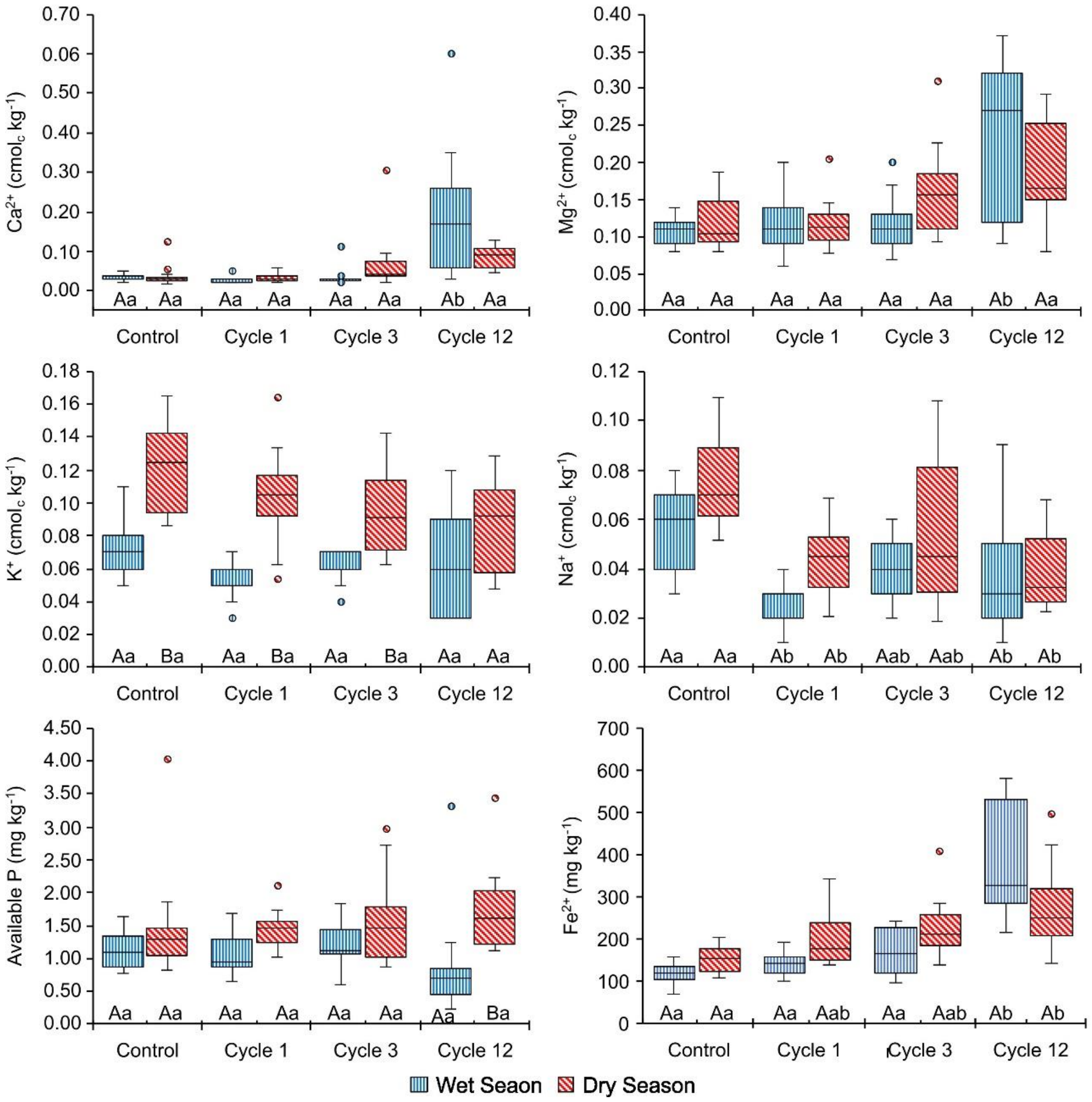

Fig. 4. Box plot data including medians, upper and lower quartiles, and outliers (circle outside of box) for calcium, magnesium, potassium, sodium, phosphorus and iron. Differences for machine cycle compaction within a single designated with different lowercase letters. Seasonal differences between controls or between cycles of the same intensity designated with different uppercase letters. Different letters represent differences at the $\alpha = 0.05$ level. *Note*: Probability data for pairwise comparisons in this figure can be found in Tables S5 and S6, Supplementary File, Appendix A.

Discussion

Soil moisture

Water retention curves previously developed for the study area placed the range for field capacity at 0.42 – 0.46 cm^3 cm^{-3} and saturation at 0.68 – 0.73 cm^3 cm^{-3} in the surface 5 cm of soil (Ferreira *et al.*, 2002). Therefore, wet season samples were at or below the point of saturation with dry season samples at or below field capacity. Even though, moisture contents for trails with 12 machine cycles were well below the range of saturation for forest soils in undisturbed areas in the wet season, it is still likely that these samples were indeed at the level of saturation due to heavy compaction. This is because increased compaction decreases non-capillary pore space, which in turn reduces the saturated water flow potential of a compacted soil (Froehlich and McNabb, 1984). Consequently, compacted soil within skid trail wheel tracks and ruts may affect air-filled porosity at high moisture levels (Hansson *et al.*, 2019).

Soil chemical properties

Seasonal differences in pH were likely caused by the variation in litter production, as well as soil moisture content. In Amazonia, increased litterfall occurs during the dry season (da Silva *et al.*, 2018). The higher levels of litter biomass help to increase pH through additional base cation contribution, as well as proton consumption that occurs during C mineralization (McCauley *et al.*, 2017; Neina, 2019). In addition, elevated litter biomass and lower precipitation levels are likely what led to higher base saturation in the dry season. Exchangeable aluminum was also substantially lower in the dry season, in part from increases in pH which are known to decrease Al^{3+} levels (Zhao *et al.*, 2018). Soil pH was also affected by increased compaction, which is commonly observed in heavily compacted skid trails (Jourgholami *et al.*, 2021a; Naghdi *et al.*, 2016b; McNabb *et al.*, 1997; Picchio *et al.*, 2019). Impacts were principally in the wet season after the 12th machine cycle, which could be indicative of anaerobic soil conditions. Soil compaction in machinery operating trails often leads to air-filled porosity below the threshold of 10% (Hartmann *et al.*, 2014; Klaes *et al.*, 2016; Riggert *et al.*, 2019), which also impacts macropores that facilitate soil drainage (Cambi *et al.*, 2015a). The combination of reduced aeration and elevated moisture could explain the increased pH levels in the wet season trails with 12 machine cycles, as reduced conditions usually lead to proton consumption and the subsequent increase to pH (Sposito, 2008).

The values for cation exchange capacity (CEC), 6.2-19.6 cmol kg^{-1}, were well within the range of values encountered in the region (Botschek *et al.*, 1996; Trindade *et al.*, 2021). Lack of a consistent trend for CEC, positive or negative, with increased compaction is in agreement with the few studies evaluating CEC in skid trails. In both tropical and temperate forests, changes to the CEC or effective cation exchange capacity varied markedly from an increase, decrease or no effect (Borchert *et al.*, 2015; Treasure *et al.*, 2019; Tchiofo Lontsi *et al.*, 2019). In regards to the CEC of the present study, the standout finding would be that there was a diminished CEC after 12 machine cycles in the wet season. This is likely because of the lower level of organic matter in these trails as evidenced by lower concentrations of organic carbon, as soil organic matter contributes considerably to the CEC (Jones and Olson-Rutz, 2016; Ramos *et al.*, 2018).

Total N, organic C, NH_4^+ and NO_3^-

Numerous studies in temperate regions have demonstrated that total N and organic C are lower in skid trails immediately after logging, with lower levels lasting decades prior to recovery of undisturbed soil concentrations (Jourgholami *et al.*, 2021a; Naghdi *et al.*, 2016b; Picchio *et al.*, 2019; Solgi *et al.*, 2019; Tavankar *et al.*, 2022). In the present study, lower N and C were mainly limited to heavily compacted tractor trails in the wet season. These lower values may be due to soil displacement, as the soil at the time of trail establishment was above field capacity (Cambi *et al.*, 2015a). Once a soils topsoil is displaced the denser subsoil can be exposed (Williamson and Neilsen, 2000). For the present study , there was only a centimeter difference in track depth between seasons and the wet season soil bulk density (BD) was lower by 5% (DeArmond *et al.*, 2023b). This lower BD could be evidence of soil displacement, as changes in soil volume can be greater than increases to soil density (Horn *et al.*, 2007; Froehlich and McNabb, 1984), although soil displacement is much lower when logging machinery is not pulling logs (Marra *et al.*, 2022), as was the case in the current study. Also, in the 5-10 cm depth of the controls at this site there was lower organic C and total N (Table 2) than the sample values encountered in the 0-5 cm depth of the trails compacted in the wet season with 12 cycles. These differences could also be evidence of soil mixing with the litter layer (Schack-Kirchner *et al.*, 2007). Another possibility for the lower organic C in the wet season after the 12th cycle, could be due to accelerated decomposition. In a boreal forest, Startsev *et al.* (1998) found that the highest rates of cellulose decomposition were in the most trafficked skid trails, and this was especially true when air-filled porosity fell below 10 m^3 m^{-3}. Furthermore, lower amounts of nitrogen in heavily compacted soils are expected, as denitrification increases drastically when soil oxygen concentrations are substantially diminished (Tiedje *et al.*, 1984).

In temperate forests, wheel tracks in skid trails have been shown to have lowered N mineralization rates, as well as substantially lower levels of nitrate and ammonium (Ebrecht and Schmidt, 2003; Shabaga *et al.*, 2017). To the contrary, five weeks after logging operations in the surrounding tropical forest there were substantially higher NH_4^+ and NO_3^- concentrations in the skid trail tracks than in the controls (Mello Ivo *et al.*, 1996). In the present study, only after the 12th machine cycle in the wet season could elevated NH_4^+ be attributed to soil compaction. As NH_4^+ is a reduced form of nitrogen, it provides some evidence that there was likely a low redox potential in the trails slowing the oxidation of NH_4^+ to NO_3^- because of the compaction and saturated soils (Weil and Brady, 2017; Zhang *et al.*, 2018). Nitrate levels were relatively the same across differences in soil compaction, whereas the differences in NH_4^+ and NO_3^- concentrations between seasons were striking. These differences are in part from dryer conditions allowing greater soil aeration, but also there are considerable differences between season for litter production and accumulation in the Amazon (da Silva *et al.*, 2018). In a recent study, Sohrabi *et al.* (2022), demonstrated that the quality and quantity of litter, as well as the tree species affect the NH_4^+ and NO_3^- concentrations in skid trails.

Soil Ca^{2+}, Mg^{2+}, Na^+, available P, K^+, and Fe^{2+}

Prior studies in the Amazon have reported elevated levels of exchangeable Ca and Mg in skid trails (McNabb *et al.*, 1997; Mello Ivo *et al.*, 1996; DeArmond *et al.*, 2021). However, the tractor trails in the current study had no differences between seasons and only a single large increase in Ca^{2+} and Mg^{2+}, which was limited to the wet season trails after the 12th machine cycle. As there was a substantial increase in pH from the 3rd to 12th machine cycle, the elevated exchangeable Ca and Mg are likely a result of pH changes. This is because Ca and Mg become more available as the pH increases (Jones and Olson-Rutz, 2016). Also, in the 12th machine cycle of the wet season concentrations of available P were very low, although this was not the case in the dry season. With the high levels of exchangeable aluminum throughout the wet season, but lowest in the 12th machine cycle, it is possible that there is fixation of P by Al^{3+} occurring, as it is well known that metal ions such as Al, Fe and Mn ions bond with phosphate, which decreases the availability P in the soil (Conklin, 2014; Weil and Brady, 2017; Husson, 2013). The increased potassium availability in the dry season is the result of higher pH levels > 4.5, as K+ availability increases substantially above a pH of 4.5 (Jones and Olson-Rutz, 2016). Ferrous iron (Fe^{2+}) was elevated after the 12th machine cycle in both seasons potentially indicating a low redox potential of the soil. This is because levels of Fe^{2+} accumulate and increase at low redox potentials (Conklin, 2014; Husson, 2013).

Conclusion

The impacts to soil chemical properties from 1 to 3 machine cycles were virtually inconsequential, regardless of season. To the contrary, the repercussion of heavy compaction from 12 machine cycles lead to increased levels of reduced species such as ammonium and ferrous iron, especially in the wet season. This has implications for revegetation of the compacted soil, as elevated concentrations of NH_4^+ and Fe^{2+} may be toxic to plants. Nevertheless, there were some beneficial aspects from the heavy compaction after 12 machine cycles. Namely, the increases to soil pH. This resulted in a reduction of Al^{3+} and a substantial increase in base saturation, which could benefit the natural revegetation of the disturbed soil.

Chapter 3

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Surface soil recovery occurs within 25 years for skid trails in the Brazilian Amazon

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ABSTRACT

Each year, thousands of km^2 of humid tropical forest are logged in the Brazilian Amazon. Many of these areas are underlain by clay soils dominated by non-expansive kaolinite. Logging operations often entail the use of heavy machinery to drag logs through the forest on skid trails, which causes substantial soil disturbance. Therefore, the objective of this study was to investigate if soil recovery occurs over time in the studied Ferralsol. The hypothesis is that soil recovery has indeed occurred and that the trend of recovery is observable. In this endeavor, a chronosequence was established composed of four logging units that were logged 13, 19, 23, and 26 years ago, as well as a control in undisturbed old-growth forest. Samples in the upper topsoil were collected for soil bulk density (BD), fine root biomass (FRB) and various soil chemical properties. Results indicated a sequential recovery. Prior to the study period of 13-26 years after logging operations, FRB recovered. The predicted recovery of the cation exchange capacity was at approximately 15 years, which was followed by soil organic carbon at 20 years. Lastly, BD was recovered within 25 years. Overall, soil organic carbon demonstrated the greatest associations with recovery variables as it accumulated over time. Although surface soils in skid trails did indeed recover, it was a lengthy process that occurred over several decades. In this context, skid trails should be planned to minimize soil disturbance in the logging area to the greatest extent feasible.

Keywords: logging, heavy clay, tropics, organic carbon, compaction

1. Introduction

In the Brazilian Amazon, thousands of km^2 are logged annually (Matricardi *et al.*, 2020). Logging operations entail the construction of a network of haul roads (*i.e.*, log transportation roads), log landings (*i.e.*, forest clearings for log storage) and skid trails (i.e., machinery paths between stumps and landings). These activities contribute to varying degrees of soil disturbance from topsoil removal to subsoil excavation that may impair soil functioning for decades (DeArmond *et al.*, 2021). In the state of Amazonas, the largest Brazilian state, road and landing construction is limited to 2.5% of the logging area, whereas limits for skid trails are not specified (CEMAAM, 2018). Throughout the Brazilian Amazon ground disturbance from skid trails accounts for approximately 3% or greater of the logging area (Pereira *et al.*, 2002; Asner *et al.*, 2004; DeArmond *et al.*, 2020), which is low compared to other forests where soil disturbance can be greater than 20% (DeArmond *et al.*, 2021). This low value for skid trail disturbance is because there are few trees harvested per area, which often averages 1-3 trees ha^{-1} (de Carvalho *et al.*, 2017; Condé *et al.*, 2022). Therefore, a considerable amount of soil disturbance is occurring each year in the world's largest tropical forest without knowing if these damaged soils will ever fully recover to a natural state.

Some of the impacts from skid trail compaction include the mixing of the litter layer and topsoil, soil displacement, rutting, increases to particle density, reduced water infiltration and increased runoff (Latterini *et al.*, 2023a; Picchio *et al.*, 2021; Cambi *et al.*, 2015). In temperate forests, three skidding cycles were sufficient to increase soil bulk density and decrease macroporosity (Solgi *et al.*, 2019; Naghdi *et al.*, 2016b). Moreover, in a tropical forest, a single ingress and egress of a skid trail was sufficient to cause root limiting conditions (DeArmond *et al.*, 2020). In addition, soil compaction may actually increase after logging operations have ceased, even for several years (McNabb and Startsev, 2022; Jusoff, 1996; Naghdi *et al.*, 2018). Increases in soil compaction over time have been attributed to soil infilling of voids created by decomposing roots, as well as age-hardening (DeArmond *et al.*, 2021). Regardless of soil texture or regional climate, soil compaction in skid trails may persist for decades (Froehlich *et al.*, 1985; DeArmond *et al.*, 2019; Mohieddinne *et al.*, 2019; Sohrabi *et al.*, 2020; Tavankar *et al.*, 2022). Because of the lengthy process of soil recovery, Nazari *et al.* (2021) suggests that further studies >10 years are needed. Also, Keller *et al.* (2021) states that there is a scarcity of information on soil recovery in regards to "a quantitative description of rates and ranking of the relative importance, interactions, and feedbacks among these key processes."

The literature is abundant with research on skid trail recovery processes, although this does not extend to the tropics. Moreover, the high clay content of many soils (>65%) common to the tropics is underrepresented in studies on soil recovery of skid trails in temperate regions. So, there is less known about the recovery processes after logging operations in the tropics. In the humid tropics, there is no freeze thaw cycle to break up the soil. Additionally, much of the clay is made up of non-expanding kaolinite (Ito and Wagai, 2017), so wet and dry cycles are less important. The primary driver of soil recovery from compaction in the tropics is from biological processes (Oades, 1993). However, with so few studies on soil recovery after logging operations in humid tropical forests, there is still much unknown about the rate of recovery. Indeed, only one known study in Amazonia has reported a full recovery of soil physical properties after compaction in skid trails (DeArmond *et al.*, 2019), although McNabb *et al.* (1997) reported a possible recovery of some chemical properties after 16 years. Nevertheless, to confirm that there is a recovery process in Amazonian soils beyond a few studies, additional studies should be implemented.

Therefore, the objective of this study was to better understand the process of soil recovery for heavy clay soils in the humid tropics. In this endeavor, a chronosequence of skid trails 13, 19, 23 and 26 years of age was chosen to test the following hypotheses:

1) There is recovery of soil attributes present.
2) There is an observable trend in soil attributes recovery over time.
3) There are significant relationships between recovered soil attributes.

2. Materials and methods

2.1. Study site

The study site was chosen as the area has a common soil type encountered in the Central Amazon, and the logging that occurred was also reflective of ground-based operations throughout Amazonia. Moreover, there is also present at this site an abundance of skid trails logged in the same manner over the last several decades. As this is the first chronosequence on soil recovery at this site, this research hopes to serve as a foundation for future research at this or similar sites.

The study area was located in the state of Amazonas, Brazil (Fig. 1). According to the Köppen climate classification system, this location has a tropical climate (Af) without a dry season, mean annual temperature greater than 26 °C and annual rainfall of 2200 to 2500 mm (Alvares *et al.*, 2013). Precipitation preceding sample collection dates was lowest for the calendar year (Fig. 2). The dominant vegetation is considered dense humid forest (FAO, 2011). The soils are Ferralsols that are strongly weathered, deep and predominately clay composed primarily of non-expansive kaolinite (Quesada *et al.*, 2011). The clay fraction generally varies from 60 to 80% in the topsoil (DeArmond *et al.*, 2020; Botschek *et al.*, 1996). In this region, Botschek *et al.* (1996) determined that the soils are very acidic and rich in Al.

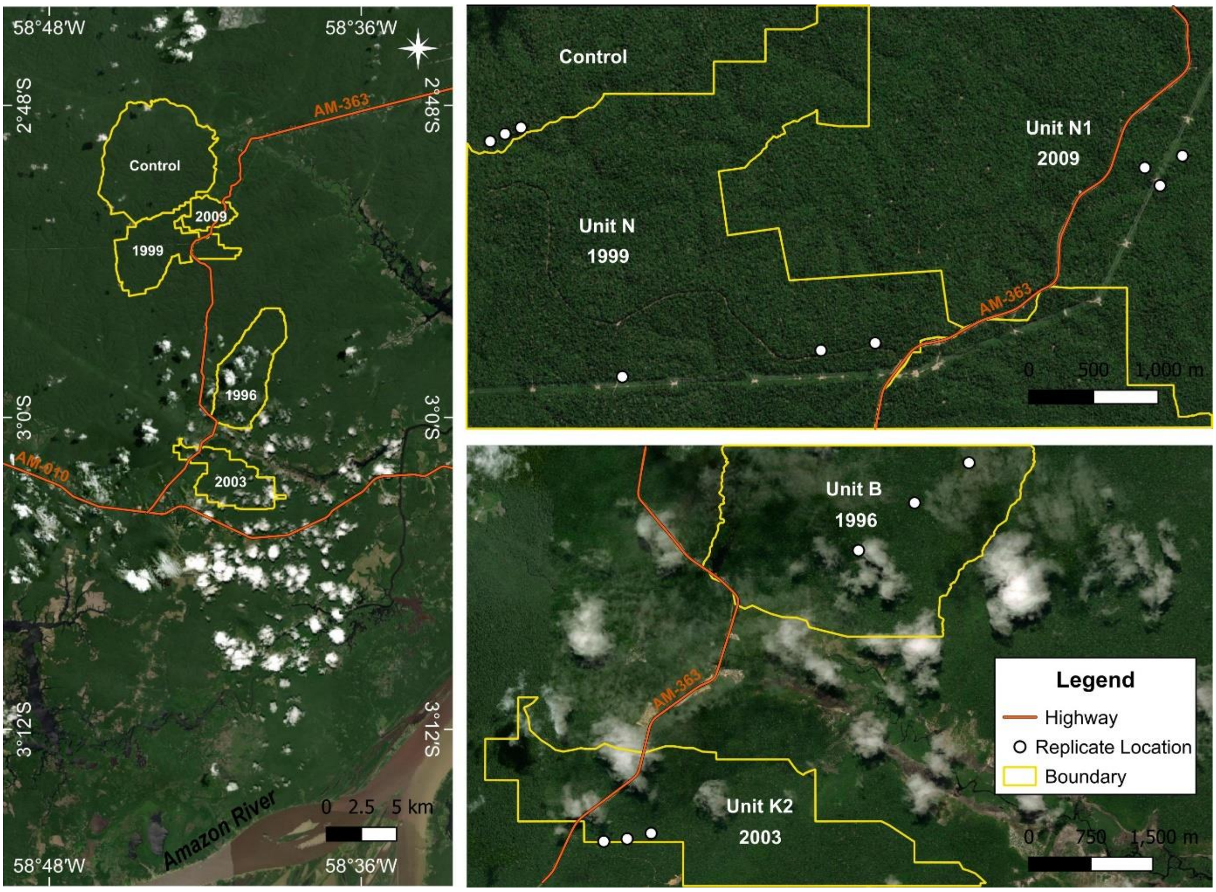

Fig. 1. General location map showing unit and control boundaries. All units are displayed with year of logging.

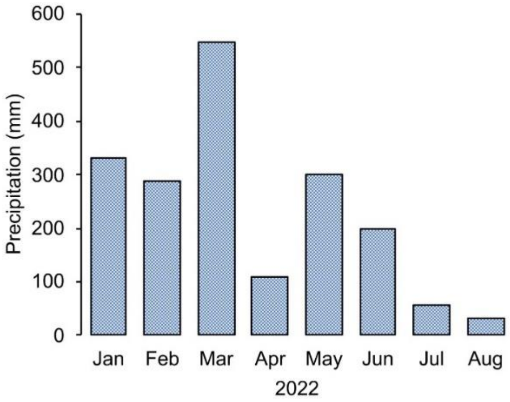

Fig. 2. Precipitation data acquired from automatic station [D0024 – CEMADEN] located in Itacoatiara, Brazil approximately 35 kilometers southeast of the study area.

The study site was located on the private ownership of the timber company Precious Woods Amazon (3°3’43”S, 58°43’43”W). The silvicultural system that is practiced by the company is polycyclic (i.e., uneven-aged, selection cutting). Logging entries are on a rotation cycle of between 30 and 35 years (PWA, 2021). All trees to be harvested are directionally felled with chainsaws towards pre-planned skid trails (*i.e.*, paths or roads where heavy machinery operate and drag logs). Once the trees have been cut into merchantable logs, they are winched to the skid trails with a track-layer type tractor. After this, the logs are dragged to the landing with rubber-tired skidders that stay within the skid trails the entire time during skidding operations (de Graaf and van Eldik, 2011). Once at the landing, logs are measured, inventoried, and organized for shipment by truck to the sawmill.

2.2. Sampling design and sample collection

A chronosequence was delineated that consisted of four different logging units that were logged at a cutting intensity of 20.77 m^3 ha^{-1} in 1996 (Unit B, 2,598 ha), 16.61 m^3 ha^{-1} in 1999 (Unit N, 2,208 ha), 11.46 m^3 ha^{-1} in 2003 (Unit K2, 1,894 ha) and 12.95 m^3 ha^{-1} in 2009 (Unit N1, 1,040 ha), with operations concluding 26, 23, 19, 13 years ago, respectively. These logging units and control were selected based on age, same soil type and logging system, as well as proximity to each other. Also, a separation in time of at least three years was chosen, as soil recovery processes are slow occurring over several years to decades (Labelle *et al.*, 2022; DeArmond *et al.*, 2021; Nazari *et al.*, 2021). In each unit, three replicates were established in three primary skid trails (>10 skidding cycles) a minimum of 100 m apart. Inside of each replicate, a single plot 10 m long was established that contained 5 randomly chosen sample points from the skid trail ruts or tracks. Randomization was conducted through a grid in each plot and selecting the sample location with the use of a random number generator. In addition, a minimum of 1 reference sample from undisturbed soil approximately 10 m outside of the skid trail was also collected. Also, a control was located in unlogged old-growth forest with three replicates that were located 100 m from each other.

The determination of soil bulk density (BD) and fine root biomass (FRB) were made with a steel ring (5 cm in diameter and 5 cm in height, 100 cm^3). The samples for BD were dried at 105° C for a minimum of 24 hours and then weighed to determine BD. The samples for FRB were dried at 65° C for a minimum of 72 hours and then weighed to determine dry mass of roots ≤ 2 mm. The sampling depth for bulk density and root biomass were in the 0-5 cm depth. In total, 90 samples of BD and 90 samples for FRB were taken. In addition, at each sampling location a small block of soil approximately 5 x 5 x 5 cm was also taken to determine soil chemical properties and texture (n = 90).

2.3. Laboratory analysis

The analysis of soil chemical properties and texture was completed at INPA's soil laboratory (*Laboratório Temático de Solos e Plantas – LTSP*). Soil organic carbon was determined by the Walkley-Black method. The determination of total nitrogen utilized the Kjeldahl method. A Perkin Elmer 1100B Atomic Absorption Spectrometer was used to determine Ca^{2+} and Mg^{2+} after extraction with KCl (1 mol L^{-1}), whereas available P, K^{+}, Na^{+}, was extracted with an Mehlich-1 solution (HCl 0.05 mol L^{-1} + H2SO4 0.125 mol L^{-1}). Exchangeable acidity (exchangeable aluminum and hydrogen ions associated with cation exchange) was determined after extraction with calcium acetate (0.05 mol L^{-1} at pH of 7.0) followed by titration. The determination of available phosphorus utilized colorimetry in a molybdate blue ascorbic acid solution of 3% and read in a Shimadzu UV mini 1240 spectrophotometer (UV-120-01; λ = 660 nm). Soil chemical analysis methods are described in greater detail in Sparks *et al.* (1996).

2.4. Data analysis

All data was evaluated for normality with the Shapiro-Wilk's test and homogeneity of variances with Levene's test prior to proceeding with the analysis. The majority of locations were considered normal according to the Shapiro-Wilk's test. The remainder were considered approximately normal after evaluating histograms and skewness and kurtosis values, except for C/N. In some cases, Levene's test revealed heterogeneity of variances due to outliers and differences in dispersion of different locations. However, the F-test has been shown to be robust to heterogeneity with up to six groups when sample sizes are equal (Blanca *et al.*, 2018). General Linear Model (ANOVA) with a nested design was utilized for comparisons between the control and logging units. Replicates were nested inside of the control and logging units. A post-hoc Tukey test with an alpha level of 0.05 was utilized to determine specific differences between pairs. The chronosequence of years was evaluated with simple linear regression with time as the explanatory variable and the dependent variables as the response variables. To determine if autocorrelation was present in the data, the

Durban-Watson test was applied. If values for the Durban-Watson statistic were below those found in the Savin and White (1977) table at 1% significance, a Prais-Winsten estimation procedure was employed. Spearman's correlation coefficient was used to determine the strength of relationships between variables. Spearman's correlation was chosen over Pearson's correlation because of occasional outliers that needed to be retained, as they reflected legitimate variability in these anthropogenically altered soils. For correlation analysis two extreme outliers in the reference area samples for bulk density (BD) and Ca^{2+} were excluded. One outlier in the reference samples was likely compacted during sample retrieval or logging operations (BD), with the other potentially contaminated (Ca^{2+}). All data was analyzed with the software package SPSS Statistics for Windows, Version 28.0 (Armonk, NY: IBM Corp).

3. Results

3.1. Soil physical properties

All site locations had a clay texture (Table 1), although two replicates inside of Unit N1 were classified as a sandy clay. In Unit N1, the skid trail with the highest sand content ranged from 55-60% sand. To the contrary, Unit N had the highest clay content, with each skid trail containing at least one sample ≥80% clay. Reference samples for texture collected outside of the skid trails also had a similar range of values as the skid trails for a given unit. Spearman's correlation revealed several strong relationships ($p < 0.001$) with sand. The strongest positive relationship was with pH_{H2O} ($r_s = 0.619$). To the contrary, the negative relationships were for Al^{3+} ($r_s = -0.748$), exchangeable acidity ($r_s = -0.697$) and cation exchange capacity ($r_s = -0.684$), with a moderate association found for soil bulk density ($r_s = 0.546$). Nonetheless, these correlations were limited to the skid trails.

The differences ($p = 0.009$) in soil bulk density (BD) were limited to the most recently logged units K2 ($p = 0.026$) and N1 ($p < 0.001$), which were logged 19 and 13 years ago, respectively. The highest value for BD was encountered in Unit N1 at 1.35 g cm^{-3} (Fig. 3a). However, even though Unit N1 had the highest mean and maximum values for BD, there were two samples encountered at 0.89 and 0.92 g cm^{-3} that were well within the range of the control. Notably, both of these samples were taken from deep ruts created by a skidder. The BD in the oldest skid trails in Units B and N were no different than the control 26 ($p = 0.868$) and 23 years ($p = 0.990$) after logging, respectively. Nevertheless, 33% of samples in these units were above the maximum value of 1.01 g cm^{-3} found in the control.

Table 1. Soil texture information for study locations and the year logging operations occurred. All values are means (*n* = 15) followed by the standard deviation (±). Particle size fractions are as follows: sand 2 – 0.05 mm, silt 0.05 – 0.002 mm and clay < 0.002 mm.

Location	Particle size distribution (%)			Soil texture
	Sand	Silt	Clay	
Control	11.7 (1.85)	13.6 (3.87)	74.7 (4.56)	Clay
Reference†	27.6 (15.2)	7.6 (2.71)	64.8 (14.7)	Clay
Unit B (1996)	21.9 (4.72)	8.2 (3.48)	69.9 (3.03)	Clay
Unit N (1999)	12.3 (0.80)	9.1 (3.62)	78.6 (3.77)	Clay
Unit K2 (2003)	21.6 (7.02)	7.8 (1.96)	70.5 (7.46)	Clay
Unit N1 (2009)	43.3 (13.3)	6.7 (2.62)	49.9 (13.1)	Clay

†Means were derived from undisturbed areas in all logged units: Unit B (*n* = 4), Unit N (*n* = 4), Unit K2 (*n* = 4) and Unit N1 (*n* = 3).

In regards to recovery of soil bulk density (BD) over time, there was a trend of decreasing BD over time that was observed (Fig 4a). The results of the regression analysis indicated that the predictor of skid trail age explained 41.1% of the variation in BD change over time. According to the regression model, 25 years is needed to attain the mean BD of 95 g cm^{-3} found in the undisturbed control of old-growth forest. This value of 95 g cm^{-3} is important as it represents the natural state of uncompacted soil of the area. Generally speaking, the Spearman correlations for BD and soil chemical concentrations were weak to moderately negative in the skid trails (Table S1). Though, BD was strongly and negatively correlated ($p < 0.001$) with total N (r_s = -0.684), organic carbon (r_s = -0.714), Al3+ (r_s = -0.646), exchangeable acidity (r_s = -0.744) and cation exchange capacity (r_s = -0.742) in the skid trails. Outside of skid trails, there were no relationships with BD and any other variable in the control and reference sites (Table S2).

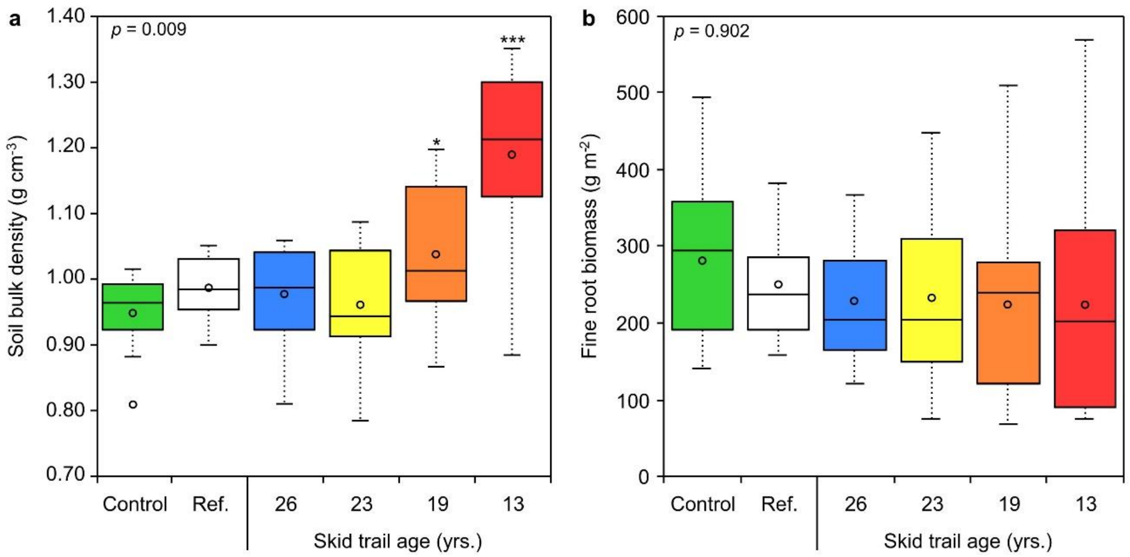

Fig. 3. Box plot data including medians, upper and lower quartiles, means (circle within box) and outliers (circle outside of box) for (a) soil bulk density (g cm^{-3}) and (b) fine root biomass (g m^{-2}). Difference with control designated with an asterisk. Levels of statistical significance: *P < 0.05, **P < 0.01 and ***P < 0.001.

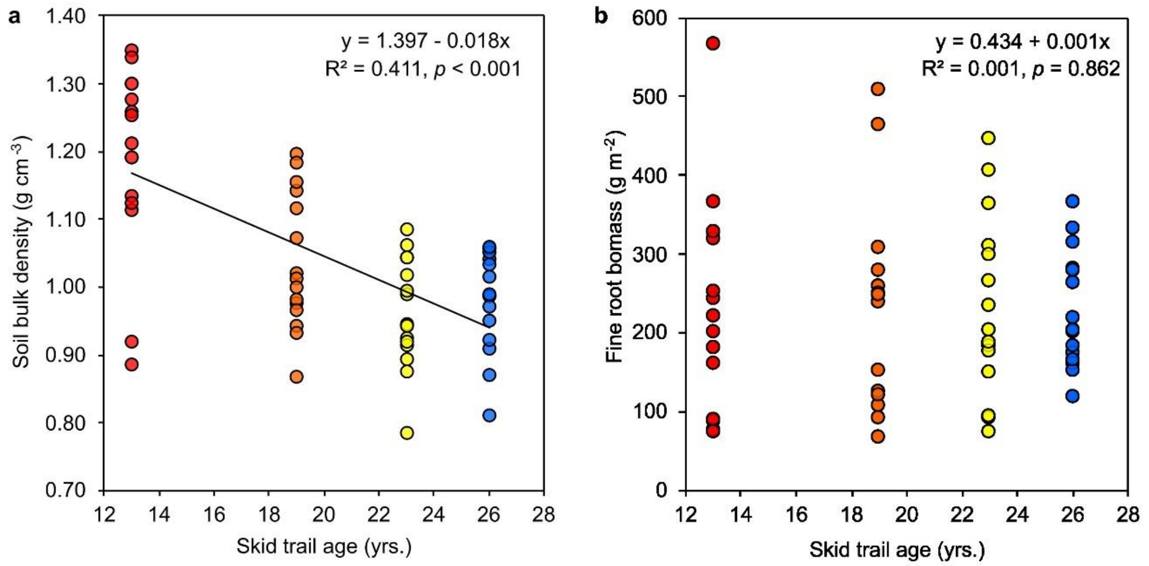

Fig. 4. Linear regression results for (a) soil bulk density (g cm^{-3}) and (b) fine root biomass (g m^{-2}) and the predictor skid trail age in years (n = 60).

3.2. Fine root biomass

There were no differences (p = 0.902) in means across locations for fine root biomass (FRB). Furthermore, the majority of FRB samples in the skid trails, regardless of skid trail age, fell within the interquartile range of the control values (Fig 3b). Though, after 26 years of recovery, the FRB in the oldest skid trails had a dispersion closest to the control. Interestingly, one of the newest skid trails had a sample containing the highest value of FRB, 13 years after logging in Unit N1, which was 569 g m^{-2}. This same sample location was also where the highest recorded sand content was recorded in a skid trail. Although Unit N1 had the highest maximum value for FRB, it also had the lowest mean of 224 g m^{-2}, whereas the control mean was the highest at 282 g m^{-2}. Concerning a linear trend over time for FRB (Fig 4b), none was encountered (p = 0.862). In regards to Spearman correlations for FRB, there was one primary association (p < 0.001), which was with Na^+. The relationship was strong in the control and reference sites (r_s = 0.626) and only moderately so in the skid trails (r_s = 0.559). Solely in the control/reference sites, there was a moderate association with aluminum saturation (r_s = - 0.439, p = 0.015) and base saturation (r_s = 0.456, p = 0.011) with FRB.

3.3. Soil chemical properties

Soil throughout the study area was very acidic pH < 5.0 (Table 2). The vast majority of skid trails had higher chemical concentrations than the control, except the 13-year-old skid trails in Unit N1 which were lower. Aluminum saturation differed by region (p = 0.031), with the control and units closest to it, having higher Al saturation levels than the two units farther away 10 km to the south. In Units B, N and K2, skid trails had substantially higher cation exchange capacity (p = 0.005) and exchangeable aluminum (p = 0.012) than the control. Across locations there were no differences in Ca^{2+} or Na^+ (Fig. 5). Total N was similar for most locations, except for Unit N1 which was lower than all other sites (p < 0.001). There was considerable variation in available P, K^+ and Mg^{2+} throughout locations. However, the added context of reference samples taken from outside of the skid trails, reveals that some differences in nutrient concentrations are potentially because of variation between sites unrelated to skid trail compaction.

Table 2. Soil chemical concentrations for study locations and the year logging operations occurred. All values are means (*n* = 15) followed by the standard deviation (±). Different superscript letters within a row represent differences at the α = 0.05 level.

Soil properties†	Locations				
	Control	Unit B (1996)	Unit N (1999)	Unit K2 (2003)	Unit N1 (2009)
pH H_2O	3.94 (0.06) ^{a}	3.89 (0.14) ^{ab}	3.84 (0.07) ^{b}	3.83 (0.10) ^{b}	4.10 (0.11) ^{c}
pH KCL	3.55 (0.05) ^{a}	3.46 (0.11) ^{a}	3.46 (0.08) ^{a}	3.49 (0.09) ^{a}	3.60 (0.09) ^{a}
Organic C (g kg^{-1})	25.1 (2.88) ^{a}	28.5 (3.14) ^{a}	27.9 (4.04) ^{a}	27.3 (4.29) ^{a}	19.6 (7.68) ^{b}
Base saturation (%)	2.26 (0.44) ^{a}	2.83 (0.51) ^{b}	1.94 (0.28) ^{a}	2.73 (0.61) ^{b}	1.98 (0.24) ^{a}
Al saturation (%)	91.9 (1.43) ^{a}	89.1 (2.34) ^{b}	92.5 (1.09) ^{a}	89.7 (2.53) ^{b}	93.0 (0.91) ^{a}
Total ex. bases (%)	0.15 (0.02) ^{a}	0.24 (0.06) ^{b}	0.18 (0.03) ^{a}	0.24 (0.08) ^{b}	0.11 (0.03) ^{c}
CEC ($cmol_c$ kg^{-1})	6.87 (0.95) ^{a}	8.47 (1.02) ^{b}	9.20 (1.13) ^{b}	8.59 (1.48) ^{b}	5.73 (1.72) ^{a}
Al^{3+} ($cmol_c$ kg^{-1})	1.75 (0.23) ^{a}	1.98 (0.22) ^{b}	2.19 (0.21) ^{b}	2.03 (0.29) ^{b}	1.49 (0.31) ^{c}
H + Al^{3+} ($cmol_c$ kg^{-1})	6.73 (0.95) ^{a}	8.23 (0.99) ^{b}	9.02 (1.12) ^{b}	8.36 (1.43) ^{b}	5.62 (1.69) ^{a}
C/N	13.4 (1.74) ^{a}	13.3 (1.87) ^{a}	13.2 (1.73) ^{a}	13.4 (2.61) ^{a}	14.9 (3.11) ^{a}

†Note: CEC, cation exchange capacity; H + Al^{3+}, exchangeable acidity

Regression analysis demonstrated that the vast majority of chemical properties had a low goodness-of-fit (Table S3) for the predictor of skid trail age ($R^2 \leq .20$). To the contrary, there were four variables that had an improved goodness-of-fit: total N (Fig. 6a), organic C (Fig. 6b), cation exchange capacity ($R^2 = 0.351$) and exchangeable acidity ($R^2 = 0.345$). According to the regression models for total N and organic C, both are predicted to reach the mean levels found in the control by 20 years, whereas the cation exchange capacity returns to that of the control sooner between 15 and 16 years after compaction. Considering organic C, Spearman correlations with other chemical properties were generally positive in both skid trails and control/reference sites, although in the skid trails these correlations were much stronger overall. Moreover, there were three strong associations ($p < 0.001$) between chemical properties found only in skid trails between K^+ and Mg^{2+} ($r_S = 0.639$), available P and aluminum saturation ($r_S = -0.689$) and cation exchange capacity and total exchangeable bases ($r_S = 0.701$). Notably, there was only one strong correlation ($r_S > 0.600$) for K^+ with other chemical properties in the control/reference sites, whereas in the skid trails there were eight strong correlations ($r_S > 0.600$) and three very strong correlations ($r_S > 0.800$) with exchangeable K. Overall, pH_{H2O} was negatively correlated with Al^{3+} ($p < 0.001$) inside ($r_s = -0.729$) and outside ($r_s = -0.823$) of skid trails.

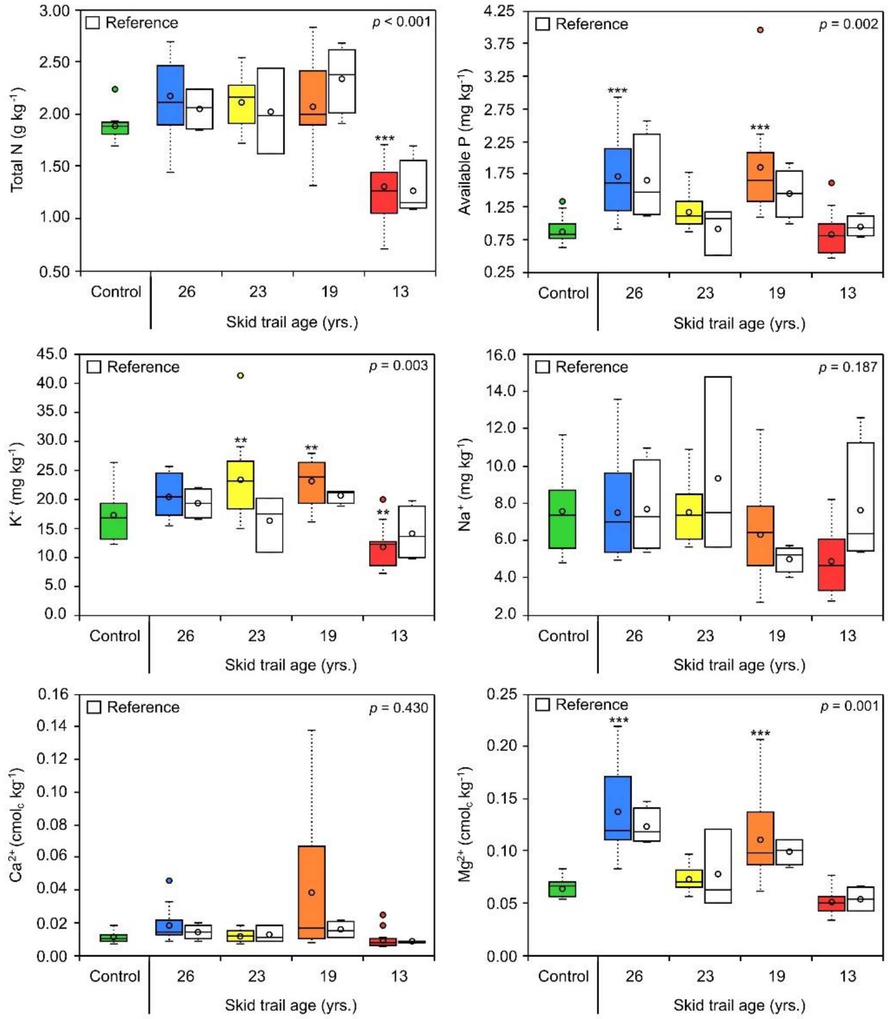

Fig. 5. Box plot data including medians, upper and lower quartiles, means (circle within box) and outliers (circle outside of box) for soil nutrient concentrations. Difference with control designated with an asterisk. Levels of statistical significance: *P < 0.05, **P < 0.01 and ***P < 0.001.

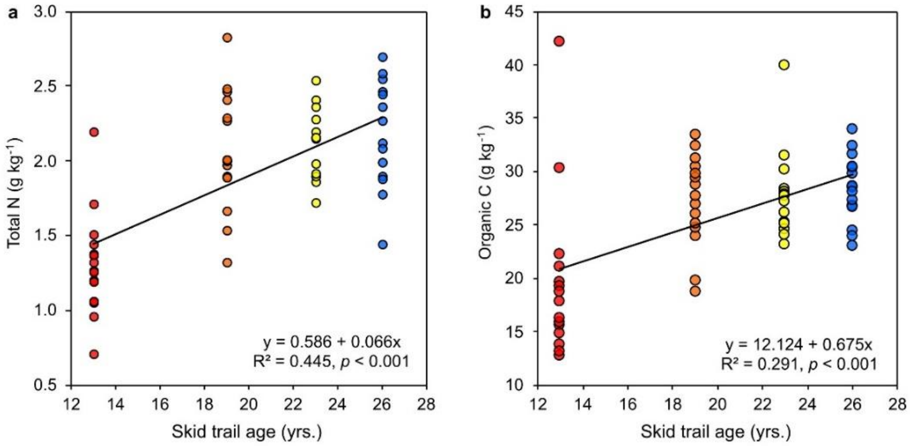

Fig. 6. Linear regression results for (a) total nitrogen (g kg^{-1}) and (b) organic carbon (g kg^{-1}) and the predictor skid trail age in years ($n = 60$).

4. Discussion

4.1. Soil physical properties

Although the site locations always had greater than 35% clay content, the sometimes-high quantity of the sand fraction possibly had an influence. This is because sand content has been shown to be positively correlated with maximum bulk density (Smith *et al.*, 1997b). In the present study, increased sand was correlated with increased pH and soil bulk density (BD). Prior studies in tropical and temperate regions have also demonstrated an increased pH in compacted skid trails and landings after logging and over time (Olander *et al.*, 2005; Tchiofo Lontsi *et al.*, 2019; Picchio *et al.*, 2019; Jourgholami *et al.*, 2019). The negative correlation between increased sand and Al^{3+} and exchangeable acidity was the result of a diminished cation exchange capacity (CEC) caused from the increased sand content.

Recovery of soil bulk density (BD) was not unexpected, as surface soils have been shown to recover various physical properties across a diversity of textures and climates (Ebeling *et al.*, 2016; Froehlich *et al.*, 1985; Mohieddinne *et al.*, 2019; DeArmond *et al.*, 2019). Also, the lack of full recovery of BD in Unit K2, after 19 years, is in agreement with a previous study conducted in the Brazilian Amazon. In McNabb *et al.* (1997), the authors found that compacted skid trails still had not fully recovered the BD values of the control after 16 years. Nevertheless, the mean BD of 1.04 g cm^{-3} in Unit K2 skid trails, was lower than that found in the more recent 13-year-old skid trails, which had a mean of 1.19 g cm^{-3} in Unit N1. In fact, skid trail BD in Unit N1 was substantially lower than the BD values of > 1.30 g cm^{-3} encountered immediately after logging in skid trails in a nearby timber harvesting operation also on a Ferralsol (DeArmond *et al.*, 2020).

The declining trend of soil bulk density (BD) enabled a prediction of 25 years for full recovery of BD. These results are similar to those found in other regions. In temperate forests of the U.S.A., Froehlich *et al.* (1985) observed a declining BD in the upper 5.1 cm of skid trails in both granitic and volcanic soils; however, a full recovery occurred only in the granitic surface soil after 23 years. In the tropical forests of Malaysia, Jusoff (1996) also observed a declining trend in BD for skid trails with a texture of sandy loam to clay loam. The author used regression analysis to estimate a recovery of 22 years for BD in skid trails based on 10 years of measurements. Thus, the recovery trend of the present study aligns with the trends encountered in other regions despite differences in texture or climate. What is likely different, at least from the temperate regions, is the climate and the subsequent mode of recovery. In the non-expansive kaolinite clay that dominates the site, biological processes are more important for the improvement of soil structure (Oades, 1993), whereas in temperate regions the climate and the oscillations therein, contribute to the recovery to a greater degree, especially in expansive clay soils (Froehlich and McNabb, 1984; Cambi *et al.*, 2015). Regardless of texture or climate, the similarities between the present study and others, is that recovery occurs primarily at the soil surface (DeArmond *et al.*, 2021).

The negative correlations with soil bulk density (BD) for total N, organic carbon, Al^{3+} and exchangeable acidity were likely a result of reduced oxygen from soil compaction. This is because lower oxygen levels can increase denitrification, slow mineralization of organic matter and lead to reduced conditions, which tend to lower the soil acidity (Tiedje *et al.*, 1984; Sposito, 2008). Denitrification lowers acidity through proton consumption (Van Breemen *et al.*, 1983). This in turn raises the pH, which subsequently lowers the amount of exchangeable aluminum in the soil (Brady and Weil, 1999). Although compaction can slow organic matter mineralization, Startsev et al. (1998) found that increased soil compaction actually accelerated decomposition. Soil compaction reduces soil oxygen largely from macropore destruction (Cambi *et al.*, 2015). Skid trails substantially lower macroporosity, even after just a few machine passes (Naghdi *et al.*, 2016b; Solgi *et al.*, 2020), which affects gas diffusion within the soil (von Wilpert and Schäffer, 2006; Ebeling *et al.*, 2016). Moreover, the overall pore size distribution is affected limiting soil biota movement and access, which can inhibit C turnover (Van Veen and Kuikman, 1990).

4.2. Fine root biomass

In the Amazon, a majority of the fine root biomass (FRB) is located in the upper 5 to 10 cm of soil (Cordeiro *et al.*, 2020; Noguchi *et al.*, 2014a). Therefore, FRB is highly susceptible to damage from skid trail construction and use, especially in the wheel tracks (Picchio *et al.*, 2019). This susceptibility of damage to FRB in skid trails mainly arises from the scraping off of the topsoil to create a smoother cleaner running surface for the machinery. Though skid trails are not always scraped clean, there is still the crushing weight and churning of the tires or tracks that severs fragile fine roots. For example, within a year after logging operations in temperate forest, machine operating trails had lower FRB than the undisturbed forests (Malo and Messier, 2011). Also in a temperate region, Jourgholami *et al.* (2019) still did not have a full recovery of FRB in skid trails located in 25-year-old plantations. In a tropical forest, landings were still deficient in FRB after 27 years (DeArmond *et al.*, 2022). Nevertheless, recovery of FRB has been reported in skid trails under a thick canopy in as little as 5 years after operations, whereas within the same study, FRB in skid trails located in clearcuts had not recovered (Jourgholami *et al.*, 2021a). The authors attributed the improved conditions for recovery under the canopy to higher organic matter and soil moisture, which benefitted overall biological activity. The skid trails in clearcuts likely had lower FRB due to a drier site, as FRB and fine root productivity has been shown to decline when experimental drought conditions were induced (Olesinski *et al.*, 2011). When evaluating fine root density in skidding tracks in soils of differing textures across a chronosequence of 10-40 years, no difference was found (Ebeling *et al.*, 2017). Those results were similar to those of the present study, where there was no difference between the control mean of 282 g m^{-2} and the chronosequence means of 224-233 g m^{-2}. These results agree with a recent meta-analysis on ground-based logging impacts to fine roots, namely that there was no observable trend with time for fine root recovery (Latterini *et al.*, 2023b). Though, recovery of fine roots in skid trails does began at the surface (von Wilpert and Schäffer, 2006).

Notably, some of the samples in the more recent, and more compacted, skid trails had higher FRB than the control samples. In fact, some fine root biomass (FRB) samples were located in some of the highest overall soil bulk densities within the skid trails. This may be linked to sand content. There was a moderate correlation with sand and soil bulk density, although not between sand and FRB. Still, in Amazonia, higher FRB has been observed in sandier soils (Silver *et al.*, 2005). Fifteen years after logging, Warlo *et al.* (2019) encountered higher fine root mass density in wheel tracks with correspondingly high bulk density. This appears to be counterintuitive, but root growth can cause a loss in porosity by compacting surrounding soil (Dexter, 1991). Therefore, the end result of increased root growth is not necessarily a lowering or improvement in bulk density, as the soil volume may remain the same (Keller *et al.*, 2021). Nevertheless, over time FRB assists in soil improvement through carbon input and various other dynamics (Colombi and Keller, 2019), especially considering the turnover time of FRB in Amazonia being 3.7 years (Cordeiro *et al.*, 2020). Over time, this accumulation of organic C results in an increased level of aggregation, which improves soil quality (Six *et al.*, 2002). Another benefit of root growth, is that after roots succumb to mortality, a biopore is formed (Dexter, 1991; Colombi and Keller, 2019). These biopores then become areas of access into the surrounding compacted soil creating additional biopores, which in turn assists the soil recover over time (Keller *et al.*, 2021).

Overall, fine root biomass (FRB) appears to have made a complete recovery in the surface of skid trail tracks and ruts across the chronosequence. Thus, the recovery occurred prior to 13 years, which was the age of the most recent skid trails studied. There were few indicators to determine the cause for such a quick recovery of FRB. Only one correlation presented itself with increases in FRB being associated with increases in Na^+ for both skid trails and controls/reference sites. As K^+ is low throughout the locations of the study, it is possible that the fine roots are utilizing Na^+ to offset the low levels of K^+ (Kronzucker *et al.*, 2013). One scenario for FRB recovery is the close proximity of the skid trails to well established trees and their root network below the trails. As skid trail construction at this timber company does not entail a complete removal of the topsoil, there are likely damaged and crushed roots remaining in the trails. These already established roots likely initiated the FRB recovery. Also, dead roots that were mixed into the compacted soil from tire churning decompose and create voids in the compacted soil. These voids may then become access points for further biological activity (Keller *et al.*, 2021). This suggested path of FRB recovery may have occurred soon after the cessation of logging operations. However, without sampling along earlier timeframes, the reason for FRB recovery remains elusive. Thus in regards to FRB, there is a limitation of what can be ascertained for FRB recovery in this study because sampling began more than a decade after the conclusion of logging.

4.3. Soil chemical properties

Heavily used skid trails in temperate regions have been shown to impoverish nutrient pools of total N, organic C, K, Ca and Mg soon after logging operations (Solgi *et al.*, 2019; Naghdi *et al.*, 2016b; Shabaga *et al.*, 2017). This impoverishment has been shown to last even after 25 years of recovery (Sohrabi *et al.*, 2020). In some cases, skid trails and landings have caused few changes in nutrients (Tchiofo Lontsi *et al.*, 2019; Treasure *et al.*, 2019), whereas in the Amazon, skid trails and landings were shown to have increased Ca, Mg and K (Olander *et al.*, 2005; Mello Ivo *et al.*, 1996). Also in Amazonia, McNabb *et al.* (1997) encountered elevated Ca and Mg in skid trails 16 years after the site was logged. In the present study, there were no differences in Ca^{2+}, whereas Mg^{2+} and K^+ displayed no clear trend across sites, although in many cases the skid trail means were elevated in contrast to the unit reference samples. Furthermore, many of the unit reference samples had elevated means above the control. Due to distance between logging units, there is likely variation related to differences in site rather than soil compaction or time of recovery. This distance between logging units of up to and over 10 km, is a limitation of the present study that could not be avoided due to logging unit size (>1,000 ha). The distance combined with high tree diversity avails the possibility that distinct differences in soil chemical properties might arise merely from variability of sites, which could affect these results. For example, in temperate monoculture and mixed plantations, researchers showed substantially different nutrient concentrations between sites of different tree species in skid trails 20 and 25 years after timber harvesting (Jourgholami *et al.*, 2019; Sohrabi *et al.*, 2022). In the tropics, comparison of differences in canopy height and foliar N content, revealed that plots with higher canopy and foliar N, had higher N mineralization, nitrification and nitrate concentrations in the soil (Osborne *et al.*, 2020). Also in the tropics, Xia *et al.* (2016) found that soil nutrient patches were influenced by topography and fluctuate by season. Unit N1, had a slightly different terrain and canopy (*e.g.*, more open and shorter) than other sites and generally had lower nutrient concentrations. However, Unit N1 also had the greatest compaction and was the most recently used skid trail, so it is plausible that some differences in chemical concentrations in Unit N1 were due to site differences, as well as skid trail compaction. Therefore, a cautious approach must be taken in the interpretation of these results on soil chemical properties.

In the skid trails, total N, organic C, exchangeable acidity and cation exchange capacity (CEC) were the chemical concentrations with the greatest goodness-of-fit with the predictor of time (e.g., skid trail age). These same concentrations were also strongly, and inversely, correlated with soil bulk density (BD). They were also predicted to recover before BD, with exchangeable acidity ($H^+ + Al^{3+}$) and CEC recovering shortly after 15 years, total N and organic C by 20 years and then followed by BD at 25 years. Organic C has been shown to accumulate in soils over time and even double, or more, in 20 years (Six *et al.*, 2002; Cambi *et al.*, 2015). As organic C had a majority of, as well as the strongest, correlations with other chemical concentrations, it would appear that organic C is pivotal in the rehabilitation of compacted skid trails. In and outside of the Amazon, studies have shown that organic C recovery precedes BD recovery (McNabb *et al.*, 1997; Hosseini *et al.*, 2015; DeArmond *et al.*, 2022). In fact, Tavankar *et al.* (2022), found that the recovery of organic C and total N paralleled each other over time and began in lightly used skid trails after 20 years, being completed even in heavily used skid trails by 30 years. Although there were few differences between total N and organic C for Units B, N and K2, they did incrementally increase over time. This strong relationship between N and organic C has been encountered in other skid trails as well (Shabaga *et al.*, 2017). This is not surprising as soil organic matter contains approximately 5% nitrogen (Weil and Brady, 2016). The strongest association for organic C in the skid trails was with CEC, which had an overall beneficial effect on all exchangeable nutrients. Outside of the skid trials, CEC in the control 6.87 $\mathrm{cmol_c\ kg^{-1}}$ and reference samples 7.75 $\mathrm{cmol_c\ kg^{-1}}$ was similar to a prior study of the area that had a CEC of 7.7 $\mathrm{cmol_c\ kg^{-1}}$ in their forest sites (Trindade *et al.*, 2021). On the other hand, the older skid trails of the present study, had a CEC of 21-29% higher than the control. This was likely due to a greater accumulation of organic matter, as the three oldest skid trails had slightly higher organic C concentrations than the control and the increasing trend was linear with age.

5. Conclusion

In the Brazilian Amazon, soil recovery in the evaluated skid trails did occur, at least at the surface and over several decades. Furthermore, there were observable trends to this recovery over time in many of the soil properties evaluated. Prior to this recovery of fine roots had already established across the skid trails, potentially contributing to the subsequent trends, especially organic carbon accumulation through fine root turnover. This contribution of soil organic carbon was apparent in all aspects of the recovery, being strongly associated with improvement of the cation exchange capacity over time, as well as the subsequent decrease that resulted in a lower soil bulk density. Nevertheless, the recovery took more than two decades. Considering this, the reduction of overall skid trail disturbance in future logging operations should be a priority to maintain site productivity.

Appendix A: Supplementary Material

Chapter 4

DeArmond, D., Ferraz, J.B.S., Lovera, L.H., Souza, C.A.S. de, Corrêa, C., Spanner, G.C., Lima, A.J.N., dos Santos, J., Higuchi, N. 2022. Impacts to soil properties still evident 27 years after abandonment in Amazonian log landings. *Forest Ecology and Management* 510:120105.

Impacts to soil properties still evident 27 years after abandonment in Amazonian log landings

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Abstract

Logging machinery impacts site soil properties mainly through topsoil removal and compaction. The greatest soil disturbance occurs in the logging infrastructure areas: skid trails, roads and log landings. Although landings generally occupy less of the site than skid trails and roads, they suffer severe compaction usually accompanied with complete topsoil removal to level the soil surface for log decking and loading. Few long-term studies have quantified if landing soil properties recover, with none in the humid tropical forests of Amazonia. The aim of this study was to determine if soil bulk density, penetration resistance and fine root biomass in 27-year-old abandoned log landings had returned to a similar state of the adjacent old-growth forest soils. The working hypothesis was that impacts on soil remained despite the regenerated stand of trees present on the landings. Results revealed that the soil physical properties in the log landings were still significantly higher than the controls. Furthermore, fine root biomass was still below the levels presented in the controls. Therefore, in log landings located on very clayey soils in Central Amazonia, soil compaction persists for at least 27 years.

Keywords: forest management, recovery, bulk density, penetration resistance, fine root biomass, seasonality

1. INTRODUCTION

Worldwide, tropical forests are threatened by conversion to non-forest uses, primarily for agricultural purposes, which cause increased fragmentation and deforestation (Seymour and Harris, 2019; de Lima *et al.*, 2020; Montibeller *et al.*, 2020). Therefore, sustainable forest management has been proposed and utilized as an alternative to forest conversion for non-forest uses (Atangana *et al.*, 2014; Lal, 2015). However, timber harvesting activities still contribute to soil degradation through the use of heavy machinery. The main impacts to soil from logging operations are caused by the timber extraction infrastructure: haul roads that are used for transporting logs on semi-trucks to sawmills, landings where logs are temporarily stored before shipping to the sawmill and skid trails used for dragging logs from the forest to landings. Generally, in terms of the total surface logging area, the greatest soil disturbance from selection harvesting systems in the tropics is from skid trails at approximately 2–4%, haul roads < 2% and landings at < 1% (Arevalo *et al.*, 2016; de Carvalho *et al.*, 2017). Soil compaction from these logging activities in tropical forests has been shown to persist for a decade or greater (Jusoff, 1996; DeArmond *et al.*, 2019).

The concerns over soil degradation in the form of compaction in forested settings is due in part to loss of site productivity, but also more recently to gas emissions. In selective logging systems which are common practice in the tropics, haul roads, skid trails and landings are considered part of the permanent infrastructure for future reentries (DeArmond *et al.*, 2021), and therefore are planned to minimize soil disturbance and site productivity losses. However, the issue of gas emissions still exists, especially considering the emissions in log landings in Amazonia (Keller *et al.*, 2005). Although forest soils are generally thought of as a CH_4 sink (Hiltbrunner *et al.*, 2012), heavily compacted skid trails and landings become sources of CH_4 emissions, as well as N_2O (Teepe *et al.*, 2004, Frey *et al.*, 2011; Hartmann *et al.*, 2014; Tchiofo Lontsi *et al.*, 2020). Several studies have shown that emissions between the compacted tracks in skid trails are higher than in the more compacted tracks (Warlo *et al.*, 2019; Vantellingen and Thomas, 2021). In contrast, the natural efflux of CO_2 out of the soil may be diminished by heavy compaction underneath the tracks or ruts within skid trails (Fründ and Averdiek, 2016; Shabaga *et al.*, 2017), which may last for decades (Ebeling *et al.*, 2016). Considering post-logging soil emissions, Keller *et al.* (2005) speculated that if the CH_4, CO_2 and NO_x emissions encountered in their study were similar across other logging sites in Amazonia, the emissions for the Brazilian Amazon would need to be adjusted upward by at least 5%.

The recovery of the soils physical, chemical and biological properties degraded by logging activities is a lengthy process measured in decades or longer (Ebeling *et al.*, 2016; Sohrabi *et al.*, 2021; Tavankar *et al.*, 2021b). This process may occur at a faster pace in clay soils with a high shrink-swell capacity by oscillating between wet- and dry- cycles (Cambi *et al.*, 2015a), whereas recovery in clay soils with a low shrink swell capacity depends on biological processes such as soil fauna and plant roots (DeArmond *et al.*, 2021). Numerous factors caused by compaction inhibit the biological processes of recovery. For example, heavily compacted soils may become anaerobic and harmful to mycorrhizal fungi, which can inhibit mineral uptake by roots (Nazari *et al.*, 2021). In combination with this, accumulation of elevated CO_2 levels can negatively affect root densities (Flores Fernández *et al.*, 2017). Macrofauna have shown promise in their ability to penetrate compacted soils (Jourgholami *et al.*, 2019; Sohrabi *et al.*, 2021). However, although promising, the few studies on earthworm colonization and inoculation of machinery compacted trails have not demonstrated a consistent recovery (Ampoorter *et al.*, 2011; Bottinelli, *et al.*, 2014b). Although, microarthropod density was shown to increase with increasing compaction, the diversity of species declined simultaneously (Cambi *et al.*, 2017). Consequently, it is highly likely that soil recovery is considerably slow in tropical regions with minimal fluctuations in temperature, low soil shrink-swell capacity, and inhibited biologically processes due to compaction (DeArmond *et al.*, 2019).

As the vast majority of published research on soil compaction in skid trails and log landings conveys long-term damage (Cambi *et al.*, 2015a; Ebeling *et al.*, 2016; Sohrabi *et al.*, 2021; Tavankar *et al.*, 2021b; DeArmond *et al.*, 2021), it is likely that abandoned log landings in Amazonia are still compacted to some degree. Long-term studies of soil degradation and subsequent recovery of landing site soils are scarce internationally and non-existent in the Amazon; however, it is possible that some recovery has occurred over the past 27 years. Even though there is an established secondary forest on the landings in the study area, it is necessary to investigate belowground soil properties to ascertain soil properties statuses. Here it is hypothesized that impacts to soil physical and biological properties remain. To test this hypothesis, differences in bulk density, penetration resistance and fine root biomass were compared between abandoned log landing sites and unentered old-growth tropical forest to determine if impacts persist.

2. MATERIALS AND METHODS

2.1. Study site

The study site was located in the Central Amazon Basin (Fig. 1). The area is characterized by a humid tropical climate without a dry season, with a mean annual temperature above 26 °C and over 2,000 mm in precipitation per year (Alvares *et al.*, 2013). At the time this study was implemented, prior to timber harvesting, the forest standing volume in this area averaged 190 m^3 ha^{-1} in stems above 25 cm DBH (breast height diameter) with the vast majority being of non-commercial volume (Higuchi *et al.*, 1985). After the study site was logged, the mean annual diameter increment was 0.17 cm $year^{-1}$ in unlogged forest, whereas logged areas of the site had been increased up to 0.30 cm $year^{-1}$ (Amaral *et al.*, 2019). The soil is a Geric Ferralsol, which is deep, well drained with a low cation exchange capacity (Quesada *et al.*, 2011). These soils are highly acid with a high clay content (Ferraz *et al.*, 2012; Ferreira *et al.*, 2002). The clay mineralogy is dominated by kaolinite with traces of gibbsite (Chauvel, 1982).

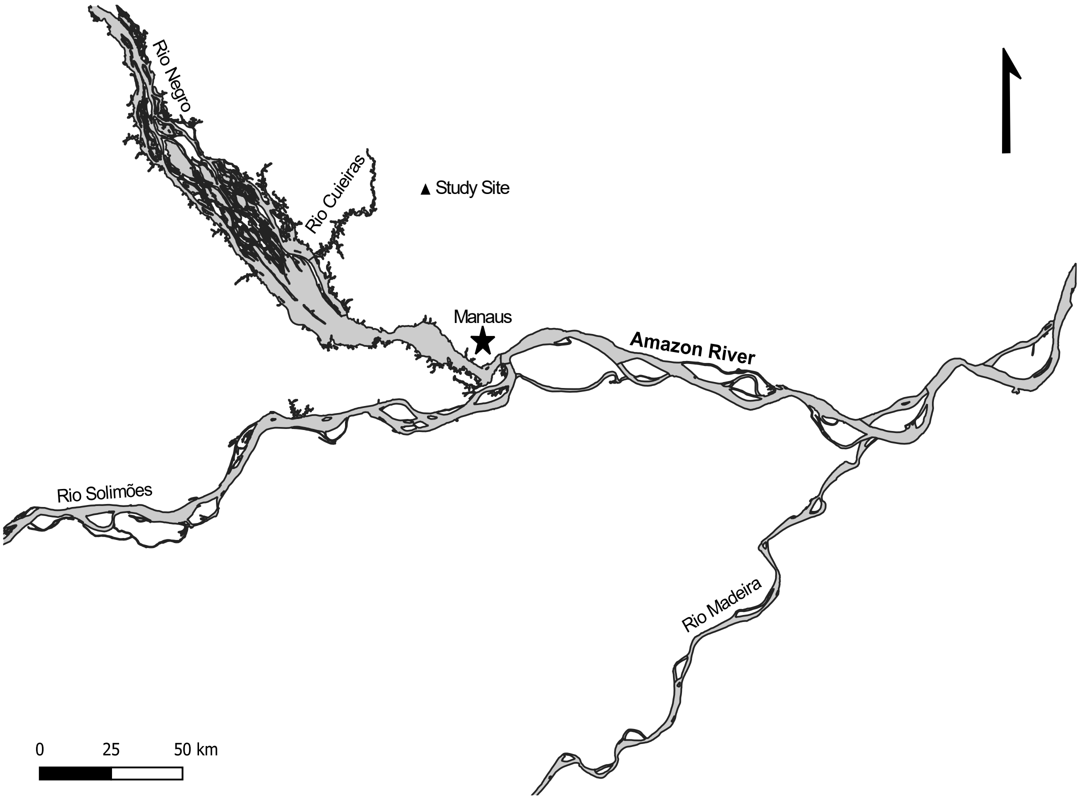

Figure 1. The study site location was approximately 90 km northwest of the capital city of Manaus, state of Amazonas, Brazil.

In 1980, the National Institute for Research in the Amazon (INPA) established an experiment to study the management of humid tropical forests. The experiment was setup as a randomized block design with four blocks consisting of 24 hectares, each containing six sub-blocks of four hectares inside of each block (Higuchi *et al.*, 1985). The six sub-blocks were then randomly designated as a control, one sub-block for pre-commercial silviculture and the other 4 blocks for the various logging intensities, from light to heavy. The volume harvested had a range of 34–67 m^3 ha^{-1} and an intensity of 5–16 trees per hectare, according to the silvicultural prescription (Amaral *et al.*, 2019). The logging operations were conducted in 1987, 1988 and 1993. A ground-based harvesting system was utilized, as the topography is composed of plateaus. Timber felling was conducted manually with chainsaws. All logs were skidded with chokers by a D6 track-type tractor on skid trails to log landings. Skid trails did not need excavation due to the flat topography and skidding occurred across the natural ground surface. Log landings were cleared of vegetation such as small trees and stumps with minimal excavation of the topsoil so that logs could be stacked on a level surface for shipment to the sawmill. There were two landings that remained without further anthropogenic disturbance since the last use in 1993, which were selected for this study. These two landings and their control counterparts served as the basis for this research.

2.2. Sample design

The two landings were each approximately 1,000 m^2 in area. One replicate landing was near Block II and the other near Block I, with controls of a similar size within each respective block (Fig. 2). Both landings were measured and a grid in square meters was placed on a map with a number for each landing and control area. Following this, a random number generator was employed to determine 15 sampling locations per replicate in both controls and landings (n = 60). At each sampling location bulk density and penetration resistance were collected, as well as fine root biomass for both wet and dry seasons. In total, samples collected for this study were as follows: bulk density (n = 120), penetration resistance (n = 480) and fine root biomass (n = 240). Due to the discovery of an old mound of leaf cutting ants underlying the terrain, two sampling locations were excluded from the control in Block I.

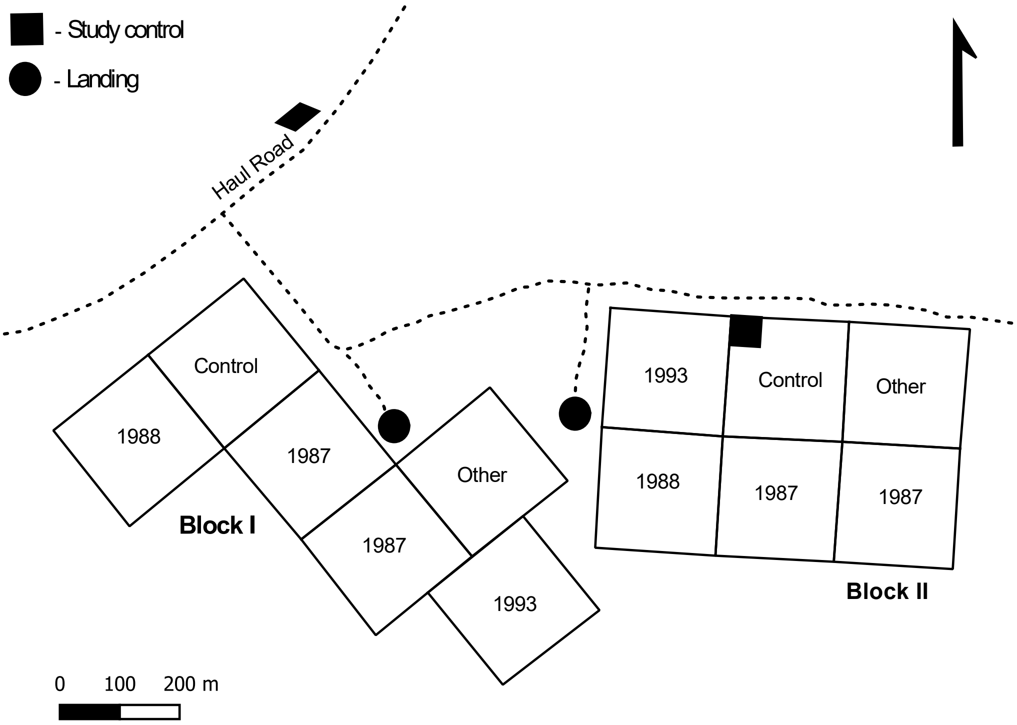

Figure 2. Study site layout with two controls and two landings.

In addition, three random sample locations were selected from each replicate to determine soil properties such as texture, organic matter, C, and pH. Soil samples were air-dried and sieved through a 2 mm sieve and analyzed in INPA's Laboratory of Soil and Plants (LTSP). Soil properties were determined in two depths of 0–5 cm and 5–10 cm with a 100 cm^3 steel ring 5 cm in height. In addition, stand basal area, stand density and tree heights were calculated for these plots, which were 100th ha circular plots with a radius of 5.64 m. Basal area per hectare was determined from diameter at breast height (DBH) 1.3 m above ground level and measurements for all tree stems greater than 5 cm DBH located within the circular plots were made. Total tree height was determined with a *TruPulse 360R* developed by Laser Technology, Inc. All plots were placed randomly and entirely within a given replicate and did not overlap.

The soil samples collected for bulk density (BD) were taken from the mineral soil in two depths, 0–5 cm and 5–10 cm, at the aforementioned sampling locations. The determination of BD was made with a 100 cm^3 steel ring 5 cm in height. The samples were then dried at 105° C for a minimum of 24 hours and then weighed to determine BD. To determine soil penetration resistance (PR), a 30° cone Stolf impact penetrometer was used until 10 cm in depth. Four sample points were established in a rectangular fashion around each BD sample point sample location at a distance of approximately 15 cm. To convert the measurement of drops into megapascals the excel VBA program developed by Stolf *et al.* (2014) was utilized. The PR data was divided into two depths of 0–5 cm and 5–10 cm. All samples for PR were taken at the same time as the corresponding sample for BD to ensure an accurate soil water measurement. In addition, due to the influence of soil moisture on PR readings (Smith et al., 1997a), all PR data was adjusted to a common water content with a formula proposed by Vaz *et al.* (2011):

$$PR = \exp(a + b^{*}\rho b + c^{*}\theta_{V}) \qquad (1)$$

where PR is the penetration resistance in MPa, ρb is bulk density, θ_V is volumetric water content, and a, b and c are fitting parameters. Then the parameters were determined through non-linear regression. Following this, bulk density was reentered with the desired volumetric water content. The value used for a common water content was field capacity, which was the average field capacity value taken from Block's I and II in the 0–10 cm depth, according to Ferreira *et al.* (2002). This data was determined from soil water retention curves that were developed previously for the study site to determine field capacity, plant available water and wilting point using a tension table and a Richards Chamber with undeformed samples submitted to tensions of 10, 30, 100, 200, 500 and 1500 kPa, for the controls and logging units (Ferreira *et al.*, 2002).

The sampling for fine root biomass (FRB) was conducted in two phases. The initial sampling occurred the first week of March 2020 during the wet season, and the final sampling was conducted during the dry season in the second week of September 2020 (Fig. 3). This was done to capture FRB data for both seasons, but to also maintain a distance between sampling dates of greater than six months. Samples for FRB were taken from the mineral soil in two depths at 0–5 cm and 5–10 cm with a 100 cm^3 steel ring 5 cm in height. The wet and dry season sampling points were separated by a minimum of one meter from each other. Samples were placed in sealable plastic bags and transported to the laboratory and stored under refrigeration until cleaning. Cleaning entailed carefully washing away soil under running water using mesh screens to capture root material. Then roots under < 2 mm in diameter were placed in paper bags and dried for 72 hours in an oven at 65 °C.

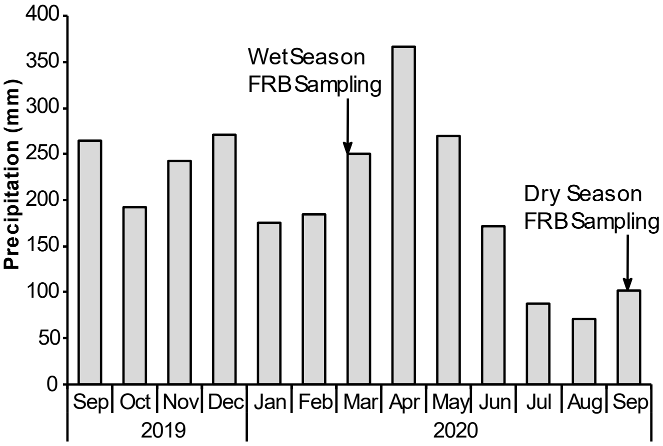

Figure 3. Monthly precipitation (mm) collected onsite preceding the collection dates for fine root biomass.

2.3. Data Analysis

All comparisons were made between data from samples of the same depth and not between depths (Tavares *et al.*, 2016). A One-Way ANOVA was used to evaluate data for bulk density and penetration resistance. Where treatment was the fixed factor and the measured variable was the dependent variable. To determine differences and interactions between seasons and treatments, and to account for non-independence of FRB samples that were matched, a mixed ANOVA was utilized. Differences between soil chemical properties and soil texture were determined with a two-tailed independent samples t-test. Pearson correlation analysis was also conducted between FRB and soil physical properties. Prior to analysis, normality was evaluated with Q-Q plots and histograms. All data were analyzed using IBM Corp. SPSS Statistics for Windows, Version 27.0 (Armonk, NY: IBM Corp).

3. RESULTS

3.1. Site description

Twenty-seven years after logging and landing abandonment some soil properties were fairly similar between controls and landings (Table 1). In fact, the only statistical differences that were encountered were limited to the 5–10 cm depth. The organic matter content (OM) was lower in the landings than in the controls at this depth $t(10) = 4.212$, $p = 0.002$. Correspondingly, C was lower in landings than the controls for the same depth $t(10) = 4.178$, $p = 0.002$. There was also a slight difference in the coarse sand content between the landings and the controls $t(10) = 2.236$, $p = 0.049$ in the 5-10 cm depth. The total mean coarse-sand content for the landings was 52 g kg^{-}

^{1} vs 65 g kg^{-1} in the controls. The lower values in coarse sand were predominately in the landing of Block II.

Table 1 Site description of soil pH, C, organic matter (OM) and texture. Each value for a given depth is the mean of three samples followed by the standard deviation.

Block	Treatment	Depth (cm)	pH (H_2O)	C (g kg^{-1})	OM (g kg^{-1})	Texture (g kg^{-1})			
						Clay	Silt	Fine-sand	Coarse-sand
I	Control	0 – 5	4.36 ± 0.36	29 ± 6.1	51 ± 10.1	637 ± 30.6	289 ± 30.9	18 ± 2.5	55 ± 9.3
		5 – 10	4.38 ± 0.15	22 ± 2.9	39 ± 4.9	601 ± 17.2	318 ± 13.9	20 ± 1.7	61 ± 3.5
	Landing	0 – 5	4.35 ± 0.37	33 ± 5.2	57 ± 9.2	612 ± 63.9	300 ± 50.5	22 ± 4.0	67 ± 16.6
		5 – 10	4.39 ± 0.40	16 ± 4.9	28 ± 8.7	650 ± 32.0	270 ± 41.9	21 ± 3.1	59 ± 12.7
II	Control	0 – 5	4.42 ± 0.14	35 ± 1.0	60 ± 1.5	663 ± 39.9	256 ± 35.4	23 ± 2.5	57 ± 4.0
		5 – 10	4.47 ± 0.15	22 ± 2.5	38 ± 4.2	614 ± 88.3	292 ± 82.0	24 ± 2.6	69 ± 11.0
	Landing	0 – 5	4.45 ± 0.14	30 ± 6.4	51 ± 10.1	636 ± 42.6	294 ± 35.2	19 ± 2.9	51 ± 5.5
		5 – 10	4.70 ± 0.09	12 ± 2.1	20 ± 3.6	628 ± 37.0	309 ± 34.2	18 ± 1.2	45 ± 2.6

As expected, the stand basal area was greater in the unentered old-growth controls than in the abandoned log landings that had previously been cleared of all vegetation prior to use for logging operations. The landing trees also had a smaller maximum diameter at breast height (DBH), which is not surprising as the vegetation on the landing sites is approximately 27 years old. The overall stand density (1367 to 1567 trees ha^{-1}) was primarily composed of stems with a DBH ≤ 10 cm. The remaining stems ≥ 10 cm accounted for 633 trees ha^{-1} in the controls and 683 trees ha^{-1} in the landings. However, the mean DBH amongst the control sites and landings was actually quite similar (Table 2).

Table 2 Description of stand basal area (BA), stem density (ha^{-1}), diameter breast height (DBH) and total tree height derived from subplots (*n* = 3) taken from each replicate of approximately 1000 m^{2}.

Block	Treatment	Basal Area (m^{2} ha^{-1})	Stem Density (ha^{-1})	DBH (cm)		Height (m)	
				Mean	Max.	Mean	Max.
I	Control	29.3	1367	13.5	47.5	13.6	26.1
	Landing	17.8	1567	11.0	23.2	12.3	19.9
II	Control	30.5	1467	12.8	47.1	14.1	30.8
	Landing	13.4	1467	9.9	22.0	11.6	17.6

3.2. Soil physical properties

Soil bulk density (BD) was still elevated in the log landings after nearly three decades (Figure 4). The differences for the values of BD were significantly higher in the log landings than for the undisturbed controls in the 0–5 cm depth $F(1,56) = 31.696$, $p < 0.001$. The BD for the landings was also significantly higher than the controls in the 5-

10 cm depth *F*(1,56) = 50.263, $p < 0.001$. The difference in compaction for BD when comparing the controls and the landings was 9.5% for the upper depth and 13.5% for the lower depth.

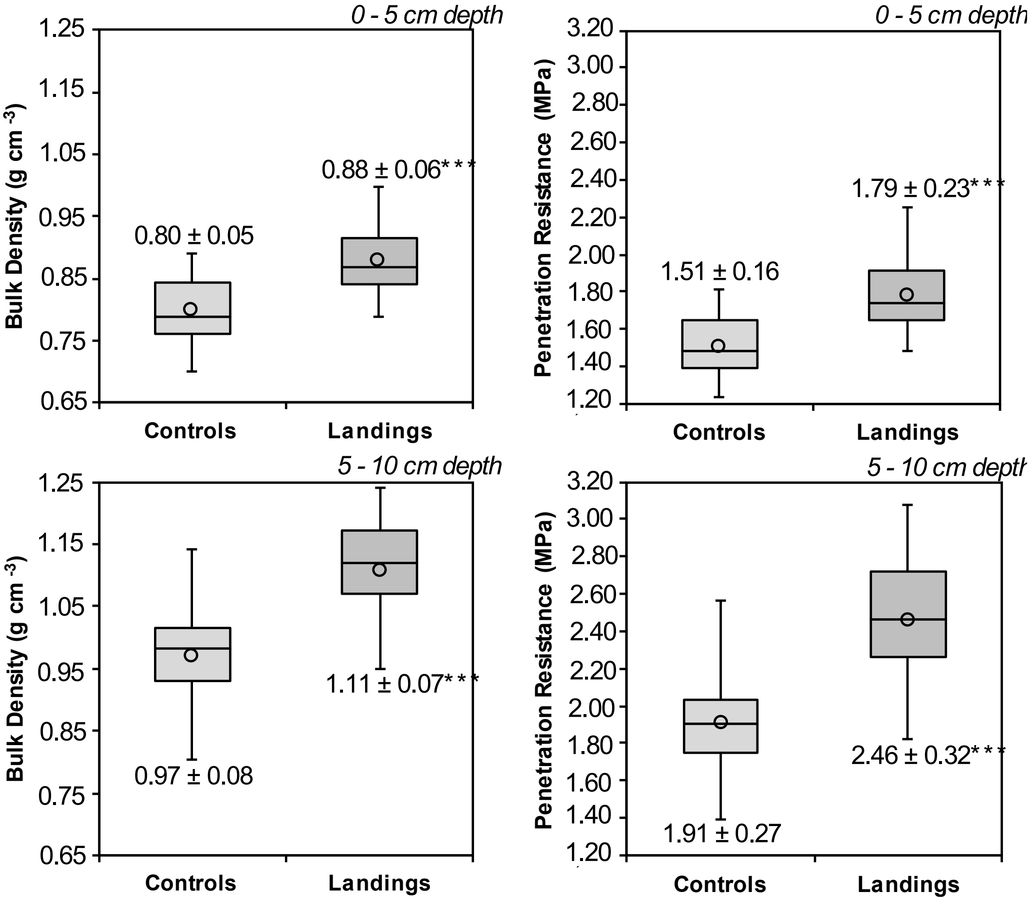

Figure 4. Box plots presenting percentiles of bulk density and penetration resistance in control and landing areas. Open circle represents mean with value, standard deviation and significance above box plot. Significance level: *** < 0.001.

Soil penetration resistance (PR) followed a similar pattern as soil bulk density, with elevated values in the landings (Fig. 4). The landings had significantly higher values than the controls in the 0–5 cm depth *F*(1,56) = 29.862, $p < 0.001$. In the lower depth, differences of values between PR were also significant *F*(1,56) = 49.314, $p < 0.001$, when comparing landings and controls. Furthermore, the differences in PR, between landings and controls, were greater in the 5-10 cm depth by 25.2% than in the 0–5 cm, which was 17.0%.

The adjustment to a common water content, field capacity in the 0–5 cm depth ($\theta_v = 0.45$) and in the 5–10 cm depth ($\theta_v = 0.46$), was made prior to the statistical analysis of PR data. Nonlinear regression resulted in the following fitting parameters for the upper depth (n = 58): $a = -1.538$, $b = 2.000$, $c = 0.779$; and for the lower depth (n = 58): a = -0.394, b = 1.811, c = -1.579. The adjustment narrowed the range of values from 0.93 to 3.97 MPa to 1.24 to 3.08 MPa. The narrowing of the range also lowered the coefficient of variation (Table 3).

Table 3 Penetration resistance data before and after adjustment to a common water content, field capacity, including the mean, coefficient of variation (CV) and the range.

Penetration resistance data					
Area	Depth (cm)	Status	Mean (MPa)	CV (%)	Min.-Max. (MPa)
Controls	0 – 5	before	1.32	18	0.93 – 1.91
		after	1.51	11	1.24 – 1.81
	5 – 10	before	1.94	14	1.47 – 2.54
		after	1.91	14	1.39 – 2.57
Landings	0 – 5	before	1.91	22	1.21 – 3.15
		after	1.79	13	1.48 – 2.25
	5 – 10	before	2.60	18	1.90 – 3.97
		after	2.46	13	1.82 – 3.08

3.3. Fine root biomass

Fine root biomass (FRB) in the 0–5 cm depth was significantly higher in the wet season than the dry season $F(1,56) = 7.027$, $p = 0.010$. In this upper depth, mean FRB for the wet season was 507 g m^{-2} in the controls and 196 g m^{-2} in the landings, whereas in the dry season FRB was 408 g m^{-2} in the controls and 157 g m^{-2} in the landings (Fig. 5). FRB was significantly lower in the landings than in the controls $F(1,56) = 153.619$, $p < 0.001$. However, there was no significant interaction between season and treatment in this depth $F(1,56) = 1.371$, $p = 0.247$. Also, in the 5–10 cm depth FRB was significantly higher in the wet season than the dry season $F(1,56) = 8.889$, $p = 0.004$. Landing FRB was significantly lower than control FRB $F(1,56) = 124.567$, $p < 0.001$. In this lower depth, mean FRB for the wet season was 191 g m^{-2} in the controls and 59 g m^{-2} in the landings, whereas in the dry season FRB was 150 g m^{-2} in the controls and 46 g m^{-2} in the landings. However, the interaction between season and treatment for this depth was not significant $F(1,56) = 2.445$, p = 0.124. The differences in FRB between seasons in the controls were 22% in the upper depth and 24% in the lower depth. For the landings, the differences in FRB between seasons were similar to the controls, with 22% in the upper depth and 25% in the lower depth. The percental differences in both depths between seasons and landings/controls are nearly identical. Furthermore, some sample areas on the edges of the landings, where presumably less compaction occurred, actually had FRB values that overlapped the control sample values. This was especially true for the 0–5 cm depth during the dry season, where numerous landing samples of FRB were near or greater than the median value in the controls (Fig. 5).

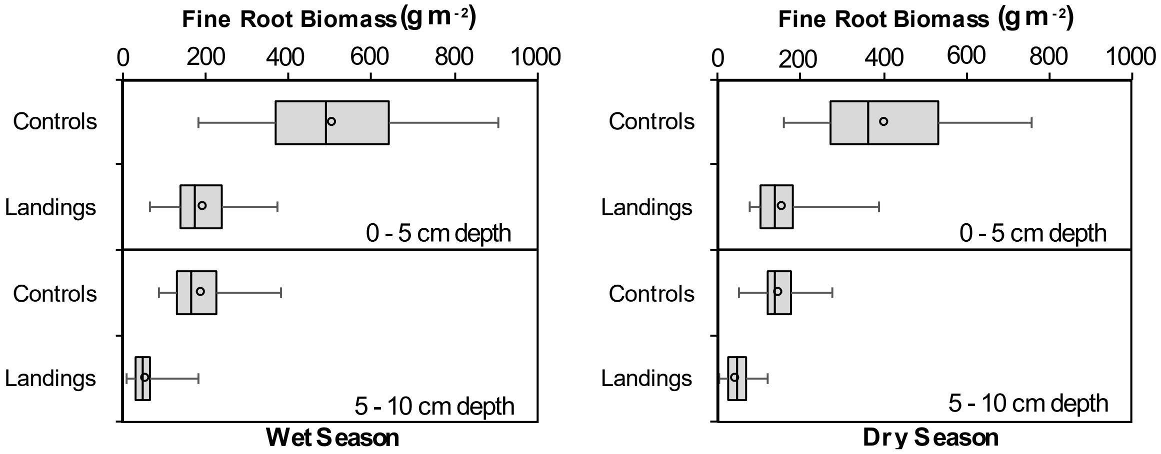

Figure 5. Fine root biomass in landings and controls after wet and dry season.

Lastly, Pearson correlation analysis revealed several statistically significant relationships (Table 4). In the wet season, the upper depth of the controls indicated a weak positive association between FRB and PR *r* = 0.396, *p* = 0.037, whereas BD in the same depth and season fell short of statistical significance at *r* = 0.373, *p* = 0.051. During the dry season, only the lower depth of the landings demonstrated a significant relationship. Increasing values of soil physical properties were negatively correlated with FRB, BD *r* = -0.414, *p* = 0.023 and PR *r* = -445, p = 0.014.

Table 4 Pearson correlations between fine root biomass (FRB) and soil physical properties of bulk density (BD) and penetration resistance (PR) by season.

		Wet Season		Dry Season	
Area	Depth (cm)	BD	PR	BD	PR
Control FRB	0 – 5	0.373	**0.396***	-0.318	-0.297
	5 – 10	0.181	0.167	0.011	0.016
Landing FRB	0 – 5	-0.195	-0.193	-0.218	-0.231
	5 – 10	-0.119	-0.144	**-0.414***	**-0.445***

Note. Significance level of p < 0.05 is indicated by bold asterisk (*).

4. DISCUSSION

4.1. Landing soil properties still in a state of recovery

Despite the passage of 27 years, the log landings have not yet attained a full recovery of the properties investigated. In this study, full recovery of a property was considered if there was no statistically significant difference between a property in the landings and in the controls. So, even though the abandoned landings have naturally regenerated trees, a closer look beneath the soil surface reveals that soil compaction still remains. Elevated values of soil physical properties continue to be evident, as well as a diminished capacity to provide an unrestricted growth environment for fine roots. However, some encouraging signs of a partial recovery present themselves when compared to the controls in the upper topsoil: namely similar organic matter content and pH. This is important as the uppermost topsoil is usually removed during landing construction, leaving a deficient subsoil surface with lower organic C (Nussbaum *et al.*, 1995; Rab, 1996; Tchiofo Lontsi *et al.*, 2019) and higher pH levels (Olander *et al.*, 2005; Blouin *et al.*, 2005). Additionally, the values in the 0–5 cm depth were well below the critical bulk density (BD) for root growth of 1.25 g cm^{-3} for soils with clay content above 60% (Reichert *et al.*, 2003). However, in the 5-10 cm depth there were samples encountered in both landing sites that were ≥ 1.20 g cm^{-3}, which is near or above the aforementioned critical threshold for root growth. Also, all values were below the established restrictive root growth threshold of 2.5 MPa (Cambi *et al.*, 2015a). Therefore, the low BD and soil strength (PR) in the 0–5 cm depth were most certainly much higher after the initial compaction event. This is supported by initial measurements of soil strength of skid trails in the logging area soon after operations, which demonstrated that the mean value of PR was more than double the current study (Mello-Ivo and Ross, 2006). Also, landing PR values are only slightly higher than those found in partially recovered 24- and 30-year-old skid trails in the study area (DeArmond *et al.*, 2019). Another study of soil compaction on a similar Ferralsol in the region, showed that soil BD in the 0–5 cm depth, immediately post-logging, was three times higher and the PR values four times greater than the landings of the current study (DeArmond *et al.*, 2020). Therefore, the soil properties of the landings do indeed appear to be recovering, although the timeframe for a full recovery is beyond that of the current study period.

The slow recovery process of soils in the landings are in accordance with the very few studies available on this subject. Simmons and Anderson (2016) found that after 4 years, log landings still had severely reduced macroporosity and saturated hydraulic conductivity, although in the same time span Reisinger *et al.* (1994) observed that BD values in the landings were declining. After 10 years, Rab (2004) observed a drastic increase in macroporosity recovery in log landings, but the initial disturbance was lighter than that of the skid trails. In the tropics, Jusoff (1996) observed a trend over a decade of decreasing BD and PR in landings, with the decrease of BD greater than PR for the same time interval. This disparity was also apparent in this study within the two landings, as well as a study of skid trail impacts in the logging area (DeArmond *et al.*, 2019). Hatchell and Ralston (1971) claimed that landing topsoil had fully recovered after 18 years, but the authors clarified that it may have been due to the historic logging equipment at the time. In this case, the track-type tractors pulled logs with an arch that elevated the log on one end and distributed the weight amongst the two tires supporting the arch. The oldest study of landing soil recovery and development over time was 23 years after logging in British Columbia, Canada. Here, the studied landings still suffered from higher bulk densities, increased soil strength and lower aeration porosity (Blouin *et al.*, 2005). The majority of these studies were conducted outside of the tropics and all at shorter timeframes than the current study. Nevertheless, they corroborate the results of this study which is that the degree of disturbance caused by landing construction incurs a lengthy recovery process, if left to ameliorate naturally.

4.2. Effect of landing compaction on fine root biomass

The impact on fine root biomass (FRB) in compacted landing soil was evident. The reduction in FRB was even apparent in the much less compacted surface layer. Even after 27 years, the combined mean annual FRB in the landings (0–10 cm) of 229 g m^{-2} was still lower than the 300 g m^{-2} encountered in the upper 15 cm of skid trails 6 years after logging in this study area (Guimarães and Mello-Ivo, 1997). Moreover, this value for FRB is less than half that found for the same depth of undisturbed forest soils in the controls, and also near the study site (Powers *et al.*, 2005). Noteworthy is the lack of interaction between seasons, as it was initially thought that the conditions for root growth in the landings would worsen in the dry season and therefore, inhibit root growth to a greater degree because of increased soil strength in the landings. This effect of soil physical properties on FRB in the dry season was only evident in the more compacted lower depth and only moderately correlated. However, the difference in FRB values between wet and dry seasons were similar for the landings and controls. Even for greater depths (0–50 cm), there were also similar differences between seasons for FRB encountered in old-growth forest near the project area (Souza, 2016).

The study of skid trail and landing impacts to FRB is important, as fine roots play a vital role in the C cycle (Germon *et al.*, 2020) and even in the recovery of degraded soils through FRB turnover (Warlo *et al.*, 2019). Moreover, as the largest fraction of FRB tends to be in the upper 10 cm of soil in Amazonia (Chauvel *et al.*, 1987; Noguchi *et al.*, 2014b; Cordeiro *et al.*, 2020), FRB is highly susceptible to damage from logging activities such as landing construction. Indeed, logging machinery can significantly impact FRB with only 1 or 2 passes (Malo and Messier, 2011). The FRB in the skid trail tracks is affected considerably more than between the tracks (Schäffer *et al.*, 2019), and these impacts have been shown to linger in skid trails many years after logging operations have been completed (Guimarães and Mello-Ivo, 1997; von Wilpert and Schäffer, 2006; Jourgholami *et al.*, 2019). The key difference in disturbance levels between skid trails and landings is that the majority of the surface of log landings makes contact with heavy machinery wheels or tracks and is compacted repeatedly from many different directions, as opposed to skid trails. This creates a challenging environment for the soil recovery in the landings, as there are wider horizontal planes of compacted soil at further distances from established trees, as opposed to skid trails. Skid trails can benefit from root systems of nearby surrounding trees for soil amelioration (Flores Fernández *et al.*, 2019), whereas landings must establish new trees through successional processes to begin improving the soil. Seedling establishment on landings can be challenging because of high bulk densities and diurnal temperatures, even for pioneers (Nussbaum *et al.*, 1995; Pinard *et al.*, 1996). However, pioneer species have been shown to overcome soil strengths above 2.5 MPa in compacted skid trails (Meyer *et al.*, 2014). Another challenge of landings, is the slow accumulation of a litter and organic layer, depending on the size of the landing, also because of the distance from the forest canopy. Experimentally established litter layers have been shown to increase fine root biomass in skid trails (Jourgholami *et al.*, 2021b). FRB can also be essential in soil amelioration by improving soil C through fine root turnover (Warlo *et al.*, 2019). Thus, the return and increase of FRB to degraded soils of log landings is imperative for the restoration of the site.

5. CONCLUSIONS

Nearly three decades after logging operations in a humid tropical forest, log landings on fine-textured soils were still degraded in the form of increased bulk densities, higher soil strength and lower fine root biomass. In terms of percentages, the biological property presented the lowest recovery, whereas bulk density the highest. All of these impacts persist despite a fully stocked stand of trees revegetating the surface of the landings. Therefore, if landings are not planned for reuse and abandoned, consideration should be given to site preparation activities (e.g., tillage and/or mulching) that could initiate a robust well stocked stand of preferred species. In this regard, losses to site productivity could be minimized for future recovery.

Chapter 5

DeArmond, D., Ferraz, J.B.S, de Oliveira, L.R., Lima, A.J.N, Falcão, N.P.S., Higuchi, N. 2023. Soil compaction in skid trails still affects topsoil recovery 28 years after logging in Central Amazonia. *Geoderma* 434:116473.

Soil compaction in skid trails affects topsoil recovery 28 years after logging in Central Amazonia

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Abstract

The use of heavy machinery in logging operations leads to soil compaction, especially in highly used skid trails. In Amazonia, recovery of topsoil physical properties has been reported in skid trails. So, the present study sought to determine if this was a full recovery by investigating additional attributes, such as soil chemical properties and fine root biomass (FRB). In addition, forest floor litter was investigated to present a more complete view of soil recovery dynamics. To accomplish this, litter above sampling locations was collected, as well as soil samples below this in two depths. These depths represented the recovered topsoil layer (0–5 cm) and the still compacted soil layer (5–10 cm) below. Three areas were compared: control, middle of the skid trails, and skid trail ruts. Dry mass, C%, N% were determined for litter and FRB. Foliar nutrients (P, K, Ca, Mg, Fe, Zn, Mn) were also determined. Soil chemical properties such as pH, cation exchange capacity, base saturation, aluminum saturation, soil organic C and nutrients (total N, available P, exchangeable Ca, Mg, K, Na, Fe, Zn, Mn) were also assessed. The primary objective was to determine if there was a full recovery of properties evaluated in the topsoil, but also to determine if the compacted soil below acted as an effective hardpan that potentially exerted influence on the recovered topsoil. In the skid trail ruts, results revealed no significant differences with the controls in the recovered topsoil for FRB and all but one soil nutrient, Mn which was elevated. Additionally, the base saturation and volumetric water content of the ruts topsoil was significantly higher than the controls indicating a potential hardpan condition below. So, even though a topsoil may be considered fully recovered, the compacted soil below may still exert influence in the form of increased soil moisture and nutrient accumulation. Therefore, the key finding of this research is that for the first time a recovered topsoil in skid trails was demonstrated to be affected and influenced by the compacted soil below. This influence in the very clayey soils of Amazonia was observed after nearly-three decades.

Keywords: Soil recovery, Forest floor litter, Fine root biomass, Soil chemical properties, Soil compaction

1. INTRODUCTION

Recent studies have demonstrated that soil physical, chemical and biological properties are sometimes adversely impacted by logging activities such as gap creation and skid trail construction and use (Treasure *et al.*, 2019, Tchiofo Lontsi *et al.*, 2019, Trindade *et al.*, 2021, Jourgholami *et al.*, 2021a). This is especially true in skid trails, where the impacts are exacerbated by the increased traffic of heavy machinery (Naghdi *et al.*, 2016b, Shabaga *et al.*, 2017, Solgi *et al.*, 2019). As many of these impacts to the soil may persist for years or decades, numerous studies have sought to ascertain a better understanding of recovery processes and timelines (DeArmond *et al.*, 2021). While some studies have encountered recovered soil properties (*e.g.*, soil bulk density, fine root biomass, macroporosity) in as little as 5–15 years after logging, these same authors also reported still present impacts to the soil chemical properties as well (Hosseini *et al.*, 2015; Ebeling *et al.*, 2017, Warlo *et al.*, 2019). Recently, several long-term chronosequence studies of skid trails have revealed that although many soil properties have not fully recovered after 25–30 years, many improvements to soil properties over time have occurred, which suggests an ongoing recovery (Jourgholami *et al.*, 2019, Sohrabi *et al.*, 2020, Tavankar *et al.*, 2021b).

The majority of studies on soil recovery in skid trails have occurred primarily in temperate forests (DeArmond *et al.*, 2021). In these regions, soil recovery happens through distinct changes in temperature and moisture patterns that lead to wetting and drying cycles that cause soil to shrink and swell, especially in expansive 2:1 clay soils (Froehlich and McNabb, 1984). To the contrary, in the humid tropics, there is generally a constant warm temperature with predominantly non-expansive 1:1 clay soils where recovery is dependent on biotic factors such as macrofauna and roots (DeArmond *et al.*, 2021). This is the case in many parts of the Amazon where logging operations occur. However, there are few studies on the recovery of soil in logging infrastructure (*e.g.*, skid trails and landings) in the world’s largest tropical forest, which leaves a considerable gap in the knowledge of Amazonian soil recovery. The importance of understanding the long-term impacts to these soils increases every year, as additional Amazonian old-growth forests are entered and logged. Indeed, in the Brazilian Amazon, surface area covered by roads and landings is regulated (*e.g.*, CEMAAM, 2018), but the area covered by skid trails and the subsequent soil disturbance is not.

To date, there is only one known long-term study of soil chemical properties after logging operations in the Amazon. In this study, McNabb *et al.* (1997) encountered elevated nutrient concentrations of Ca and Mg in skid trails 16 years after logging operations. In a much shorter time frame, five weeks after logging operations Mello-Ivo *et al.* (1996) encountered elevated levels of NO_3^-, NH_4^+, Ca, Mg, K and Na in soil water at a 0–10 cm depth in skid trail tractor tracks, when compared to the adjacent old-growth forest. The authors attributed these differences in nutrient concentrations to temporarily reduced root uptake in damaged sites and litter accumulation. Nearly-two years later in the same depth, Ferreira *et al.* (2001) examining the same skid trails and adjacent forest found that there were no statistical differences between the soil available P and the exchangeable cations K, Ca, Mg and Al. Also, in the same skid trails 24 years after the cessation of logging operations, a more recent study determined that soil physical properties in the upper 5 cm of the skid trail ruts had returned to control levels (DeArmond *et al.*, 2019). Nevertheless, since the focus was limited to soil physical properties, there is still uncertainty as to whether the upper 5 cm of topsoil has had a full recovery for other parameters, such as fine root biomass and soil chemical properties. So, to form a better understanding of the recovery process of soils impacted by logging operations in the Amazon region, further investigations are imperative.

Therefore, this paper sought to confirm if the soil in abandoned 28-year-old skid trails, that previously reported a recovery of soil physical properties after 24 years, has indeed experienced a full recovery in terms of fine root biomass and soil chemical properties. To realize this objective, the skid trails litter layer, soil bulk density, moisture, chemical properties and fine root biomass were compared with adjacent reference forest sites. The skid trails were also divided into areas between the ruts, as well as the area inside the ruts. In addition to the recovered topsoil evaluation, the compacted soil below was evaluated as well. These two depths (0–5 and 5–10 cm) were evaluated to determine if there were conditions similar to a hardpan caused by the compacted soil that impacts the physically recovered topsoil above. In this context the objectives of this study were to answer the following questions: 1. Do differences in the skid trail microtopography (*i.e.*, concave trail rut and convex middle) influence litter and nutrient accumulation? 2. Is there any accumulation, or depletion, of nutrients and fine root biomass in the skid trails between the studied soil depths? 3. Lastly, based on the current evaluation what is the assessment of the recovered topsoil?

2 MATERIALS AND METHODS

2.1. Study site

The study site is located approximately 90 km north of Manaus, the capital city of the Brazilian state of Amazonas (2° 38′ 18.76″ S; 60° 09′ 25.74″ W) (Fig. 1).

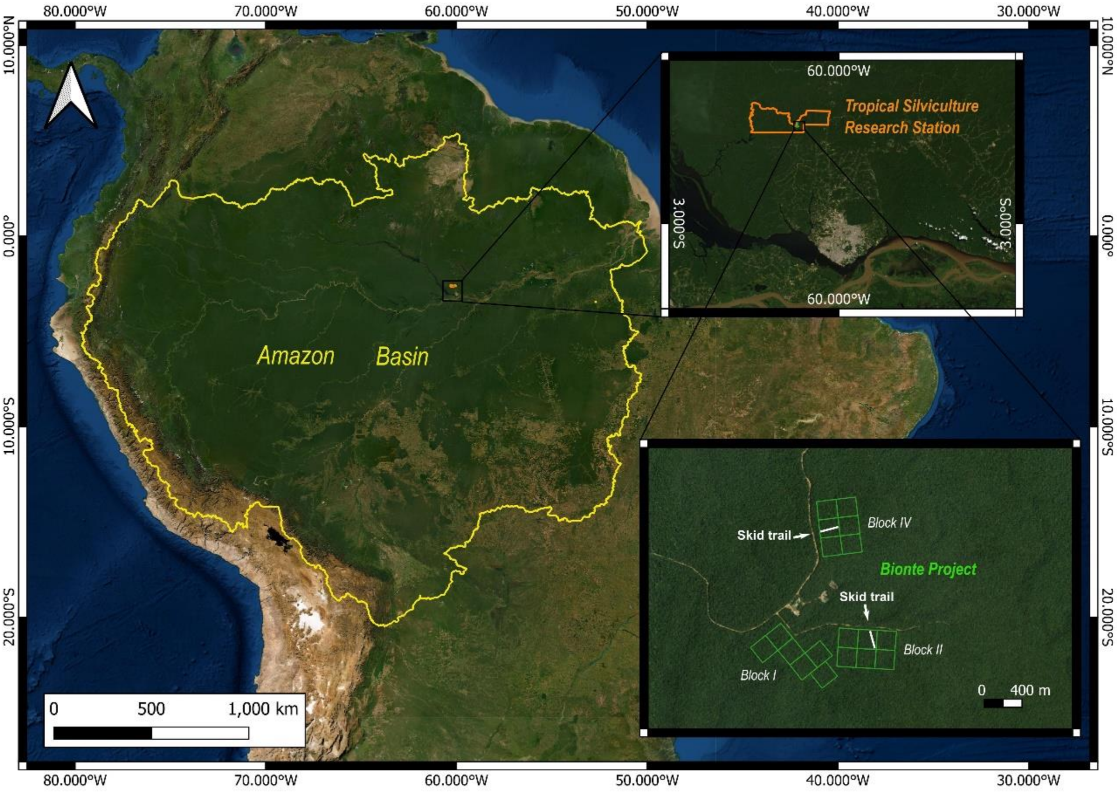

Fig. 1 Study site location map.

The forest cover of the area is considered terra firme, also known as non-flooded upland forest (Bredin *et al.*, 2020). The topography of the site is dominated by a plateau. Plateaus of this area support a closed canopy humid tropical forest of 632 ± 46 trees ha^{-1} with a basal area of 29.1 ± 4.4 m2 ha^{-1} (Marra *et al.*, 2014). According to the Köppen classification system the area climate is classified as tropical without a dry season (Af), with the driest month of precipitation ≥ 60 mm and a mean annual temperature of > 26° (Alvares *et al.*, 2013). However, in the year preceding the final sampling for this project, no monthly precipitation total fell below 100 mm as determined by the onsite rain gauge (non-recording). Annual precipitation data collected from the site pluviometric gauges demonstrated a range of 2353 to 2708 mm

(Higuchi *et al.*, 2011). The study site soil is classified as a Geric Ferralsol (Alumic, Hyperdystric, Clayic) (Quesada *et al.*, 2010). The clay fraction is dominated by kaolinite (80 %), with small amounts of gibbsite (10 %) (Chauvel, 1982). Soil texture data collected for this research project reveals a high clay content for the area (Table 1). Generally, fine-textured soils are considered to be at greater risk to compaction than coarse-textured soils (Cambi *et al.*, 2015a). In many cases, moisture content aggravates the severity of compaction (Brady and Weil, 1999), although due to the non-expansive nature of clay at this site, the level of compaction is similar regardless of moisture content (Froehlich and McNabb, 1984).

Table 1. Soil texture data collected from the studied skid trails. Each value is the mean of six samples, followed by the standard deviation (±).

Depth	Soil texture†	Control	Middle	Rut
0-5 cm	Coarse sand (%)	7.3 (0.9)	9.2 (2.0)	7.7 (1.2)
	Fine sand (%)	2.3 (0.3)	2.9 (0.3)	2.5 (0.4)
	Total sand (%)	9.6 (1.2)	12.2 (2.2)	10.3 (1.5)
	Silt (%)	27.5 (5.6)	24.0 (8.0)	19.5 (3.8)
	Clay (%)	62.9 (4.8)	63.8 (6.8)	70.2 (4.3)
5-10 cm	Coarse sand (%)	7.4 (0.8)	7.7 (1.1)	7.5 (3.1)
	Fine sand (%)	2.4 (0.2)	2.6 (0.2)	2.4 (0.9)
	Total sand (%)	9.9 (1.0)	10.2 (1.2)	9.9 (3.9)
	Silt (%)	30.4 (6.5)	22.7 (5.5)	22.3 (7.0)
	Clay (%)	59.7 (5.8)	67.1 (5.3)	67.8 (5.4)

2.2. Experimental design

In 1980, an experiment designed to study tropical forest management (*e.g.*, natural regeneration and felling cycle) was established by the National Institute for Research in the Amazon (Higuchi, 1987). The original design consisted of four experimental blocks (400 X 600 m) of 24 ha each containing six sub-blocks, although this was reduced to three due to floristic differences between Block III and the other blocks (Higuchi, 1987). Each of the four-hectare sub-blocks was then randomly assigned to a control or various silviculture treatments. The three remanent blocks are collectively called the Bionte Project.

Logging operations occurred in four sub-blocks of Block I, II and IV. The timber harvesting was conducted in 1987, 1988 and 1993. Harvest intensity ranged from light to heavy, with the felling of 5 to 16 commercial trees per hectare that were ≥ 40 cm in diameter at breast height (Amaral *et al.*, 2019). All timber felling and log manufacture was done by hand with chainsaws. Logs were then skidded (*i.e.*, dragged) to log landings (*i.e.*, storage area) with a D6 track-type tractor. Due to the gentle topography, primarily plateaus, there was no need to excavate the skid trails, the logs were merely dragged across the ground surface. Primary skid trails (>10 skidding cycles) that were used in 1987 and again in 1993 in Block's II and IV serve as the basis for the present research.

2.3. Sample collection and preparation

The study design was based on two primary skid trails that were used in the timber harvesting operations of 1987 and 1993. They were located in Block's II and IV of the Bionte Project with a length of approximately 200 m each (Fig. 1). In each skid trail, six sampling locations were located randomly with a grid and random number generator. At each sampling location, three sample points were located in a perpendicular fashion from the middle of the skid trial covering the rut and out to the undisturbed forested control (Fig. 2). Samples were taken in mineral soil at two depths of 0–5 and 5–10 cm. Three samples for each sample point and depth were taken for the following characteristics: soil bulk density (BD), volumetric water content (VWC), fine root biomass (FRB), and soil chemical properties (CP). The collection of BD, VWC, and FRB utilized a steel ring 5 cm in length and width for a total of 100 cm^3 in volume. To determine CP, a small monolith (approximately 125 cm^3) was taken in each depth. In addition, at each sample point directly above the aforementioned samples, the litter layer above the mineral soil was collected using a wooden frame 25 cm X 25 cm with an interior area of 625 cm^2. All samples were collected in June and September of 2021, with the preceding months of collection having nearly identical quantities of precipitation (Fig. 3).

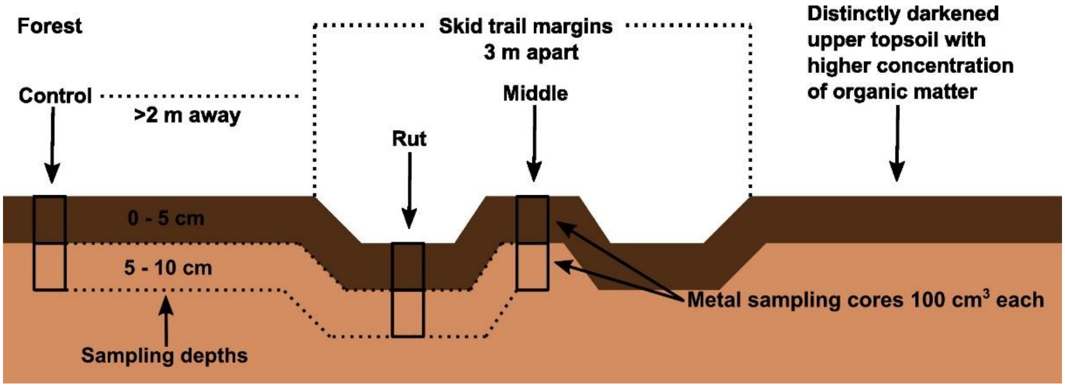

Fig. 2 Sample design within the skid trail profile.

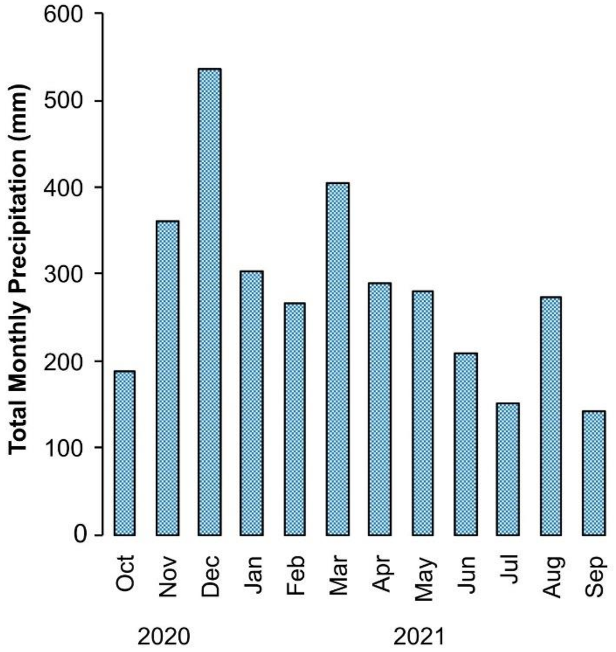

Fig. 3 Study site monthly precipitation totals from 2020-2021. Rain gauge located at study site in the Tropical Silviculture Research Station of the National Institute for Research in the Amazon.

The litter samples were meticulously cleaned and separated into four groups: leaves, twigs with a diameter ≤ 2 cm, reproductive material (*i.e.*, seeds and flowers) and discardable material. The discardable material was not used in this study and included soil, insects, feces, fine roots and unrecognizable debris too small or decomposed to identify. The first three groups were then dried at 65° C for 72 h and then weighed. Soil BD, and correspondingly VWC field samples were weighed and then dried for 24 h at 105 °C. The FRB samples were stored under refrigeration until cleaned with mesh screens and running water. All roots < 2 mm diameter were retained and dried at 65° C for 72 h and then weighed. For soil chemical properties, soil samples were air dried prior to passing through a 2 mm sieve and removing visible organic debris.

2.4. Laboratory analysis

All soil chemical analysis was conducted at INPA's soil laboratory (*Laboratório Temático de Solos e Plantas – LTSP*). Chemical analysis of the forest floor leaves was also conducted at the LTSP. The percent carbon and nitrogen, as well as the C:N ratio for leaves and FRB, were determined with a Perkin Elmer 2400 Elemental Analyzer at INPA's Forest Management Laboratory (*Laboratório de Manejo Florestal – LMF*). Soil organic carbon was determined through the Walkley-Black method and correspondingly soil organic matter with the Van Bemmelen factor of 1.724 (Walkley and Black, 1934, Van Bemmelen, 1890). Soil total nitrogen was determined using the Kjeldahl method (Bremner, 1960). A Perkin Elmer 1100B Atomic Absorption Spectrometer was used to determine Ca^{2+} and Mg^{2+} after extraction with KCl (1 mol/L), whereas available P, K^{+}, Na^{+}, Fe^{2+}, Zn^{2+}, Mn^{2+} was extracted with an Mehlich-1 solution (HCl 0.05 mol/L + H2SO4 0.125 mol/L) (Teixeira *et al.*, 2017). Exchangeable Al^{3+} and H^{+} were determined after extraction with calcium acetate (0.05 mol/L at pH of 7.0) followed by titration. The determination of available phosphorus was conducted by colorimetry in a molybdate blue ascorbic acid solution of 3 % and read in a Shimadzu UV mini 1240 spectrophotometer (UV-120–01; $\lambda = 660$ nm).

2.5. Statistical analysis

Prior to statistical analysis all data were evaluated for a normal distribution and homogeneity of variances. This was accomplished with a combination of the Shapiro-Wilk test, as well as Q-Q plots and histograms. The homogeneity of variances was determined with Levene's test. Determination of the influence of microtopography on litter and nutrient accumulation was done by comparing means of dry litter mass (g m^{-2}) and the leaf litter nutrients N, P, K, Ca, Mg, Fe, Zn and Mn. Litter dry mass and elemental analysis, soil bulk density (g cm^{-3}) and volumetric water content (%) were compared utilizing a General Linear Model (ANOVA), followed by a post hoc Tukey's test. Block and location (i.e., skid trail middle, skid trail ruts and undisturbed forest control) were considered fixed factors in the analysis. Interactions between block and locations were not included in the model, as only main effects were of interest. Assessing the accumulation or deficiency of soil N, P, K, Ca, Mg, Na, Fe, Mn, Zn was done by evaluating the nutrient distributions in the soil through a Kruskal Wallis test followed by a post hoc Dunn's Test with a Bonferroni correction. Also, soil OM, pH, C (%), N (%), C:N, CEC, exchangeable Al, base saturation and Al saturation were evaluated with a General Linear Model (ANOVA) followed by a post hoc Tukey's test. Evaluation of the effect that skid trails have on fine root biomass (g cm^{-3}), C (%), N (%), C:N was made by comparing means with a General Linear Model (ANOVA). Although a few outliers were encountered, they were retained, as they were likely a result of natural variability. All data were analyzed using IBM Corp. SPSS Statistics for Windows, Version 27.0 (Armonk, NY: IBM Corp).

3. RESULTS

3.1. Forest floor litter properties

When compared to controls, there were no differences (*p* = 0.328) in total mean litter mass accumulation for the middle of the skid trails or ruts. Even so, litter dry mass was 7.2 % lower in the middle of the skid trails and 18.6 % higher in the ruts. Individually, the dry mass (g m^{-2}) of the various components that made up the litter were similar across sites for leaves (*p* = 0.087), twigs (*p* = 0.494) and reproductive material (*p* = 0.993) (Fig. 4). Overall, leaves were the dominant component of the forest floor litter. In the controls, leaves composed 74.6 % of the litter followed by ruts at 71.7 % and the middle of the skid trails at 61.5 %. Elemental analysis of leaves revealed two differences between skid trail and control contents of Fe and N (Fig. 5). The element Fe was substantially higher in the leaves of the ruts than the controls or middle of the skid trails (*p* = 0.005). To the contrary, the soil Fe^{2+} concentrations were similar across controls and skid trails with means ranging from 138 to 155 mg kg^{-1} in the upper soil depth and 145 to 153 mg kg^{-1} in the lower depth. The N content in leaf litter was 8.8 % lower in the middle of the skid trails compared to the control (*p* = 0.047), and even though, leaf litter N content in the ruts was 8.6 % lower than the controls, this difference was not significant (*p* = 0.051). In controls and skid trail areas, the ranges

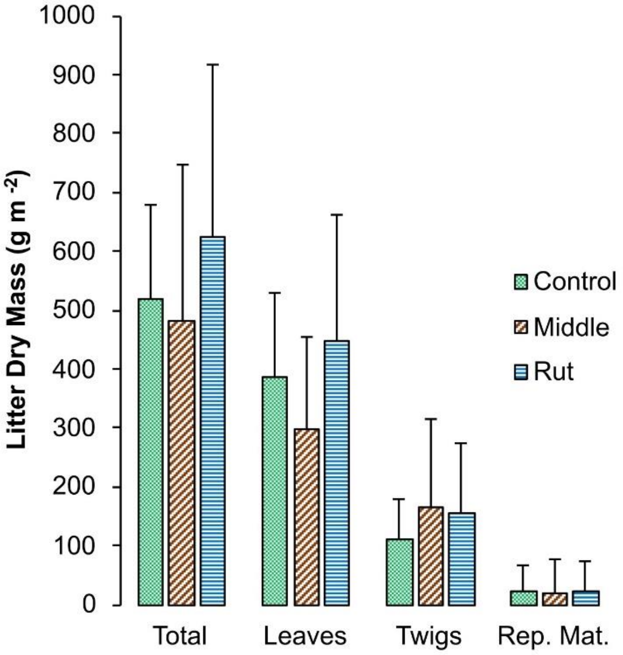

Fig. 4 Litter dry mass (g m^{-2}) total, leaves, twigs, reproductive material, collected from the forest floor surface directly above soil sample locations. Whiskers represent standard deviations.

were similar for leaf litter C 45.5–46.3 % and N 1.6 – 1.7 %, as well as the C:N ratio of 27 – 29.

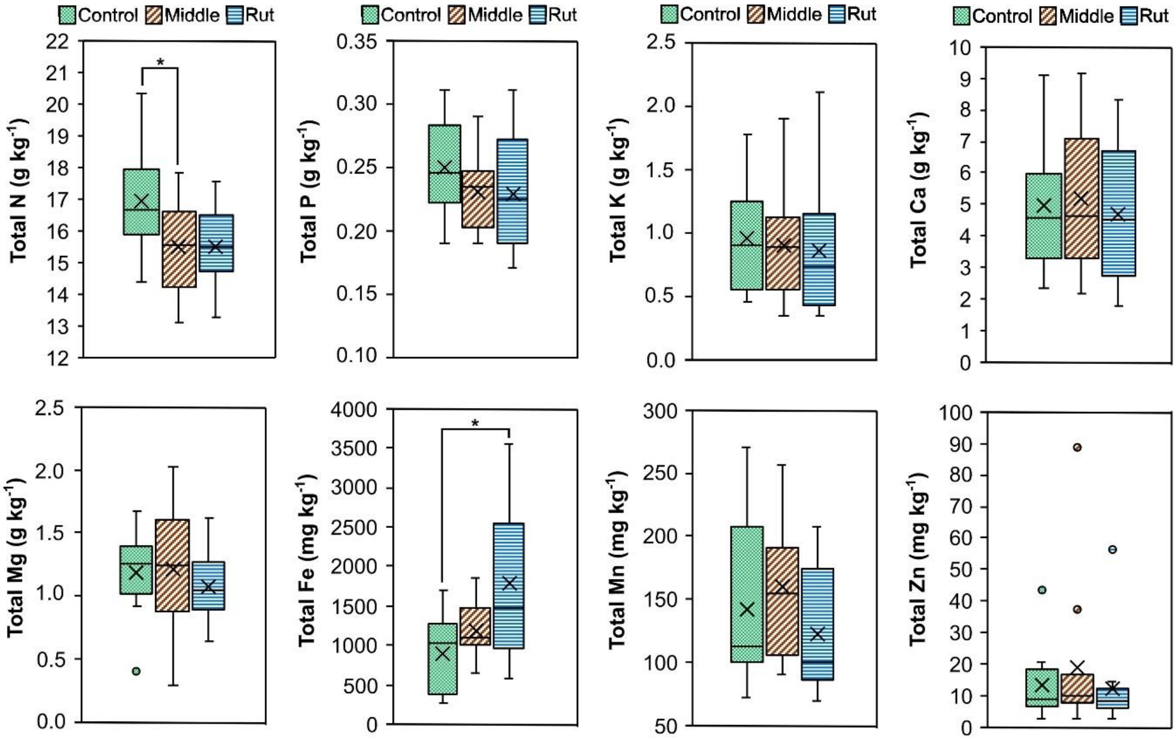

Fig. 5 Nutrient concentrations in leaves from litter collected in controls, skid trail middles and ruts displayed in quartiles with means represented by an x. Small infilled circles represent outliers. Significance levels: **p* < 0.05, ***p* < 0.01 and ****p* < 0.001.

3.2. Soil physical properties

In the 0–5 cm soil depth, elevated soil bulk density (BD) was still encountered 28 years after the last use in the middle of the skid trails at 0.88 g cm^{-3} (p = 0.030). This elevated mean BD was limited to this position between the ruts where logs were dragged across the soil surface. To the contrary, there was only a slight difference (p = 0.666) between the control value of 0.81 g cm^{-3} and that found in the ruts 0.83 g cm^{-3}. In the 5–10 cm depth, the entirety of the skid trail was still compacted with higher values of BD than the control (p = < 0.001). The highest value for BD observed was in the ruts at 1.23 g cm^{-3}, whereas for the same depth, the control values never exceeded 1.05 g cm^{-3}.

In the upper soil depth, volumetric water content (VWC) was different (p = 0.004). The mean VWC in the controls for this depth was 43.9 %, whereas in the ruts VWC was 49.7 %. Also, in the lower depth of 5–10 cm the VWC demonstrated differences (*p* = 0.011). Once again, this difference in VWC was limited to the controls and ruts (*p* = 0.009) at 44.2 % and 47.5 %, respectively.

3.3. Soil chemical properties

The vast majority of macro- and micronutrients had similar distributions across controls and skid trail locations in the upper soil depth of 5 cm (Fig. 6). However, the element manganese was elevated in both the middle of skid trails and ruts when compared to the controls, and the distributions were not the same (H(2) = 8.923, *p* = 0.012). In the 5–10 cm depth, Mn was again elevated in the skid trails with different distributions (H(2) = 12.459, *p* = 0.002) when compared to the controls. Also in the lower depth, nitrogen and magnesium were lower with different distributions (H(2) = 9.312, *p* = 0.010) and (H(2) = 10.029, *p* = 0.007). respectively.

In the upper depth, means of soil chemical properties were similar across the skid trails and controls, except for base and aluminum saturation (Table 2).

Table 2. Soil chemical property means by sample depth and location, followed by the standard deviation (±) in parenthesis. Row with asterisk denotes difference with control (Tukey's HSD test, **p* < 0.05 and ***p* < 0.01). Each value is the mean of 12 samples.

Soil depth	Soil property[a]	Control	Middle	Rut
0-5 cm	Organic Matter (%)	5.82 (1.51)	5.36 (1.36)	6.40 (1.90)
	pH (H_20)	4.06 (0.28)	4.20 (0.23)	4.10 (0.28)
	Organic C (%)	3.38 (0.88)	3.11 (0.78)	3.71 (1.10)
	Total N (%)	0.24 (0.02)	0.23 (0.04)	0.28 (0.06)
	C:N	14.3 (3.82)	13.2 (1.15)	13.3 (1.65)
	CEC (cmol_c kg^{-1})	9.86 (2.80)	8.18 (2.16)	9.81 (3.14)
	Exchangeable Al (cmol_c kg^{-1})	2.08 (0.62)	1.71 (0.40)	1.97 (0.64)
	Base saturation (%)	2.67 (0.75)	3.30 (0.76)	3.47 (0.84)*
	Aluminum saturation (%)	88.7 (3.37)	86.4 (3.08)	85.4 (3.13)*
5-10 cm	Organic Matter (%)	3.66 (0.81)	2.83 (0.78)*	2.58 (0.51)**
	pH (H_20)	4.15 (0.15)	4.36 (0.23)*	4.26 (0.17)
	Organic C (%)	2.12 (0.47)	1.64 (0.45)*	1.50 (0.30)**
	Total N (%)	0.17 (0.02)	0.14 (0.03)**	0.15 (0.02)*
	C:N	12.3 (1.65)	11.5 (1.45)	10.3 (2.12)*
	CEC (cmol_c kg^{-1})	6.79 (1.87)	4.94 (1.20)**	4.84 (0.94)**
	Exchangeable Al (cmol_c kg^{-1})	1.54 (0.44)	1.15 (0.24)*	1.21 (0.14)*
	Base saturation (%)	2.43 (0.72)	2.66 (0.70)	2.66 (0.77)
	Aluminum saturation (%)	90.4 (2.19)	89.8 (2.68)	90.4 (3.18)

[a] Soil organic C was determined by the Walkley-Black method and total N by the Kjeldahl method.

The majority of differences were found in the compacted soils of the lower depth. The organic carbon and total nitrogen levels were significantly different than controls in the compacted lower depth (5–10 cm). However, when combined into a single depth of 0–10 cm there were no differences among the skid trail areas and the controls, for both C_{org} ($p = 0.332$) and N_{tot} ($p = 0.188$). Moreover, when C and N were combined into a single depth and assessed with other studies over time, there appears to be an increasing trend of accumulation of these elements in skid trails (Fig. 7).

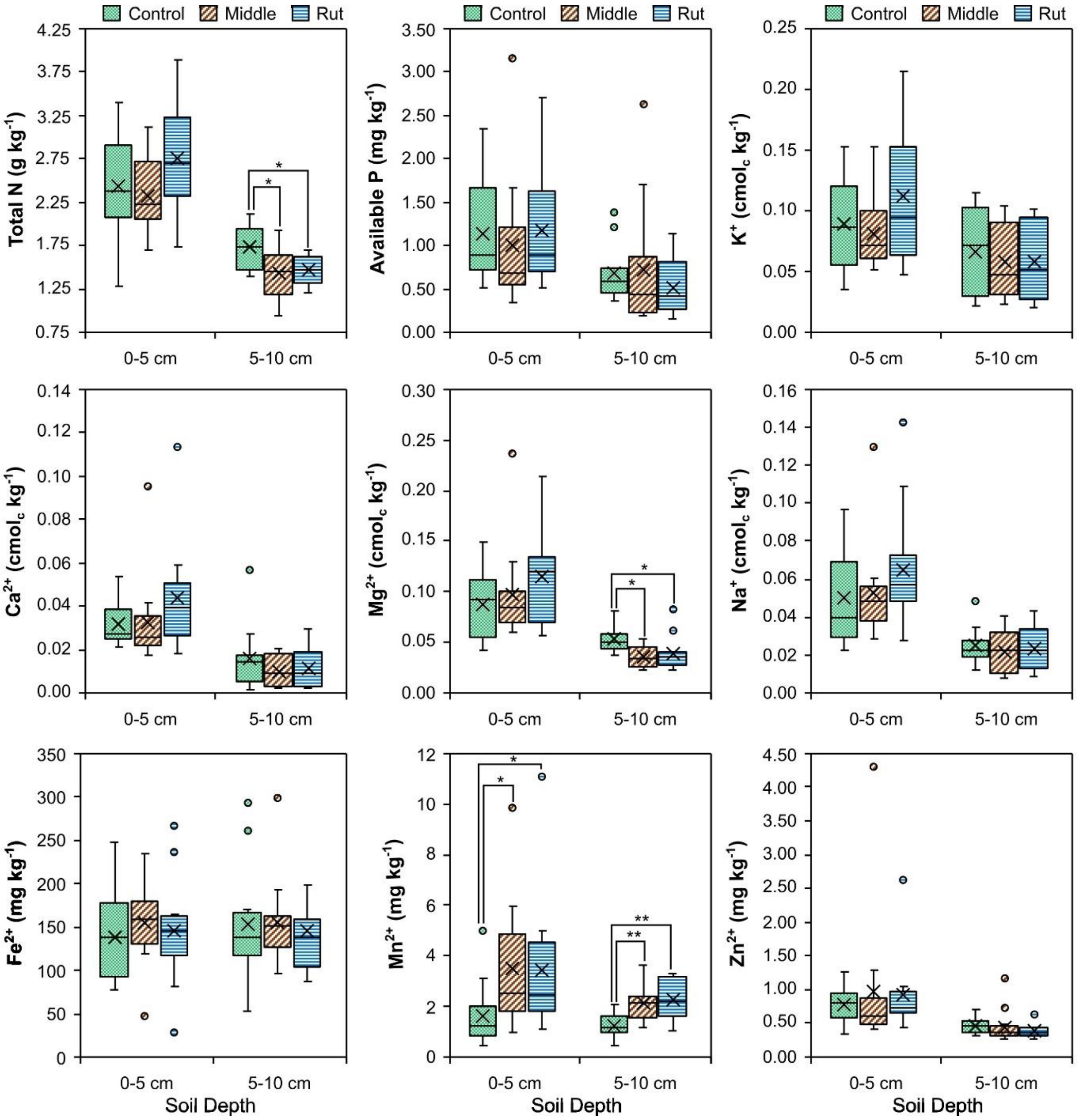

Fig. 6 Soil chemical properties in two depths for the controls, skid trail middles and ruts displayed in quartiles with means represented by an x. Small infilled circles represent outliers. Significance levels: *$p < 0.05$, **$p < 0.01$ and ***$p < 0.001$.

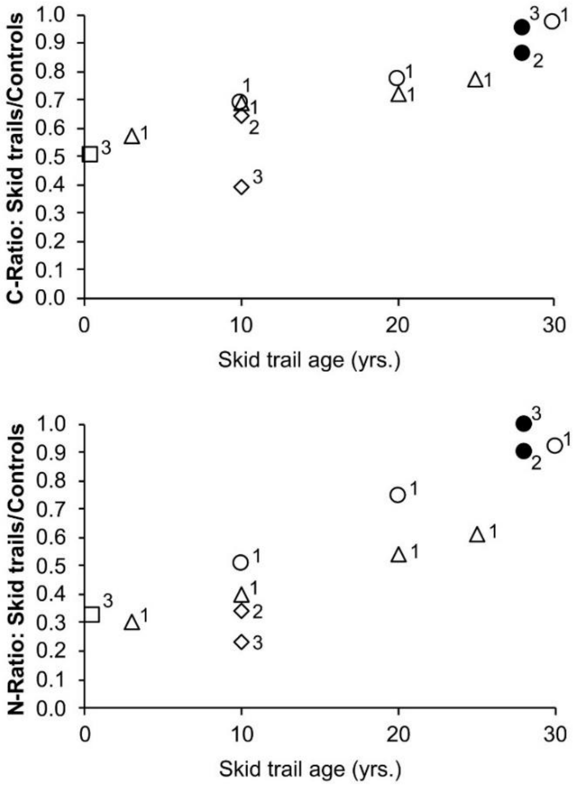

Fig. 7 Ratios of soil C (%) and N (%) between skid trails and controls compared to other studies in the 0-10 cm depth by skid trail age in years. Infilled circles are the present study and open circles the other studies. Numbers represent the following: 1 – skid trail; 2 – skid trail middle; 3 – skid trail rut. Data derived from the following studies: □ - Naghdi et al. (2016b), ◊ - Picchio et al. (2019), Δ - Sohrabi et al. (2020) and ○ - Tavankar et al. (2021b). Analytical methods for C and N determination were the same across studies.

3.4. Fine root biomass

In the 0–5 cm depth, fine root biomass (FRB) and the fine root properties of C (%), N (%) and C:N ratio between 30 and 32 were not different between sample locations. In the 5–10 cm depth, the fine root C:N was lower in the skid trail middles (34) and ruts (33) than the controls (37) with C (%) lower and N (%) higher, although these differences were not considerable (p = 0.153). The only difference was for FRB between the controls and the skid trails in the lower depth (Fig. 8). Also, it should be noted that if depths were not stratified into 5 cm intervals, but rather were combined into a single 0–10 cm depth measurement, there would be similar FRB values for the control at 413 g m^{-2} and the ruts at 410 g m^{-2}. This is because the upper depth in the ruts had such a high value of FRB, which offset the low value in the compacted 5–10 cm soil layer.

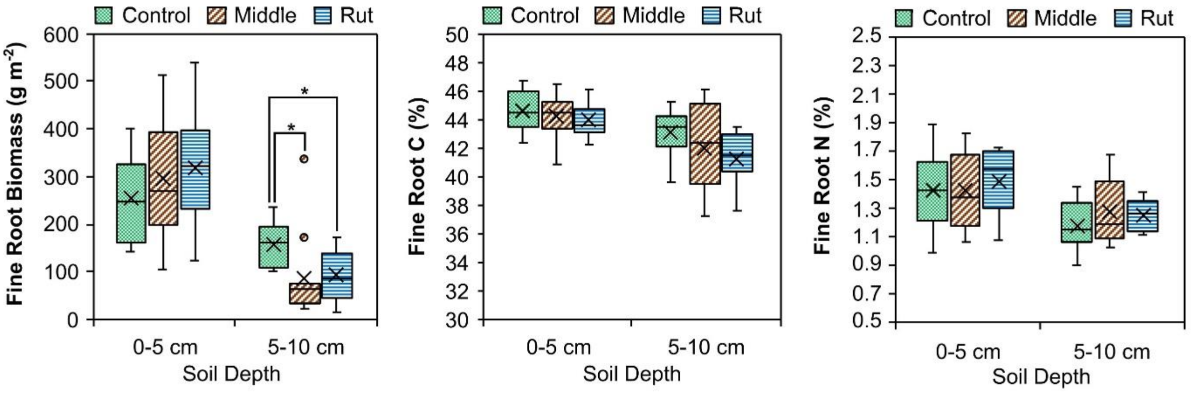

Fig. 8 Fine root biomass, fine root C and fine root N in two depths for the controls, skid trail middles and ruts displayed in quartiles with means represented by an x. Small infilled circles represent outliers. Significance levels: *$p < 0.05$, **$p < 0.01$ and ***$p < 0.001$.

4. DISCUSSION

4.1. Forest floor litter properties

The composition of litter encountered in the present study aligns with other studies of logged Amazonian forests in Brazil. Namely that the vast majority of litter is dominated by leaves, followed by twigs and then reproductive material (Almeida *et al.*, 2015, da Silva *et al.*, 2018). Lack of differences between litter biomass in skid trails and forest reference sites was also encountered 4–6 months after logging in the eastern Amazon (Olander *et al.*, 2005). The same has also been observed in skid trails of temperate forests, where litter depth was not statistically different than the controls after 6, 10 and 20 years (Sohrabi *et al.*, 2022). Nonetheless, Sohrabi *et al.* (2022) still found that the percent of C and N in litter increased over time, although the greatest differences in litter thickness and chemical properties were between forest stands composed of different species. The total litterfall in the skid trails and controls was slightly lower than a previous study of litterfall in the area (Ourique *et al.*, 2016). However, the two litter collections for this study were done after months of nearly identical precipitation totals (May 280 mm and August 273 mm). It should be noted, that this value for precipitation for the month of August is more than double a normal year, which negatively affects litterfall. This is because leaf litter production is negatively affected by precipitation (de Morais *et al.*, 2021).

In the chemical analysis of the leaves, a noteworthy and elevated Fe content was encountered in the litter of the ruts. A high concentration of Fe is not uncommon in decomposing litter (Bonanomi *et al.*, 2010). However, the elevated Fe values were only found in the ruts, whereas in the middle of the skid trail and control sites values were quite similar. This could be related to the water accumulation in the skid trail ruts that was observed during sample collection after heavy precipitation events. This did not occur in the middle of the skid trails or controls. Studies have shown that with elevated moisture conditions, Fe can permeate the surface and accumulate in the litter (Gosz *et al.*, 1973, Lousier and Parkinson, 1978).

4.2. Soil physical properties

The soil bulk density (BD) in the upper 5 cm of the ruts was already determined to be recovered in terms of compaction and not statistically different than the controls, corroborating a previous study in the area (DeArmond *et al.*, 2019). However, the BD values here declined by 6.7 % since the last sampling four years prior. Whereas, the BD in the compacted layer below this (5–10 cm), only declined by 1.8 % in the last four years. In fact, this lower depth is actually quite similar to the initial compaction reported 6 months after logging operations 28 years ago in the 4–7 cm depth recorded for these skid trails (Mello-Ivo and Ross, 2006). This is in agreement with studies on soil recovery in skid trails that demonstrate the topsoil recovers at a faster rate because of the atmospheric interface, litter and biological activity (DeArmond *et al.*, 2021).

The volumetric water content (VWC) seems to infer a potential hardpan below the top 5 cm of recovered soil in the ruts. This is because there was an elevated soil VWC in the recovered topsoil, which indicates slower drainage than the control. So, even if the soil does not initially have a hardpan, heavy machinery traffic may lead to the development of one (Raper *et al.*, 1994), which appears to be the case in these skid trail ruts. A further indication of a hardpan, would be the wide difference in fine root biomass between the upper and the lower compacted depth, as hardpans restrict root growth (Dexter, 1991). Nevertheless, although root restrictive conditions are created by a hardpan, studies have shown some beneficial aspects to areas above hardpans such as increased water use efficiency and increased root length, area, volume and weight (St Aime *et al.*, 2021). Therefore, it appears that in the skid trail ruts, fine roots in the upper soil have benefitted from the compacted hardpan conditions below.

4.3. Soil chemical properties

The micronutrient Mn stands out as the sole nutrient that was elevated in both depths throughout the skid trail when compared to the control. This can be a concern, as high levels of exchangeable manganese can be toxic (Brady and Weil, 1999, Li *et al.*, 2021). Increases in Mn were also observed in Southern Cameroon, where logging activities such as construction of skid trails, log landings and haul roads occurred, all activities that cause soil compaction (Tchiofo Lontsi *et al.*, 2019). To the contrary, felling gaps in Amazonia with little to no increases in soil compaction, had 3.5 times the Mn content of the control, as well as a lower pH 18 months after logging operations (Trindade *et al.*, 2021). So, the question remains why is there abundant Mn in the entirety of the skid trails which have a higher pH than the controls after 28 years? Here there are anoxic and suboxic conditions created from waterlogging and poor drainage that cause increases in the reduction of Mn (IV) to its exchangeable and more mobile form Mn (II) (Warrinnier *et al.*, 2020, Li *et al.*, 2021). Although the upper 5 cm of soil in the ruts has no difference in soil bulk density and penetration resistance than controls, the subadjacent layer is still compacted. Therefore, it appears that this still compacted soil layer is acting as a hardpan and impacting the surface soil by affecting the redox potential through increased moisture levels.

The percent base saturation was higher in the skid trails, but much higher in the topsoil of the skid trail ruts. The compaction was greatest in the lower depth below this topsoil in the ruts, so it appears that there may have been an impediment to the leaching of base metals. This would not be without precedent, as Kurozumi *et al.* (2020) recently demonstrated that the retainment of exchangeable cations was greatest when a hardpan was present. Initially after logging, the skid trails in the present study had reported higher levels of Ca, Mg, K and Na (Mello-Ivo *et al.*, 1996), although almost 2 years after logging operations they were no longer different than the controls (Ferreira *et al.*, 2001). The elevated levels of base cations in the rut topsoil are in accordance with other studies in Amazonia outside the study area. Six months after logging Olander *et al.* (2005) found increased exchangeable K, Mg and Ca in log landing topsoil, whereas McNabb *et al.* (1997) encountered higher levels of Ca and Mg in skid trails 16 years after logging.

When it comes to data on exchangeable aluminum in skid trails, there are only a few studies available. Nevertheless, in temperate regions skid trails appear to increase exchangeable Al (Borchert *et al.*, 2015, Treasure *et al.*, 2019), whereas in the tropics skid trails have shown decreases in Al (Ferreira *et al.*, 2001, Tchiofo Lontsi et al., 2019), although one study in the Amazon found no difference (Olander *et al.*, 2005). In the present study, lower levels of exchangeable Al were encountered throughout the skid trails. The values for Al in the more compacted lower depth were slightly lower than the controls. This is the result of higher pH levels in the skid trails. Numerous studies in temperate and tropical regions have demonstrated increases to pH in skid trails when compared to forest controls (Ferreira *et al.*, 2001, Olander *et al.*, 2005, Warlo *et al.*, 2019, Tchiofo Lontsi *et al.*, 2019, Jourgholami *et al.*, 2021a), especially in skid trails with increasing machinery passes and soil compaction (Naghdi *et al.*, 2016b). Furthermore, even though the compaction in the topsoil of the ruts was no different than the control, the organic matter (OM) content was higher and OM strongly binds up soluble aluminum (Brady and Weil, 1999). However, in the lower depth, the OM was actually lower, but with a higher pH, which was higher in the middle of the skid trails than the ruts. Consequently, as organic C has been shown to recover prior to soil physical properties such as soil bulk density (Hosseini *et al.*, 2015; Jourgholami *et al.*, 2019, DeArmond *et al.*, 2022), it appears that recovery of the compacted soil of these heavy clay soils is a lengthy process that requires decades, or more.

This recovery process is further inhibited by the nitrogen deficiency in the compacted soil of the skid trails. Although there has been 28 years since these skid trails were last used, it is not surprising that soil N is still impoverished in the compacted layer. In a temperate forest in Iran, Sohrabi *et al.* (2020) also found that after 25 years the N in the skid trail soils had still not yet recovered. Furthermore, the skid trails in the present study were primary skid trails for the logging operation, which entails heavy usage by tractors. Indeed, several studies have demonstrated that increasing traffic and the subsequent compaction negatively impacts N (Naghdi *et al.*, 2016b, Solgi *et al.*, 2019). Overall, skid trails have been shown to impact N mineralization, ammonium and total N (Ebrecht and Schmidt, 2003, Ilstedt *et al.*, 2006, Shabaga *et al.*, 2017). Some of these N losses in the compacted skid trails can be attributed to denitrification of the soils from inadequate drainage patterns and low oxygen levels (Barton *et al.*, 1999, Brady and Weil, 1999).

4.4. Fine root biomass

In terms of fine root biomass (FRB), the topsoil of the skid trails (0–5 cm) has experienced a full recovery, which is noteworthy as the greatest impact to FRB occurs in the ruts of skid trails (Malo and Messier, 2011). In the same skid trails, Guimarães and Mello-Ivo (1997) reported 410 g m−2 in the upper 15 cm of depth seven months after logging operations. In contrast, the current study encountered after 28 years in the same skid trails an average of 395 g m^{-2} in the upper 10 cm. However, these two studies were conducted in different seasons making direct comparisons difficult, as there are differences in FRB and fine root productivity in the tropics because of seasonal influence (DeArmond *et al.*, 2022; Cordeiro *et al.*, 2020). Additionally, the log landings that supported these skid trails had approximately 225 g m^{-2} in the upper 10 cm, which still had not recovered to the FRB levels of the controls 27 years after use (DeArmond *et al.*, 2022). So, the skid trails in this area have recovered faster than the landings in regards to FRB, at least in the topsoil. This is not unexpected as fine root recovery in skid trails occurs at the surface (von Wilpert and Schäffer, 2006, Ebeling *et al.*, 2017, DeArmond *et al.*, 2021). Also noteworthy, the skid trail ruts had a higher base saturation than the control, which may have benefited and even led to the slightly higher FRB. This is likely, as a recent fertilization study in the Central Amazon demonstrated that fine root tissues benefitted from the addition of exchangeable bases (Lugli *et al.*, 2021), although a fertilization experiment in Panama with only K addition found lower FRB (Wurzburger and Wright, 2015). In the present study, in contrast to the FRB in the topsoil, the compacted soil at the 5–10 cm depth, FRB was severely impoverished, even 28 years after logging operations.

5. CONCLUSION

Logging operations every year generate compaction in forest soils from heavy machinery, primarily from skid trails. In Central Amazonia, the question posed was if the observed soil recovery in the topsoil of heavily used skid trails was complete. The present investigation seems to indicate that a full recovery of the soil properties evaluated has indeed occurred, with one caveat. This being that the influence of the still impaired compacted layer below has a direct impact on the recovered soil layer above it. Consequently, the hardpan conditions below the skid trail ruts resulted in increased soil moisture, higher accumulation of nutrients and greater fine root biomass in the recovered topsoil. Therefore, a recovered topsoil is likely to be affected and influenced by the compacted soil below it for decades or more in the clay soils of Amazonia. The consequence for forest management is the potential loss of site productivity in skid trails for the foreseeable future. This further reinforces the need to designate and consider skid trails as permanent logging infrastructure. Lastly, the authors recommend that the surface area covered by skid trails in timber harvesting operations should be minimized to the greatest extent feasible.

GENERAL CONCLUSION

Each year, previously undisturbed old-growth forest in the Brazilian Amazon is logged. Subsequently, large areas of topsoil disturbance and soil compaction occur in these areas, year after year. Moreover, after nearly three decades, soil compaction in log landings remained, although surface soil recovery in skid trails was observed. Despite this, soil compaction persisted below the soil recovery in skid trails, even after 28 years. Therefore, skid trail should always be considered a permanent part of the logging infrastructure network with log landings and haul roads. As such, the maximum distribution of skid trail coverage in logging areas should be stipulated in future legislation.

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APPENDIX A

Supplementary Material for

Logging machinery traffic has greatest influence on soil chemical properties in the Amazonian rainy season

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This file includes:

Tables S1 to S6

Table S1. Pairwise comparisons for soil chemical properties for a given location between wet and dry seasons. All values adjusted with the Bonferroni correction for multiple tests.

Factor†	Location			
	Control	1 cycle	3 cycles	12 cycles
pH$_{\mathrm{H2O}}$	**0.001**	**0.016**	**<0.001**	1.000
pH$_{\mathrm{KCL}}$	0.086	1.000	**0.028**	1.000
C.E.C.	1.000	1.000	1.000	1.000
T.E.B.	0.679	0.350	**0.011**	1.000
H^{+} + Al^{3+}	0.729	1.000	1.000	1.000
Al^{3+}	**<0.001**	**0.002**	**<0.001**	0.235
B. sat.	**0.049**	0.926	**0.002**	1.000
Al sat.	**0.001**	**0.004**	**<0.001**	1.000

†C.E.C – cation exchange capacity; T.E.B. – total exchangeable bases;
H^{+} + Al^{3+} – exchangeable acidity; B. sat. – base saturation;
Al sat. – aluminum saturation.
Note: All differences between locations (p < 0.05) bolded.

Table S2. Pairwise comparisons for soil chemical properties and various locations. All values adjusted with the Bonferroni correction for multiple tests.

Factor†		Wet Season			Dry Season		
	Location	1 cycle	3 cycles	12 cycles	1 cycle	3 cycles	12 cycles
pH$_{\mathrm{H2O}}$	Control	1.000	1.000	**<0.001**	1.000	1.000	1.000
	1 cycle		1.000	**<0.001**		1.000	1.000
	3 cycles			**<0.001**			1.000
pH$_{\mathrm{KCL}}$	Control	1.000	1.000	**<0.001**	1.000	1.000	1.000
	1 cycle		0.924	**0.008**		1.000	1.000
	3 cycles			**<0.001**			1.000
C.E.C.	Control	0.067	1.000	**0.019**	1.000	1.000	1.000
	1 cycle		**0.013**	1.000		1.000	1.000
	3 cycles			**0.003**			1.000
T.E.B.	Control	1.000	1.000	0.077	1.000	1.000	1.000
	1 cycle		1.000	**<0.001**		1.000	1.000
	3 cycles			**0.001**			1.000
H^{+} + Al^{3+}	Control	0.099	1.000	**0.010**	1.000	1.000	1.000
	1 cycle		**0.017**	1.000		1.000	1.000
	3 cycles			**0.001**			1.000
Al^{3+}	Control	1.000	1.000	0.082	1.000	1.000	1.000
	1 cycle		1.000	1.000		1.000	1.000
	3 cycles			**0.012**			1.000
B. sat.	Control	1.000	1.000	**0.009**	1.000	1.000	1.000
	1 cycle		1.000	**0.001**		1.000	1.000
	3 cycles			**<0.001**			1.000
Al sat.	Control	1.000	1.000	**0.010**	1.000	1.000	1.000
	1 cycle		1.000	**0.002**		1.000	1.000
	3 cycles			**<0.001**			1.000

†C.E.C – cation exchange capacity; T.E.B. – total exchangeable bases;
H^{+} + Al^{3+} – exchangeable acidity; B. sat. – base saturation; Al sat. – aluminum saturation.
Note: All differences between locations (p < 0.05) bolded.

Table S3. Pairwise comparisons for total N, organic C, NO_3^- and NH_4^+ for a given location between wet and dry seasons. All values adjusted with the Bonferroni correction for multiple tests.

Factor	Location			
	Control	1 cycle	3 cycles	12 cycles
Total N	1.000	1.000	1.000	**0.006**
Organic C	1.000	0.057	1.000	**0.008**
NO_3^-	**0.003**	0.188	**<0.001**	**<0.001**
NH_4^+	**<0.001**	**0.001**	**<0.001**	1.000

Note: All differences between locations ($p < 0.05$) bolded.

Table S4. Pairwise comparisons for total N, organic C, NO_3^- and NH_4^+ and various locations. All values adjusted with the Bonferroni correction for multiple tests.

Factor		Wet Season			Dry Season		
	Location	1 cycle	3 cycles	12 cycles	1 cycle	3 cycles	12 cycles
Total N	Control	1.000	1.000	**0.026**	1.000	1.000	1.000
	1 cycle		0.099	1.000		1.000	1.000
	3 cycles			**<0.001**			1.000
Organic C	Control	0.705	1.000	**0.040**	1.000	1.000	1.000
	1 cycle		0.251	1.000		1.000	1.000
	3 cycles			**0.010**			1.000
NO_3^-	Control	1.000	1.000	0.512	1.000	1.000	1.000
	1 cycle		1.000	0.172		1.000	1.000
	3 cycles			1.000			1.000
NH_4^+	Control	1.000	1.000	**<0.001**	1.000	1.000	1.000
	1 cycle		1.000	**0.003**		1.000	1.000
	3 cycles			**0.004**			1.000

Note: All differences between locations ($p < 0.05$) bolded.

Table S5. Pairwise comparisons for Ca^{2+}, Mg^{2+}, K^{+}, Na^{+}, Available P and Fe^{2+} for a given location between wet and dry seasons. All values adjusted with the Bonferroni correction for multiple tests.

Factor	Location			
	Control	1 cycle	3 cycles	12 cycles
Ca^{2+}	1.000	1.000	0.521	1.000
Mg^{2+}	1.000	1.000	0.903	1.000
K^{+}	**0.006**	**<0.001**	**0.033**	0.701
Na^{+}	1.000	0.261	1.000	1.000
Available P	1.000	0.188	1.000	**<0.001**
Fe^{2+}	1.000	0.481	1.000	1.000

Note: All differences between locations ($p < 0.05$) bolded.

Table S6. Pairwise comparisons for soil chemical properties and various locations. All values adjusted with the Bonferroni correction for multiple tests.

Factor		Wet Season			Dry Season		
	Location	1 cycle	3 cycles	12 cycles	1 cycle	3 cycles	12 cycles
Ca^{2+}	Control	1.000	1.000	**0.002**	1.000	1.000	0.418
	1 cycle		1.000	**<0.001**		1.000	0.488
	3 cycles			**<0.001**			1.000
Mg^{2+}	Control	1.000	1.000	**0.001**	1.000	0.892	0.098
	1 cycle		1.000	**0.005**		1.000	0.188
	3 cycles			**0.013**			1.000
K^{+}	Control	1.000	1.000	1.000	1.000	1.000	0.498
	1 cycle		1.000	1.000		1.000	1.000
	3 cycles			1.000			1.000
Na^{+}	Control	**<0.001**	0.416	**0.019**	**0.010**	0.563	**0.002**
	1 cycle		0.635	1.000		1.000	1.000
	3 cycles			1.000			1.000
Avail. P	Control	1.000	1.000	1.000	1.000	1.000	1.000
	1 cycle		1.000	1.000		1.000	1.000
	3 cycles			0.188			1.000
Fe^{2+}	Control	1.000	0.225	**<0.001**	1.000	0.135	**0.002**
	1 cycle		1.000	**<0.001**		1.000	1.000
	3 cycles			**0.001**			1.000

Note: All differences between locations ($p < 0.05$) bolded.

APPENDIX B

Supplementary Material for

Surface soil recovery occurs within 25 years for skid trails in the Brazilian Amazon

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This file includes:

Tables S1 to S3

Table S1. Spearman's correlation coefficients for soil properties and fine root biomass for skid trails (*n* = 60).

	BD	FRB	pH$_{\mathrm{H20}}$	pH$_{\mathrm{KCL}}$	OC	N	P	Na^{+}	K^{+}	Ca^{2+}	Mg^{2+}	Al^{3+}	H + Al^{3+}	CEC	PBS	AS	TEB	Sand	Silt	Clay
BD	1.000	-0.152	0.289*	0.293*	-0.714***	-0.684***	-0.391**	-0.486***	-0.551***	-0.442***	-0.424**	-0.646***	-0.744***	-0.742***	0.021	0.193	-0.494***	0.546***	-0.155	-0.098
FRB		1.000	0.228	0.140	0.016	0.055	-0.072	0.559***	0.040	-0.251	-0.050	-0.117	-0.087	-0.088	0.020	-0.109	-0.009	0.156	0.011	0.015
pH$_{\mathrm{H20}}$			1.000	0.818***	-0.528***	-0.513***	-0.509***	-0.119	-0.647***	-0.611***	-0.466***	-0.729***	-0.578***	-0.578***	-0.199	0.242	-0.558***	0.619***	-0.306*	0.111
pH$_{\mathrm{KCL}}$				1.000	-0.585***	-0.551***	-0.367**	-0.154	-0.640***	-0.572***	-0.432**	-0.693***	-0.595***	-0.595***	-0.180	0.229	-0.553***	0.548***	-0.267*	-0.042
OC					1.000	0.801***	0.566***	0.355**	0.780***	0.654***	0.646***	0.778***	0.902***	0.907***	0.217	-0.418**	0.754***	-0.502***	0.217	0.050
N						1.000	0.561***	0.363**	0.787***	0.594***	0.681***	0.611***	0.774***	0.779***	0.346**	-0.512***	0.759***	-0.510***	0.062	0.060
P							1.000	0.177	0.648***	0.528***	0.792***	0.390**	0.516***	0.532***	0.599***	-0.689***	0.776***	-0.241	0.171	-0.071
Na^{+}								1.000	0.385**	0.025	0.195	0.299*	0.337**	0.327*	0.086	-0.239	0.314*	-0.239	0.176	0.189
K^{+}									1.000	0.639***	0.647***	0.699***	0.814***	0.816***	0.411**	-0.558***	0.833***	-0.557***	0.152	-0.170
Ca^{2+}										1.000	0.711***	0.608***	0.630***	0.641***	0.495***	-0.543***	0.770***	-0.432**	0.212	0.000
Mg^{2+}											1.000	0.388**	0.531***	0.553***	0.789***	-0.855***	0.934***	-0.267*	0.147	0.107
Al^{3+}												1.000	0.879***	0.871***	-0.049	-0.063	0.534***	-0.748***	0.286*	-0.013
H + Al^{3+}													1.000	0.999***	0.080	-0.290*	0.684***	-0.697***	0.217	-0.055
CEC														1.000	0.106	-0.316*	0.701***	-0.684***	0.216	-0.061
PBS															1.000	-0.929***	0.740***	0.105	0.007	-0.005
AS																1.000	-0.843***	0.016	-0.061	0.026
TEB																	1.000	-0.381**	0.190	0.016
Sand																		1.000	-0.397**	-0.004
Silt																			1.000	0.057
Clay																				1.000

Note: BD - bulk density, FRB - fine root biomass, OC - organic carbon, N - total nitrogen, P - available phosphorus, H + Al^{3+} - exchangeable acidity, CEC - cation exchange capacity, PBS - percent base saturation, AS - aluminum saturataion, TEB - total exchangeable bases. Levels of statistical significance: *P <0.05, **P <0.01 and ***P <0.001.

Table S2. Spearman's correlation coefficients for soil properties and fine root biomass for control/references (*n* = 30) [BD, *n* = 29; Ca^{2+}, *n* = 29].

	BD	FRB	pH$_{H20}$	pH$_{KCL}$	OC	N	P	Na^+	K^+	Ca^{2+}	Mg^{2+}	Al^{3+}	$H + Al^{3+}$	CEC	PBS	AS	TEB	Sand	Silt	Clay
BD	1.000	-0.122	-0.203	-0.223	-0.067	0.001	0.254	-0.086	0.195	0.313	0.203	-0.035	-0.091	-0.080	0.230	-0.188	0.352	0.292	-0.348	-0.063
FRB		1.000	0.268	0.095	0.048	-0.025	0.096	0.626***	0.302	0.011	0.096	-0.199	-0.140	-0.144	0.456*	-0.439*	0.353	-0.195	0.331	-0.035
pH$_{H20}$			1.000	0.700***	-0.630***	-0.649***	-0.525**	0.245	-0.378*	-0.486**	-0.220	-0.823***	-0.624***	-0.618***	0.262	-0.266	-0.316	0.009	0.284	-0.391*
pH$_{KCL}$				1.000	-0.658***	-0.475**	-0.596**	0.092	-0.350	-0.476**	-0.298	-0.755***	-0.726***	-0.724***	0.209	-0.226	-0.393*	-0.206	0.295	-0.147
OC					1.000	0.739***	0.642***	-0.029	0.566**	0.447*	0.400*	0.832***	0.856***	0.855***	-0.176	0.139	0.488**	-0.066	0.093	0.154
N						1.000	0.603***	-0.078	0.466**	0.426*	0.554**	0.593**	0.680***	0.682***	0.021	-0.081	0.522**	-0.005	-0.069	0.254
P							1.000	-0.039	0.544**	0.404*	0.578**	0.511**	0.542**	0.542**	0.214	-0.193	0.685***	0.441**	-0.286	-0.171
Na^+								1.000	0.412*	-0.120	0.035	-0.272	-0.211	-0.205	0.563**	-0.547**	0.414*	-0.249	0.162	0.042
K^+									1.000	0.355	0.477**	0.393*	0.517**	0.517**	0.380*	-0.394*	0.772***	-0.139	-0.034	0.269
Ca^{2+}										1.000	0.311	0.491**	0.453*	0.447*	-0.011	0.022	0.432*	0.076	-0.147	0.262
Mg^{2+}											1.000	0.174	0.353	0.376*	0.589**	-0.639***	0.787***	0.225	0.008	-0.089
Al^{3+}												1.000	0.879***	0.870***	-0.475**	0.460*	0.266	-0.043	-0.087	0.290
$H + Al^{3+}$													1.000	0.999***	-0.370*	0.307	0.403*	0.029	-0.103	0.230
CEC														1.000	-0.353	0.288	0.417*	0.033	-0.101	0.222
PBS															1.000	-0.978***	0.619***	0.061	0.107	-0.152
AS																1.000	-0.646***	-0.044	-0.130	0.144
TEB																	1.000	0.222	-0.156	-0.028
Sand																		1.000	-0.684***	-0.684***
Silt																			1.000	0.030
Clay																				1.000

Note: BD - bulk density, FRB - fine root biomass, OC - organic carbon, N - total nitrogen, P - available phosphorus, $H + Al^{3+}$ - exchangeable acidity, CEC - cation exchange capacity, PBS - percent base saturation, AS - aluminum saturataion, TEB - total exchangeable bases. Levels of statistical significance: *P <0.05, **P <0.01 and ***P <0.001.

Table S3. Linear regression summary.

Dependent	Coefficients				Model Fit	
Variable	Constant	SE	Year	SE	R^2	D-W Statistic
pH H_2O	4.200***	0.121	-0.014*	0.006	0.090	2.205†
pH KCL	3.723***	0.070	-0.011**	0.003	0.153	2.038†
Organic C	12.124***	2.882	0.675***	0.138	0.291	1.893
Total N	0.586**	0.201	0.066***	0.010	0.445	1.703
Available P	0.377	0.333	0.050**	0.016	0.147	1.417
K^+	5.808	4.580	0.677**	0.220	0.143	2.186†
Na^+	2.170	1.120	0.216***	0.054	0.217	1.553
Ca^{2+}	0.034	0.024	-0.001	0.001	0.007	2.226†
Mg^{2+}	-0.009	0.031	0.005**	0.001	0.172	2.083†
Al^{3+}	1.121***	0.238	0.039**	0.011	0.172	2.187†
CEC	3.361***	0.851	0.229***	0.041	0.351	1.441
Base Saturation	1.339*	0.536	0.051	0.026	0.066	1.949†
Al Saturation	95.457***	2.176	-0.217*	0.104	0.071	1.957†
Total Ex. Bases	0.039	0.054	0.008**	0.003	0.128	2.153†
$H+Al^{3+}$	3.338***	0.832	0.221***	0.040	0.345	1.439

†The Prais-Winsten estimation method is used for data in this row.

Levels of statistical significance: *P < 0.05, **P < 0.01, ***P < 0.001.